

Senate Agriculture & Natural Resources

03/28/2024 01:30 PM

SB24-159 Mod to Energy & Carbon Management Processes

Typed Text of Testimony Submitted

Name, Position, Representing	Typed Text of Testimony
Molly Jacobs For themselves	<p>I'm writing to beg you to please stop approving permits for oil companies. They only create 1% of the jobs in Colorado but have skyrocketed our pollution to the be 6th worst in the entire country. They've also littered our state with 120,000 toxic oil wells. SB24-159 is a common sense bill that protects our children's futures from the billion-dollar corporations that are still taking more than they give to our state. When you review the details of the bill, you will see that it's a thoughtful and just transition that will benefit Coloradans and put an end to the abuse our state has been subjected to up to this point.</p>
David Bishton For themselves	<p>I wish to state my support for SB24-159 Mod to Energy & Carbon Management Processes. It is very timely to take action to end the era of limitless exploration and production of fossil fuels. We know with certainty that what has enabled the engines of modern life is also creating havoc on the natural systems and life forms of our planet. The impact of this damage, both now and in the future, far outweighs the temporary economic impacts to a private and well-subsidized industry. It's time for them to accept that their time is over.</p> <p>This bill generously starts with the concept of ceasing new permitting 6 years in the future, but also beginning a reduction period 2 years prior to that end date to avoid an overwhelming of the application process sure to otherwise occur. The fossil industry CAN adapt despite their vociferous positions to the contrary.</p> <p>It is also very important to deal with the problem of orphaned oil and gas infrastructure. It is well known that corporations can be created within the industry for the sole purpose of making it hard to discover past ownership & operation of wells at the end of their lives in an attempt to evade financial responsibility. This is a horrible tactic that must be stopped.</p>

	<p>In order to end the "it wasn't me" approach to the current problem, I would also support a bill (or amendment) that immediately establishes a fee on future permits that will fund ALL state mitigation operations when owners or operators cannot be determined. This can be proportional to how many wells a proposed permit applicant already operates in the state, so as to avoid small producers having to pay the same fee as large ones.</p> <p>Thank you for considering my testimony.</p>
<p>Janet Chapman For Citizens' Climate Lobby.org- Montrose</p>	<p>I spoke with Cleave Simpson Feb 21 via zoom with Montrose county commissioners. After he explained SB24-159 bill I asked to reform Oil and Gas Conservation Act to hold prior owners liable.Representing my Montrose Citizens' Climate Lobby.org of 400 Montrose members-nonpartisan national we support curtailment of oil and gas to benefit the environment</p>
<p>Karen Kalavity For themselves</p>	<p>For too long, we have caved in to oil and gas interests. It is true, that I - myself - use gasoline to propel my automobile into movement, and it is also true that I "depend" on natural gas to heat my home, etc.</p> <p>But these dependencies can be broken, just as any harmful addiction can be stopped.</p> <p>We have the power to generate electricity from solar roofs, and to generate heat from heat pumps and other forms of renewable energy - which also happen to be fossil free. The time to cut the cord is now. Especially when we understand the damage that is being done to our planet's air, water and soil through dangerous and dirty use of fossil fuels.</p> <p>This bill will require that no more oil and gas wells be drilled in Colorado after 2030 (or slightly after). It will also require that the "perpetrators" of the dirty actions be MANDATED to clean up their leaky and left-behind-wells, etc. This is not too much to ask for, in fact, it is necessary to start asking and demanding it NOW, rather than later.</p>

	<p>Stop the mess and clean up your mess is what this bill mandates. Our energy needs can be met in cleaner ways and the time to start is NOW!</p>
<p>El Sealey For themselves</p>	<p>My name is El Sealey and I am a 27 year old Colorado resident and constituent in Denver county. I am writing testimony on behalf of support for Bill SB24-159, Mod to Energy and Carbon Management (Phase Out and Clean Up).</p> <p>This Bill concerns me because climate change is one of the biggest threats to our state of Colorado. My family owns land in Green Mountain Falls, a small town between Colorado Springs and Woodland Park. I have seen firsthand the changes in our mountain ecosystems over the course of my 27 years. When I was a child, the mountains by our cabin flourished every summer with wildflowers and had permanent riverlets that flowed beside our favorite hiking spots. In my teenage years, the riverlets dried up, the flowers vanished, and the mountain ecosystem changed drastically as summers got hotter, drier, and longer.</p> <p>In 2012, the Waldo Canyon fire almost burned down our cabin. The sky was black with smoke, our neighbors were forced to evacuate, the mountain animals were left to choke on ash or run from it if they could. The forests I played in as a child were burned into nothing.</p> <p>The Bill SB24-159 is a meaningful step in the right direction to help protect our diverse mountain ecosystems, prevent future wildfires from destroying our forests, and can help protect Coloradan homes. Young people like me deserve safety, we deserve meaningful action to prevent climate change, and the time to act is now. Every year that we do not act, the problem of climate change will become harder and harder to tackle. Every year that we do not act, more communities are put in danger.</p> <p>I have watched for over a decade as the blackened burn scar has recovered, bit by bit, sapling by sapling. There is hope for our planet. There is hope for recovery. But only if you choose to take action on behalf of your state.</p> <p>I urge the committee to pass this legislation to ensure our mountain communities have a future.</p>

	<p>I appreciate your consideration of these matters and solutions. Thank you,</p> <p>El Sealey, District 1</p>
<p>Ginger Barrett For themselves</p>	<p>I urge you to support SB24-159, which helps Colorado align with the science on climate change and would help our state manage the transition beyond fossil fuels in a way that reduces economic disruption and helps protect public health and safety and the environment from orphan wells while reducing the liability for taxpayers.</p> <p>We must make these moves, in order to get where we must go: a future without fossil fuels. Thank you.</p>
<p>Barbara Krupnik-Goldman For themselves</p>	<p>I am in favor of SB24-159, the phase out and clean up bill. This bill will help to slow the accelerating climate crisis and will also address local pollution in Colorado. The timeline in this bill allows plenty of time for planning and transition, and if anything is too slow, given the rapid heating of the Earth with attendant extreme weather and widespread damage to ecosystems. Please allow this bill to pass out of committee for consideration by the full legislature. Thank-you, Barbara Krupnik-Goldman</p>
<p>Sandra Spence For themselves</p>	<p>My name is Sandra Spence of Evergreen, Colorado. First, thank you for your service to the people of Colorado - your work is so important for our state. Today I want to ask for your support in passing SB24-159. I'm am a retired environmental scientist with 34 years of experience working on the science and regulations of environmental protection. The impacts of climate change are being felt earlier than expected and there is no time left for us to wait. We must act now. It is critical that we transition away from oil and gas dependency and toward more sustainable energy solutions. SB24-159 provides the incentive necessary for this inevitable transition. In Evergreen the impacts of climate change are here. In the nation, Evergreen ranks >99% of all communities for the risk of catastrophic wildfire with likely loss of life. I have lived through one house fire and know that I can recover and rebuild if needed; but, I fear that in Evergreen the issue now is surviving the evacuation from a fast moving fire. The modeled evacuation congestion for Evergreen during a wildfire is similar to, if not higher than, that of the Palisade, CA fire in which people were unable to escape and died in their vehicles. I fear that Colorado is heading toward its own Palisade. This</p>

	<p>is just one example of the impacts climate change is having on Colorado. I'm doing what I can to take personal responsibility for my impact on the environment and to prepare. Individual actions are important but collective action and legislative incentives are need to change the course we are on. I ask that you support SB24-159 - there is no time left. Thank you for the opportunity to provide this testimony.</p>
<p>Debra Gerkin For themselves</p>	<p>Vote YES on SB24-159, Mod to Energy and Carbon Management Processes.</p> <p>As a person of faith who acknowledges our responsibility to care for the Earth and all its creatures, I know it's time to phase out and clean up our use of oil and gas. Oil and gas operations are the biggest cause of ozone and climate pollution in Colorado. This pollution accelerates climate change and creates an enormous, global threat to public health, including the impacts of extreme heat, drought, flooding, and wildfires. Asthma and other respiratory ailments are commonplace now due to the effects of carbon emissions. Premature death, heart disease, neurological issues, and gastrointestinal problems are also brought on by oil and gas pollution.¹ Incredibly, over half of all Coloradans live in areas exposed to pollution from oil and gas operations, including many communities who are disproportionately impacted.</p> <p>Carbon emissions, including oil and gas operations, have already resulted in billions of dollars in damages to Colorado. Emissions from oil and gas operations harm our agriculture and recreation sectors and increase the occurrence of natural disasters. Damages cost the state 1.36 billion dollars per year, which is one and a half times greater than the total taxes and fees paid by the oil and gas industry.</p> <p>Colorado doesn't need all the oil and gas it produces. Let's phase it out now and provide Coloradans with clean air and healthy living conditions. Let's take responsibility for securing a thriving planet for future generations.</p> <p>I urge you to vote yes on SB24-159.</p> <hr/>

	<p>1. Intergovernmental Panel on Climate Change, Summary Report for Policy Makers, (https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf)</p>
<p>Jette Carlson For themselves</p>	<p>Devoted and Hard Working Committee,</p> <p>I thank you very much for having composed such a bill and I am in support of SB24-159. It will prioritize the health of the people, nature and the animal world. I was born and raised in Germany and follow the politics of that nation. Germany's Climate Law set out for reaching net zero emissions by 2045. In order to achieve the ambitious Energiewende by 2030, 80% of all electricity supply will need to come from renewable energy sources (and 100% by 2035). Now, I am an American, and proud to be so, but I do not want my new home country to lag behind my former country. Please, pass this bill to keep us on track with the rest of the world. Jette Carlson</p>
<p>Emily Swallow For themselves</p>	<p>Dear Committee Members,</p> <p>I urge you to vote yes on SB 159. We are living in a climate emergency and we need to act now to preserve any chance of having a livable planet for ourselves and future generations. The oil and gas industry is Colorado's top climate polluter, higher even than transportation and electric power generation. Passing this piece of legislation would be an important step in addressing Colorado's contributions to climate change and improving the health of people, ecosystems and the economy in our state. Climate change has already wrought devastation on many of Colorado's major industries, such as agriculture (through drought, extreme weather events, and rising temperatures) and outdoor recreation (through wildfires, air pollution, drought, reduced snowpack, and more). In terms of health, 4 million people in Colorado are at risk from ground level ozone at levels known to cause cardiovascular and respiratory emergencies and scar healthy lung tissue. Oil and gas operations are the top emitter of ozone causing substances as reported by CDPHE. It is time to phase out the permitting of new oil and gas operations and hold current operators responsible for clean up. These are both reasonable and just measures that will promote health, equity, and sustainability for all Coloradans.</p> <p>As a new mom, I am very concerned about the future of our state and our planet. I want my son to be able to play outside in clean air, enjoy</p>

	<p>Colorado's beautiful places, and not have to live on a planet that has been irreparably devastated by past generations. My son was born six weeks early and is at high risk for asthma and other respiratory conditions. It saddens me that he may not be able to enjoy the outdoors for much of the year, due to the poor air quality that plagues Colorado for much of the year. Phasing out oil and gas operations and cleaning up dead and dying wells could make a huge difference for families like ours across the state, particularly in frontline communities.</p> <p>Please vote yes on SB24-159 and do the right thing for Colorado's people and environment.</p> <p>Thank you for your time.</p>
<p>Sherwood Dunlop For themselves</p>	<p>Dear Honorable Committee Members,</p> <p>Colorado's greatest assets consist of our pristine Rocky Mountain wilderness, fresh air and abundant natural beauty. These features improve the quality of life in Colorado and also property values.</p> <p>It's a key time for us to decide how we will focus our intention on the future. We now have what we need to upgrade our relationships with natural resources. If we look back in history, we can see countless examples of species and societies who did not take the limitations of their resources into consideration. These examples are the great failures of the past.</p> <p>I am asking you to open up space to look into more creative strategies; to find out how Colorado can express itself into a more intelligent future, because poisoning our own air and water is the choice of a suicidal entity, is that what we want to be?</p> <p>Fossil fuel extraction carries many externalities, it doesn't make sense to place an extreme burden on the environment and human health to extract as much resource now, when we are presently using it in such an irresponsible manner. Technology is going to reveal much more valuable uses for petroleum in the future.</p>

	<p>As the 5th highest oil producer and the 8th highest natural gas producer in the country, Colorado has the chance to demonstrate real leadership through this bill – taking seriously the science-based need to stop moving forward with new fossil fuel projects in order to slow global warming and reduce the increasing pollution from oil and gas operations that over half of Colorado’s population is exposed to. To ensure Colorado’s 100,000 active and closed wells don’t continue polluting, it is also crucial that polluters pay the cost of plugging and remediation that has too often been pushed off to the taxpayers.</p> <p>This bill will phase out the approval of new oil and gas permits by 2030, prioritizing permit reductions in disproportionately impacted communities first, and hold oil and gas operators responsible for the costs to cleanup dead and dying wells. It would not affect production from current wells. It also requires follow up on the in-progress study required by HB23-1074 to determine how to support oil and gas workers and communities impacted by the transition away from oil & gas expansion.</p>
<p>damien Kern For themselves</p>	<p>I'm sure you read a lot of these! Thank you for your time. As a young Coloradan, this bill is vastly important to me. It is of paramount importance that we protect our watersheds, and our natural world as a whole. Not even from a moral standpoint, but from a monetary one. We can't keep making money off oil forever. It's finite, and if we see fires, raising seas, and extreme weather events like we have the past few years, there won't be a whole lot of customers left. Yet the sun doesn't stop shining, and the wind is gonna keep blowing. There was 64,000 green energy employees in Colorado last year, oil and gas employed 32,000. Those numbers come from Colorado newswire & e2.org. This bill is a step towards the future of energy in Colorado. This bill is a step towards innovation, and optimization in Colorado. Be a part of the technologies of the future, not of the past.</p>
<p>Jason Farbman For themselves</p>	<p>I live on the east side of Standley Lake in Westminster. Many in my community voted against Prop 112, thinking that it went too far against the oil and gas industry. Then, shortly after, an oil company stated they were going to build wells 250 feet from Standley Lake, at the Westminster Hills Dog Park, and on Rocky Flats. This caused a community outrage and lots of regret from those who voted against 112. Because of the outrage, the foreign company cancelled these permits. This, and because my son has asthma with numerous long hospitalizations are why I support these two bills.</p>

	<p>My issue with the drilling is that there is no moderation. The oil and gas industry will drill wherever it is profitable without hesitation. If it were left to them, the front range would be only oil and gas wells. Without government intervention, our air quality will continue to worsen, especially during the summer months. As stated in bill SB24-159, the amount of drilling that will take place after 2030 is still extensive. There are so many outstanding permits and there are so many new wells that these will operate for decades to come. Why do we need to worsen an already bad air quality area by allowing these permits to continue? Almost everyday during the summer is an ozone alert day. These laws do not say no oil and gas operations can take place. They ask for moderation. No amount of wells will be enough for the oil and gas industry. It's up to the government to place these limitations.</p>
<p>Carolyn Farbman For themselves</p>	<p>I live on the east side of Standley Lake in Westminster. Many in my community voted against Prop 112, thinking that it went too far against the oil and gas industry. Then, shortly after, an oil company stated they were going to build wells 250 feet from Standley Lake, at the Westminster Hills Dog Park, and on Rocky Flats. This caused a community outrage and lots of regret from those who voted against 112. Because of the outrage, the foreign company cancelled these permits. This, and because my son has asthma with numerous long hospitalizations are why I support these two bills.</p> <p>My issue with the drilling is that there is no moderation. The oil and gas industry will drill wherever it is profitable without hesitation. If it were left to them, the front range would be only oil and gas wells. Without government intervention, our air quality will continue to worsen, especially during the summer months. As stated in bill SB24-159, the amount of drilling that will take place after 2030 is still extensive. There are so many outstanding permits and there are so many new wells that these will operate for decades to come. Why do we need to worsen an already bad air quality area by allowing these permits to continue? Almost everyday during the summer is an ozone alert day. These laws do not say no oil and gas operations can take place. They ask for moderation. No amount of wells will be enough for the oil and gas industry. It's up to the government to place these limitations.</p>
<p>Richard Griffin Against themselves</p>	<p>I understand the need to mitigate climate change, but this bill is the wrong approach. We need to stop the USE of fossil fuel, not cut off the supply in Colorado. With no more Colorado sources, Coloradans will just have to get oil and gas from Texas, Oklahoma, and Wyoming</p>

	<p>at a much higher price. The change could result in even more greenhouse gases being emitted due to transport.</p> <p>You can't just pick an arbitrary deadline of 2030. Sponsors need to provide a roadmap that identifies how and when we can eliminate the need for fossil fuels in Colorado. Once the roadmap identifies the "when", then a date when we should stop drilling can be established.</p> <p>The roadmap needs to consider when:</p> <ol style="list-style-type: none">1. Fossil fuel is no longer needed for cars and trucks as they are replaced over time with battery-electric vehicles.2. Fossil-based jet fuel is no longer needed at DIA, one of the World's largest airports. *3. Natural gas will no longer be needed to heat our homes, businesses, water, and cook our food. **4. Natural gas will no longer be needed for industry. <p>It would be irresponsible to mess with the entire Colorado economy without complete knowledge of impacts, benefits, and timing.</p> <p>Climate change is a global issue and anything Colorado does would only be a drop in the worldwide bucket. It needs to be addressed at the federal level with a carbon fee and dividend legislation that would let free enterprise sort out the best answers, and border fees to pressure worldwide changes.</p> <p>* Although sustainable aviation fuel (SAF) is being developed, it still costs over twice as much as fossil-fuel-based jet fuel, and all chemical processes developed so far are limited to 50% blends or less. A mandate at the federal level will be required but has yet to be discussed.</p> <p>**We are still building houses with gas appliances, locking in natural gas usage by these new homes for at least the next 15 years along with all the existing homes. Gas taps for new subdivisions need to be banned as a first step. Natural gas supply is much more fragile than crude oil and shortages could occur quickly if drilling is stopped.</p>
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<p>Keith Ela For themselves</p>	<p>I live in an area that frequently has ozone warnings saying, "stay indoors". This is not the Colorado I moved to almost 50 years ago. The Front Range air quality ranks among the worst in the United States. We're becoming a national sacrifice zone.</p> <p>I helped get signatures for Proposition 112. It was enjoyable meeting so many like minded people who wanted to improve the quality of Colorado's air and the health of its citizens. I'm ready to work towards getting this kind of a phase out of done via a citizen initiative if it fails to get through the Legislature.</p> <p>Thank you for protecting what makes Colorado a great place. Please pass this legislation. Keith Ela</p>
<p>Gail Nordheim For themselves</p>	<p>I urge the Committee to support SB24-159.</p> <p>Virtually everyday, we hear news of catastrophic climate events. Extreme fires and drought, storms, floods, melting glaciers, record high temperatures. The list goes on. It is clear that the world is now feeling the impacts of climate change. And the longer greenhouse gas emissions from fossil fuels continue, the worse it will become.</p> <p>In a recent report, the International Energy Agency, or IEA, says: "The energy sector is the source of around three-quarters of greenhouse gas emissions today and holds the key to averting the worst effects of climate change, perhaps the greatest challenge humankind has faced." The IEA calls on all governments to significantly strengthen and successfully implement their energy and climate policies. If this doesn't happen, it warns that we are on course for a 2.1 degree increase in temperatures, well in excess of the 1.5 degrees that represents the maximum safe level.</p> <p>Everyone—including the State of Colorado –needs to heed this dire warning. SB24-159 represents a modest but important step in this direction, by phasing out new oil and gas drilling and fracking by 2030. It is a responsible step towards averting climate disaster. Allowing drilling of new wells that will be active for many decades to come is exactly the wrong direction to go.</p>

	<p>Like many of you, I have children and grandchildren. What will their lives be like if we fail to act? What kind of environment will they live in? Any costs of acting now pale before the future costs of deaths, species extinction, coastal flooding, massive climate migration and wars for scarce water and food that will ensue if we fail to act. The time for excuses is over.</p> <p>In closing, I ask you to approve this bill so it can be considered by the full Senate.</p>
<p>Kelly Hegarty Against themselves</p>	<p>Dear Committee Members, Please vote "NO" on SB24-159 Modification to Energy & Carbon Management.</p> <p>This is a bill that would effectively ban new oil and gas development, and threatens to harm millions of Coloradans.</p> <p>Colorado's economy, environment, and energy security depend on the oil and gas industry. But this bill would effectively ban all oil and gas development in Colorado by not issuing new oil and gas permits after January 1, 2030. It also would affect permits needed to modify old wells to increase production and requires wells falling under permits issued between date of enactment of bill and January 1, 2030, to begin drilling before the end of 2032.</p> <p>This is a bad bill for Coloradans who care about affordable, reliable and ever-cleaner energy. Coloradans' number one concern is the rising cost of living, including for the energy they rely on to power and heat their homes. Colorado's abundant oil and natural gas resources are developed with some of the lowest carbon intensities anywhere in North America. Banning the responsible development of oil and natural gas in Colorado could increase those costs, increase Colorado's reliance on energy from other states and increase carbon emissions.</p> <p>Colorado's oil and gas industry supports 300,000 jobs and contributes \$48 billion to the state's economy. The bill puts the jobs of hardworking Coloradan VOTERS at risk while reducing tax revenues that support schools and public services.</p>

	<p>Colorado deserves a balanced and sensible approach to energy development, that protects the environment, supports the economy, and respects property rights.</p> <p>I urge you to vote "NO" on this bill - Thank You, Kelly Hegarty</p>
<p>Jutta Seeger For themselves</p>	<p>Dear Members of the Senate Agriculture & Natural Resources Committee!</p> <p>Thank you for the opportunity to send my concerns regarding Oil and Gas development in written form to you. Thank you for reading, noting my note.</p> <p>My name is Jutta Seeger, I am a Greeley, CO resident since 1996, since 2009 as a naturalized citizen. (CO-13, CO-50)</p> <p>I urge you to vote for SB24-159 to phase out new oil and gas permits in the state of Colorado as well as holding the industry accountable for the costs of cleaning up after wells have become unprofitable.</p> <p>I wish to point out to you a very valuable report from the conservative Colorado Fiscal Institute on Oil and Gas impact, published in 2023: "Clearing the Air The Real Costs and Benefits of Oil and Gas for Colorado". This report opened my eyes to the propaganda by the industry, overstating the dependency of Colorado on the industry and underreporting the costs the industry places on all of us regarding health, environment and social degradation.</p> <p>Colorado enjoys already a diverse economy.</p> <p>Our natural environment which sustains industries that build and give back as agriculture and outdoor recreation is suffering. Emissions from fossil fuel companies are linked to increased water demand of crops, drying of water-wells, increased forest fires, drought.</p> <p>But we can do better.</p> <p>Clean energy legislation can transform the way we transport, light, warm and feed ourselves. And we need that transformation NOW.</p>

	<p>Now is the time to act, to legislate and to implement rules, regulations to protect Colorado and the world while we still can from the disaster fossil fuel dependency brings upon us.</p> <p>I am hoping for your vote. I want to walk along the Poudre River without the smell, noise and sight of huge oil and gas facilities. I want to be able to sleep with my windows open in good, fresh night air. I don't ever want to see the orange sky from an other exploding forest fire, seeing ashes falling in my backyard. I want to be able to water my front yard trees as they give shade to my house. I want to know that our children are safe at school and not studying next to a time bomb fracking for fossil fuels arms length from their school play ground, fuming toxicity. I want Colorado to truly have the blue sky and the clean air we are famous for and I want the world to survive human activities. There is no planet B.</p> <p>Please vote yes on Senat Bill 24-159!</p> <p>Respectfully Jutta Seeger</p>
<p>Natalie Pierce For themselves</p>	<p>Thank you Chair Roberts and members of the Committee. I am Natalie Pierce. I am here representing myself. Please vote yes on SB 159. We are currently facing a desperate crisis which deserves to be treated as an emergency. If we continue to produce and use oil at the current rate and don't make significant reductions, our land, children, and communities will suffer. This bill may seem bold or extreme, but please remember to see it in light of all of the wildfires, floods, droughts, heatwaves, loss of biodiversity, and human lives lost. In light of this crisis, this bill is the bare minimum. Thank you to senator Priola and Senator Lewis for sponsoring this important bill.</p> <p>There are many reasons I am passionate about this, but like many people, it took personal experience to spur me into action. My husband was raises in Lahaina on Maui, Hawaii. As you likely know, Lahaina was burned down on August 8th of last year. There have been many wildfires on the Island throughout the years, but this one was historically destructive and would not have cause so much damage if it weren't for climate change, if it weren't for our over production and consumption of oil, if it weren't for my neighbors in Colorado producing oil and not taking responsibility. I will never experience the beauty of Lahaina and having my husband show me</p>

	<p>his old stomping grounds. My people destroyed the homelands of my husband's people. I can't stand for it anymore.</p> <p>If you're worried about the money that we'll lose due to cutting down production, please consider the 5.5 Billion dollars in damage caused by the Lahaina wildfires. Or the \$2 Billion caused by the Marshall Fires. It costs us more to clean up than it costs to prevent the issues and protect our people in the first place.</p> <p>This bill phases out permits starting in 2030. This means that current production and even future wells will be producing for at least the next 70 years. This gives us time to creatively secure funding for the areas of our lives that currently are funded by fossil fuel production. But we need you to take action by passing this bill NOW.</p>
<p>Denise Shoaf For themselves</p>	<p>We now have years of research, testing, and evidence showing fracking in neighborhoods near homes and schools seriously affects all human beings from newborn to centenarian. Stop the unreasonable practice of fracking in neighborhoods where our children and grandchildren play and grow, our parents and grandparents live and our way of life and our health being severely impacted! Our air is our lifeline and we demand Colorado prohibit such dangerous practices as fracking where we live! As a mother and grandmother I whole heartedly support SB-159 and request that as human beings yourself you understand why pass this bill! Thank you.</p>
<p>Jennifer Garone For themselves</p>	<p>Hello, I am Jennifer, and I live in in 80503 zip code. Climate and pollution are among my number one issues and concerns. Please make sure Colorado reduces our air pollution and helps to leave a world that is healthy for future generations. The Oil and Gas industry is the #1 cause of toxic and climate pollution in our state. We already have nearly 50,000 active wells in Colorado but the energy transition is well underway and we need to stop adding more. Colorado's economy is ready for the clean energy transition. We need SB24-159 to create certainty for businesses and workers, and to make sure the industry cleans up after itself now and in the future. Please support SB24-159, to phase out new permits and make sure oil and gas companies clean up after themselves.</p>

<p>Kevin Cross For Colorado Coalition for a Livable Climate</p>	<p>I had intended to provide this testimony in support of SB24-159 on March 14th, and am unable to attend the hearing this Thursday. So I am providing this written testimony instead.</p> <p>The Colorado Coalition for a Livable Climate applauds the fact that since our founding in 2015, Colorado has established reasonably ambitious climate goals and has been taking steps to achieve them. Those steps have largely focused on making buildings more efficient, moving toward the greater use of renewables to generate electricity, and electrifying both the building sector and transportation by promoting technologies like heat pumps and electric vehicles. This is all good.</p> <p>However, the latest Colorado Greenhouse Gas Inventory Report shows us missing our 2030 and 2050 goals, in the first case by a narrow margin, in the second case by a fairly large margin. So we are going to need to take additional actions in the areas of building energy efficiency, adoption of renewables, and electrification. A bigger challenge, however, is that we have done little so far to transition away from the production of oil and gas, much of which is used out of state. That needs to change.</p> <p>Dr. Fatih Birol, the Executive Director of the International Energy Agency, said in 2021 that “the pathway to net zero is narrow but still achievable.” He further stated that, “If we want to reach net zero by 2050, we do not need any more investments in new oil, gas and coal projects.” Net zero by 2050 is of course our goal here in Colorado.</p> <p>We must act to stop making new investments in fossil fuel projects to protect our state, country, and world from the worst effects of the climate crisis. Phasing down the number of new permits for oil and gas wells, starting in 2028 and continuing through 2030 as SB24-159 would do, is an excellent step in this direction. Please vote to move this bill out of committee this Thursday.</p> <p>Thank you,</p> <p>Kevin Cross Convener</p>
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	<p>Colorado Coalition for a Livable Climate P.O. Box 672 Fort Collins, CO 80522 Ph. 970-484-3141 https://colivableclimate.org</p> <p>The CCLC is a project of the Northern Colorado Alliance for a Livable Future (NCALF), which is incorporated under section 501(c)3 of the IRS code.</p> <p>We adhere to all requirements applying to 501(c)3 organizations, including those related to political and commercial activity.</p>
<p>David Rogers For themself</p>	<p>The Oil and Gas industry is the #1 cause of toxic and climate pollution in our state. We already have nearly 50,000 active wells in Colorado. The energy transition is well underway and we need to stop adding more polluting wells. Colorado’s economy is ready for the clean energy transition. We need SB24-159 to create certainty for businesses and workers, and to make sure the industry cleans up after itself now and in the future. There are already too many orphan wells polluting the air, leaving taxpayers the burden of paying to close those wells.</p> <p>I urge you support SB24-159 to phase out new permits and make sure oil and gas companies clean up after themselves.</p>
<p>Brian Klocke For themself</p>	<p>We owe it to future generations of Coloradans to do everything we can to mitigate the impending disasters of the climate crisis. This means transitioning to a renewable energy economy as soon as possible. Yet Colorado is the 5th highest crude oil-producing state (https://worldpopulationreview.com/state-rankings/oil-production-by-state) and the 2nd highest (in 2020) number of wells extracting oil and gas through the environmentally destructive fracking process (https://stacker.com/science/12-states-where-fracking-most-prevalent). Denver consistently ranks among the worst cities in the world for ozone pollution, a byproduct of the oil and gas industry.</p> <p>SB24-159 protects our air, water, and land, prioritizes oil and gas permit reductions in disproportionately impacted communities, and protects taxpayers from clean-up costs of dead and dying wells. This</p>

	<p>bill will also help the health of Coloradoans and the planet through cleanup and by phasing out permits for new wells so that Colorado, with its solar power from many days of sun can become a renewable energy leader.</p>
<p>Kimberly Medina For themselves</p>	<p>I grew up in Colorado, my father is from South Routt County and my mother from the Larimer County foothills. Climate change and air quality are my number one issues and our state is being destroyed by uncontrolled oil and gas. In 2012 my childhood home burned in the High Park fire. I am 62 years old and there were no fires near my home growing up. This is all climate change, caused by fossil fuel emissions. When I visit my father's ranch in South Routt instead of seeing beautiful ranches all I can see are ugly fracking wells. The front range is so polluted it looks and feels like Los Angeles. How can we promote our mountains when you can't see them through the smog? Drilling and fracking are ruining our state. We have a chance to make Colorado better and this bill is a step in the right direction.</p>
<p>Angela Kantola For themselves</p>	<p>I support SB-159 because its "Phase Out Fracking" provisions would dramatically improve air quality for all Coloradans and eventually end neighborhood fracking.</p> <p>As the fifth highest oil producer and eighth highest natural gas producer in the U.S., Colorado can demonstrate real leadership through this bill – taking seriously the science-based need to stop moving forward with new fossil fuel projects in order to slow global warming and to reduce the pollution from oil and gas operations that over half of Colorado’s population is exposed to. To ensure Colorado’s 100,000 active and closed wells don’t continue polluting, it is also crucial that polluters pay the cost of plugging and remediation that has too often been pushed off to the state.</p> <p>This bill will phase out the approval of new oil and gas permits by 2030, prioritizing disproportionately impacted communities for reduction, and holding operators responsible for the cleanup costs. It would not affect production from current wells. It also has provisions for follow up on the study to determine how to support oil and gas workers and communities put in place last year by HB23-1074.</p> <p>As a follower of Jesus, I understand humans' first mandate is to serve and protect all of God's good creation. As a professional ecologist, I am appalled at how poorly we've exercised this work given to us. My</p>

	<p>family works hard to reduce our personal greenhouse gas emissions. We must have strong greenhouse-gas-reducing policies at every level if we are to ameliorate the worst impacts of global climate change. Let's do this!</p>
<p>Scott Miller For themselves</p>	<p>I am a husband and dad to two young kids, living in unincorporated Boulder County. We cherish our beautiful state. After watching the 2013 Boulder floods, having our farm destroyed by a 100-year flood in 2018, and witnessing the 2021 Marshall fire, I'm terrified by what my children may lose from our overheating planet.</p> <p>We in Boulder feel the deadly and costly impacts of extreme weather caused by global overheating. 2023 was the hottest year on record since the 1850s. The hottest 10 years have occurred in the last 10 years. And earth's temperature will continue to rise until we stop burning fossil fuels like coal, oil, and methane (natural gas) as sources of energy, and properly close/cap all energy infrastructure that is leaking methane gasses.</p> <p>Fortunately, there are alternatives which are cleaner, healthier, and transformative to our energy economy. In Colorado, we're blessed with abundant wind and solar energy. Ending dependence on dirty expensive fossil fuel energy will provide benefits to us, our community, and our economy.</p> <p>I urge our Colorado lawmakers to pass SB24-159 which guides Colorado's responsible transition from fossil fuels to clean energy. It's the only responsible choice. It's ok to give oil and gas companies and utilities plenty of time to prepare. But let's not pretend that we can continue approving new sources of carbon emissions past 2030 and also say we care about local pollution and global warming.</p> <p>Let's manage this transition responsibly. Let's reduce pollution on the front range. Let's reduce carbon emissions in Boulder and the state of Colorado. Our health and safety is in your hands. Please make the right choices for now and for our future, even if they are hard.</p> <p>Thank you for making courageous decisions!</p> <p>Best,</p>

	<p>Scott Miller</p>
<p>Sonia Koetting For themselves</p>	<p>Committee Members,</p> <p>I have lived to see Colorado go from a clean-air state to one of the nation's worst for air quality. I hope to see my state swing toward health again. This can be true if we recognize that the production of oil and gas has seen its peak and should retreat to promote the emergence of alternative energy sources, as well as more efficient usage and distribution. Even with the phase out, we have wells enough for nearly 4X the state's usage.</p> <p>With this legislation, taking a stand for climate change is also fiscally responsible for the taxpayers. Corporations who have profited immensely should not be allowed to stand by as federal dollars pay to clean up toxic messes that enrich the industry. Do not allow this type of corporate subsidy to happen! Make Colorado clean again while bringing justice to the communities impacted by abandoned wells. The law must be on the side of the people who suffer the risks and affects -- often without advance warning that their schools and homes have these subterranean monsters.</p> <p>I'm tired of us leading in oil and gas production and polluted skies. O&G production is NOT the underpinning of our economy that the industry would have us believe.</p> <p>I want Colorado to lead the nation where it so obviously needs to go, with no time to spare.</p> <p>Please make SB-159 law now!</p> <p>Sonia Koetting Northern Colorado</p>
<p>Jim Brett For Slow Food Western Slope</p>	<p>I am the leader of Slow Food Western Slope, which functions as a chapter of Slow Food USA - a 501(c)3 non-profit organization. Slow Food USA's and its chapters' mission is to create a dramatic and lasting change in the food system. We envision a world in which all people can eat food that is good for them, good for the people who grow it and good for the planet: good, clean and fair food for all.</p>

	<p>Our chapter promotes and supports over 60 farmers, orchardists, ranchers, agricultural businesses and winemakers of the North Fork Valley - all of which depend on good and clean water, air and soil.</p> <p>I urge you to support SB24-159. With this bill you have a chance to protect our land, air, and water now and for future generations and responsibly manage the energy transition for workers and local governments.</p> <p>Warming temperatures - already more than 2°C (nearly 4°F) in much of our district - are already impacting agriculture and recreation industries in our district. Our already depleted water resources are threatened by new drilling and fracking in our district. Billions of gallons of fresh water are used, polluted, and permanently removed from the water cycle by oil and gas fracking. Continuing to add new wells exacerbates both climate change and our water crisis. Droughts are worsening due to climate change, and we need to think carefully about how we use our water.</p> <p>This bill will also ensure both current and prior operators can be held liable for cleanup so the public doesn't get stuck with costs - protecting taxpayers now is critical since our district already has hundreds of wells that are at risk of being orphaned.</p> <p>Colorado should lead the way in responsible management of the transition to clean energy that is already underway, not wait for other states to take action. It's time to end the boom and bust cycle, which has historically devastated workers and communities economically. This bill needs strong political leadership and I'm asking you to be courageous enough to put public health, protecting our precious water resources and communities, and climate action above industry self-preservation.</p>
<p>Hilje Kuiper For themselves</p>	<p>Dear members of the committee,</p> <p>I am writing as a constituent of Senator Joann Ginal and Representative Andrew Boesenecker to urge you to support SB24-159.</p>

	<p>With this bill you have the opportunity to protect our land, air, and water now and for future generations, our children and grandchildren.</p> <p>Oil and gas drilling and fracking pollutes our communities, removes billions of gallons of water from the water cycle and adds to the climate crisis.</p> <p>A large portion of what is produced gets exported rather than used here. Our communities get polluted while oil and gas companies make the profit. Thousands of dead and dying wells are at risk of being orphaned and we need to ensure both current and prior operators can be held liable for cleanup costs so the public does not get stuck with it.</p> <p>This bill needs strong political leadership and I am asking you to be courageous enough to put public health and climate action above industry profit.</p> <p>Please protect Colorado's land, air, water and our health.</p> <p>Please reply to confirm that I can count on you to support SB24-159.</p> <p>Thank you,</p> <p>Sincerely, Hilje Kuiper</p>
<p>Lynne Sullivan For themselves</p>	<p>Thank you, Chair Roberts and members of the Committee for allowing me this opportunity. My name is Lynne Sullivan and I am representing myself. Within the past few years, I have had increasing difficulty doing my work as a ranch hand in Colorado, as I am forced to breathe extremely polluted air. Air that is polluted by Colorado's oil and gas operations.</p> <p>I am urging you to vote yes on SB 159.</p> <p>I am not alone. Four million people in Colorado are at risk of cardiovascular and respiratory emergencies, due to excessive levels of ground ozone, and the CDPHE reports that Oil and Gas operations are the top emitter of ozone causing substances.</p>

Regarding Phase out, it's straightforward:

As climate change escalates, Colorado families experience increasingly unbearable burdens of ill health and financial crisis. Climate change fueled extreme disasters, are also draining State and Federal coffers. All of this is because we continue to extract and use fossil fuels. It is time to stop investing in this toxic and problematic form of energy production, and increase our investment in the creation jobs needed to support renewable energy as our clean energy source.

A critical piece of this bill supports workers and communities, requiring a follow up study to last year's House Bill 23-1074, which examined how to support oil and gas workers who need or want to transition to other industries. Senate Bill 159's follow-up study leaves time to plan, and put in place, programs to support communities before any reduction to drilling takes place.

And it is important to remember that The oil and gas industry in Colorado is a small fraction of our economy. It contributes only 3.3% of our GDP and less than 1% of jobs.

And yes, Senate Bill 159 would ban new oil and gas wells starting in 2030, however, we all know that wells can produce for 20 to 40 years.

Regarding Clean up:

The burden of cleaning up abandoned wells should belong to those who profited from the wells, not the taxpayers who face health challenges and financial insecurity because of the pollution emitted from these wells and industry practices. This is only logical and fair.

All who are suffering ill effects from this industry's pollution want this to stop.

Please vote yes on SB24-159.

I would like to thank the sponsors of this bill, and everyone working to create cleaner air and a healthier place for our families to live.

Sincerely,
Lynne Sullivan

<p>Michael Crist Against themselves</p>	<p>I am opposed to the proposed modifications as NOAA and NASA data shows there is no correlation between fossil fuel production/use and climate change. We should be using actual science based data in establishing policy, not misinformation driven by profit motivated special interests seeking to push unproven/uneconomical alternative energy systems.</p>
<p>Denzil Inman Amend themselves</p>	<p>I am one of the approximate 4 million people who live in the nine county Denver Metro/North Front Range Non Attainment Area, which is classified as SEVERE by EPA, thus requiring substantial changes by the Clean Air Act. We all breathe toxic air all year around, but especially from May to October.</p> <p>I could be a poster geezer for having breathed this air since 1971. I come from a long-lived family, have climbed all the 14,000 foot peaks, have mountain biked over most of the high jeep road passes, and have hiked Colorado trails for 50 years. How did I end up with asthma and heart disease? Likely by breathing Denver’s air. Now, I have to check the air quality daily to determine my level of exertion.</p> <p>Denver’s air is hazardous for everyone but more so for the elderly and the 70% of Colorado’s children who live, play, and engage in outdoor sports during high ozone season.</p> <p>The provisions of SB24-159 are the very least that should be implemented. The air pollution is so serious, what is needed is an immediate year around suspension of oil and gas permits and preproduction activity in the non attainment area. Existing wells and collateral equipment need to receive frequent unannounced inspections by well-trained AQCD Inspectors equipped with the proper instruments to document emissions violations. Fines for violations need to be sufficiently severe to incentivize voluntary compliance.</p> <p>Our health is more important than jobs or the economy.</p>
<p>Barbara Mills Bria For Be The Change - Colorado</p>	<p>My name is Barbara Mills-Bria and I am with Be The Change - Colorado. Thank you for allowing me to speak to SB24-159</p>

	<p>As you know, citizens of Colorado have been trying to ensure that the heavily polluting oil and gas industry are held responsible for their actions in Colorado. The industry has long shown that it is unwilling to clean up after themselves.</p> <p>During the Financial Assurance rulemaking many of us demanded that the big companies, the ones who have been making record profits for years, put \$250,000 in escrow for each new well they drill. This seemed eminently reasonable when it costs between \$8 and \$12 million dollars to drill that well. Hardly even a drop in the bucket.</p> <p>But no, they argued, that isn't fair and look at us, we're good for the clean up money, we have plenty of money. But as we have consistently seen, the close relationship between the ECMC and the oil and gas industry has made it even more unlikely that any of these companies will be held accountable when the final tab come due.</p> <p>The big companies slough off old, low producing wells to small companies (note the case of Painted Pegasus) that cannot afford to plug the wells. And the ECMC is delighted that Federal taxpayer money has been made available to plug these "orphaned" wells. In fact, the orphan well program, according to the ECMC website which had consistently had in the past approximately 250 wells yearly on its list, now suddenly once the taxpayer money has become available, has closer to 1000 wells on its list.</p> <p>The API cries "it's not fair to go after previous owners for the money." This is one facet of SB24-159 called Joint and Several Liability which used to be the law in Colorado and which should be reinstated in Colorado. This legal concept is in use at the federal level and in various states.</p> <p>I would suggest that it is not fair to expect taxpayers at both the state and federal level to foot the bill to clean up after this dirty industrial business. These companies have and are making the profits and have shown very little inclination to clean up the mess they have made. For this reason Joint and Several Liability is vital so that Colorado taxpayers can avoid the burden of the costly clean up.</p>
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	<p>Thank you for your time. I encourage you to pass SB24-159.</p> <p>Barbara Mills-Bria Be The Change - Colorado</p>
<p>Louise Brooke For themselves</p>	<p>Greetings,</p> <p>It is of utmost importance that Colorado transfers exclusively to environmentally sound renewable energy production and use. As a teacher of young children, a parent, and a grandparent, I both experience and read about how pollutants in our air affect children and adults. As a statistically proven way to prevent deaths and to contribute toward healthy, better-quality lives for Coloradans and beyond, we need to pass this bill now. It is now less expensive to produce renewable energy than to produce energy degrades the air we breathe and water we drink. Renewable energy production brings plenty of job opportunities and some Colorado high schools are already training students for these jobs. Looking at a brown layer of the horizon for the past few years, it is more than evident that the time has come to act.</p> <p>Thank you. -L. Brooke</p>
<p>Diane Gimber For themselves</p>	<p>We need to protect the health of 4 million people who live in the 9 county region of Colorado’s Denver Metro/North Front Range Non Attainment area. We are contaminated by ground level Ozone pollution. The Environmental Protection Agency has said the pollution is at the “Severe” category.</p> <p>Pollution at this level is known to cause harm: prenatal, respiratory, cancer, heart disease, mental health and premature death. (Sources: National Institute of Health, Harvard TH Chan School of Public Health and Physicians for Social Responsibility).</p> <p>We have choices and proposed solutions for reducing this Ozone pollution. Just because some places in Colorado still have clean air, that’s no excuse to refuse the 4 million of us who do live in toxic air the right to try to attain our own healthy environment.</p>

	<p>If we deliberately ignore the causes of pollution to our fellow citizens we cannot hope to proceed as a happy thriving community of Colorado. I give strong heartfelt support to SB 24-159.</p>
<p>Linda Baggus For themselves</p>	<p>I hope you don't listen to or believe the oil & gas ads that are running against SB24-159 We will not lose 300,000 jobs in Colorado! The truth is that "Federal data show that direct employment in Colorado's oil and gas sector declined from roughly 32,700 workers in March 2019 to about 20,500 in March 2022, or seven-tenths of one percent of total state employment."</p> <p>Don't believe that 1 out of every 8 jobs in Colorado are in oil and gas! That's what the American Petroleum Institute claims, but that is not the truth!</p> <p>In this chart at https://www.energy.gov/sites/default/files/2021-07/USEER%202021%20State%20Reports.pdf page 37 from Energy.gov/user, you will see the following:</p> <p>UNITED STATES ENERGY & EMPLOYMENT REPORT 2021 " Colorado has a high concentration of energy employment, with 81,709 Energy workers statewide (representing 2.6 percent of all U.S. Energy jobs). Of these Energy workers, 22,996 are in Electric Power Generation, 30,538 are in Fuels, and 28,174 are in Transmission, Distribution, and Storage. The Energy sector in Colorado is 3.8 percent of total state employment (compared to 2.6 percent of national employment). Colorado has an additional 32,595 jobs in Energy Efficiency (1.5 percent of all U.S. Energy Efficiency jobs) and 29,509 jobs in Motor Vehicles (1.3 percent of all U.S. Motor Vehicle jobs)."</p> <p>Colorado has 81,709 jobs in energy employment. Not all of that is in oil and gas generation! Let's do some math:</p> <p>81,709 total jobs in energy employment in Colorado - 22,996 in Electric Power generation =58,713 if all of the rest of the energy jobs are in oil and gas in Colorado, but they aren't!</p> <p>So the oil and gas ads decrying SB24-159 are lying when they claim that 300,000 jobs would disappear from Colorado if we cease new permits for oil and gas wells. Their math is hogwash! Instead of that,</p>

	<p>please protect our people and our environment and set future restrictions on oil and gas wells. Thank you.</p>
<p>Rodney Sato For themselves</p>	<p>I strongly support this bill to Phase Out & Clean Up oil and gas and stop issuing drill permits. Too long now the Oil and Gas industry has pushed their drilling into communities causing negative health impact to disproportionate-affected citizens and indigenous nations.</p>
<p>Randall Willard For themselves</p>	<p>It is time for Colorado to take a stand against the dirty and uncooperative oil and gas industry. Colorado can show international leadership by stopping permitting by 2030. The planet desperately needs for us to make drastic changes and if you have seen all of the advertising targeting this bill you will understand that the industry wants nothing to do with solving the climate crisis. This means that the states leaders need to come forward to enact change that will benefit the 80+% of residents that live along the front-range. Continuing to permit in Weld County and adding massive numbers of permits in Arapahoe County will only exacerbate this problem. Colorado has shown leadership in renewables, this is the logical next step. Several independent organizations are working on solutions for the redeployment of O&G workers to commensurate positions in renewables and other energy tech. IT IS TIME FOR US TO TAKE A STAND FOR CLEAN AIR first and foremost and to protect our absolutely necessary clean water supplies. Fracking is diametrically on the opposite side of both clean air and water. Time to ratchet back and put people first.</p> <p>Thank you for opportunity to comment.</p> <p>-randy</p>
<p>Mark Billings For themselves</p>	<p>Thank you for taking the time to hear my perspective on SB24-159. Whether for or against, this bill has potential for a lot of impacts on Coloradans.</p> <p>I would like to point out a few facts that also impact us. Right now in Colorado, 4 million people are at risk from ground level ozone at levels known to cause cardiovascular and respiratory emergencies and scar healthy lung tissue. Unsurprisingly, oil and gas operations are the top emitter of ozone causing substances as reported by CDPHE. According to a September 2022 report by Clean Air Task Force, the cancer risk of 3.7 million Coloradans in 12 counties is higher than the EPA level of concern - directly caused by oil and gas</p>

	<p>operations. And 288,898 people in Colorado live within ½ mile of oil and gas facilities.</p> <p>The renewable energy transition is already fully underway. In 2022, renewables accounted for 37% of Colorado's energy generation. And it is growing. Colorado has an opportunity to give an example of how we can make that transition economically viable. HB23-1074 is currently studying how to support transitioning workers from oil and gas to a more renewable centric economy. The sooner we take this idea seriously, the more effective we can be in creating systems that generate clean energy and empower communities.</p> <p>Cleaning up orphaned wells is and will continue to be a major issue everywhere there is drilling and fracking. Making sure operators are held accountable for protecting the environment is imperative, and should be common sense.</p> <p>In short, passing this bill will propel Colorado to be a clean energy leader, as we can create sustainable ways of managing the clean energy transition. We don't have generations to fix climate change - we need to move away from oil and gas dependence now.</p>
<p>Janet Chapman For Citizens' Climate Lobby- Montrose</p>	<p>I have spoken to Senator Cleave Simpson on a zoom Feb 21st with Montrose after he presented on SB24-159. I then encouraged to reform the Oil and Gas Conservation Act to hold prior owners liable. Please consider for the environment. Thank you</p>
<p>David Roy For themselves</p>	<p>Thank you for your work, and for this opportunity to testify in support of Senate Bill 24-159.</p> <p>There is nothing sadder than hiking in the mountains, finding a vantage point to look out over the Great Plains, and seeing only dirty air.</p> <p>Worse, this 'air' is some of the most polluted in the entire United States. Colorado, the home of mountain streams, peaks, vistas, and blue skies, is also one of the worst States at spewing life threatening air pollution into all of our lives.</p>

	<p>We know how to begin mitigating this air pollution. Your support of Senate Bill 24-159 will go a long way in doing two things: cleaning up our environment and protecting the health and lives of your constituents.</p> <p>In addition to adopting the common sense solutions to improve air quality contained in Senate Bill 24-159, I am also requesting that you include partnering with NCAR https://docs.google.com/document/d/1FS6Z7831g3b_-xhw6yuEUYUgT1Me3d91BCNTXKe71IA/edit as a part of your worthy effort to improve the air quality in Colorado, some of the worst in the United States.</p> <p>Every resident in Colorado is vulnerable to bad air quality; every single Coloradoan deserves to breathe clean air. We are depending on you to make this happen.</p> <p>The State of Colorado has many great assets. Clean air is not one of them.</p> <p>Thank you for your positive consideration of my requests, and for supporting Senate Bill 24-159.</p> <p>Best regards, David Roy 2016 Evergreen Court Fort Collins CO 80521 (970) 493-9201</p>
<p>Sally Lewis For themselves</p>	<p>I strongly support SB-159. I believe that it is time to put self interest aside and act in the interest of the world as a whole, for Bangladesh and many other places, which will be under water, for our future as a species, to prevent massive human suffering, displacement, death and disruption on a global scale. And yes, to help our air quality, our ski industry and our comfort too of course. It would be wonderful if our federal government would take this action, but unfortunately it is completely dysfunctional now and for the foreseeable future, so it is up to states like Colorado to lead the way forward. Thank you for doing the right thing</p>

	Sally Lewis
Elaine Spencer For themselves	Please support this bill. For too long the oil and gas lobby has protected oil and gas producers to the detriment of air quality for fellow Coloradoans. We need to be phasing out fossil fuels, and this would help our world that is being devastated by rising temperatures and drought from those very fossil fuels.
fred munger For themselves	I would like to support SB24-159. People have a right to clean air and clean water. People should not have to involuntarily ingest toxic poisons in the air just to breathe, and in the water just to drink. Pollution is also a major cause of health problems. Passing this bill can enable all Coloradans to be healthier, and lower the medical costs for the state. Reducing pollution also helps solve the global warming climate change crisis. This is an existential problem for everyone, that we must take action on, in the very near future. The poorest people are affected the most because they can only afford to live in the most polluted, low cost areas. Being poor should not sentence you to being poisoned by pollution. Finally we must protect the natural beauty of Colorado, the animals, plants, beautiful blue skies, and nature that we are famous for!!! We have a great alternative to massively polluting fossil fuels. Clean, green, renewable energy, is the cheapest energy on the planet, it will save everybody money, including the state. It is the most job producing energy on the planet. The economy will boom with new green, high paying jobs. It is the most abundant energy on the planet. Wind, solar, geothermal, and hydro power, are all over the planet. It is also the most healthy energy on the planet, does not pollute, and less pollution will improve everyone's health. And is the solution to the climate change disaster, that literally threatens all of us, and all future generations! We simply have to use renewable energy to solve the biggest problems we face today. We also have to reduce fossil fuels carbon pollution, the direct cause of climate disaster, to avoid severe climate disaster. The air in the state is in the severe category. I sincerely ask all the legislators today to pass SB24-159, and lead the way, reducing fossil fuel pollution that poisons all of us, and also transition to renewable energy, the answer to many problems, and the energy of the future!
Macey Austin For themselves	Dear Senators, I'm Macey Austin, a senior at Monarch High School in Louisville, writing to express my strong support for the proposed modification to the Energy & Carbon Management Processes Bill. This bill is pivotal in fostering a sustainable energy future, an issue of utmost

	<p>importance to me as a concerned citizen deeply invested in our environment & the future of our state.</p> <p>As a student, I've witnessed firsthand that environmental responsibility often falls upon consumers, burdening us with limited choices constrained by larger entities within the energy industry. This bill shifts this burden by holding producers directly accountable for environmental impacts. Regulatory measures incentivizing sustainable energy production & carbon management processes rectify this imbalance, fostering a more equitable distribution of responsibility across the industry. It acknowledges the necessity of gradual transition, understanding that complete elimination of fossil fuels is unrealistic. By setting targets for carbon reduction & promoting renewable energy technologies, this bill signifies a commitment to safeguarding our environment for future generations.</p> <p>Passing this bill is not just a moral imperative but a practical necessity for Colorado's future prosperity. Embracing clean energy solutions & reducing our carbon footprint creates a healthier, more resilient, & prosperous future for all. I urge you to take swift, decisive action in support of this legislation.</p> <p>Sincerely, Macey Austin</p>
<p>Susan Permut For themselves</p>	<p>I want Colorado to be a leader by taking seriously the science-based need to stop moving forward with new fossil fuel projects in order to slow global warming and reduce the increasing pollution from oil and gas operations. I also want polluters to pay the cost of plugging and remediation that has so often been left to the taxpayers.</p> <p>This bill will phase out the approval of new oil and gas permits by 2030, prioritizing permit reductions in disproportionately impacted communities first, and hold oil and gas operators responsible for the costs to cleanup dead and dying wells. It would not affect production from current wells. It also requires follow up on the in-progress study required by HB23-1074 to determine how to support oil and gas workers and communities impacted by the transition away from oil & gas expansion.</p>
<p>Karen Kalavity For themselves</p>	<p>It is time to get off our dangerous addiction...and oil and gas is an addiction!</p>

<p>Faith Agarwal For themselves</p>	<p>I am a mother of 3 young children and see the lack of meaningful regulations in unconventional hydraulic fracturing. We have enjoyed our home and unbeknown to us, had the fracking possibility all around and under us. Now there is a large CAP application looming at the ECMC that threatens the Aurora Reservoir and our communities health and safety. I would not have moved into this area if we had known fracking was the sole purpose for all state land in Colorado. Please remove this requirement as it is destroying Colorado.</p> <p>There are a multitude of issues with oil and gas operations in Colorado that I cannot begin to have the time to express or am not aware of. The unattainment of federal ozone, draught with continuous removal of freshwater from the Earth’s water cycle, blatant lack of attempt to reuse the precious resource of fresh water, lack of monitoring uncombusted VOC at sites, seismic implications from injection wells, and constant air pollution and health impacts to Coloradans such as childhood leukemia and early death. ECMC has been tasked with regulating a multi billion dollar industry. I have not seen the change to regulate rather than foster. There are too many boundaries between health and safety that the phase out process is the most logical course of action.</p> <p>Please show your strength and approve SB 24-159 to protect the health and safety of all of Colorado. It tried and was not successful under SB 19-181. This is the most “necessary and reasonable” thing you could do. The “legal” pressure from oil and gas is a smokescreen and should be countered with this mandate. The focus should be on cleaning up the current operations and moving toward a cleaner and more sustainable operation.</p> <p>There are alternatives which need to be prioritized which will provide jobs and a robust economy. Protect Coloradans from further harm that we now know for a fact has already been done, you cannot change the past, but the future and responsibility is in your hands by approving SB 24-159. Thank you.</p>
<p>Cynthia Dozier Against</p>	<p>This comment is in opposition to SB24-159. Prohibiting oil and gas production in Colorado will harm the state economically along with the loss of severance dollars that are used for many good programs.</p>

themselves	An all-of-the-above energy policy is what makes sense. Colorado already has very strict environmental rules in place to protect all. Renewable energy sources have their drawbacks that should be considered when taking drastic steps such as this bill. Please vote NO. Thank you.
Rhea Esposito For themselves	Hello, I want the Senator to know that climate and pollution are my number one issues. I want the Senator to make sure Colorado reduces our air pollution and helps to leave a world that is healthy for future generations. The Oil and Gas industry is the #1 cause of toxic and climate pollution in our state. We already have nearly 50,000 active wells in Colorado but the energy transition is well underway and we need to stop adding more. Colorado's economy is ready for the clean energy transition. We need SB24-159 to create certainty for businesses and workers, and to make sure the industry cleans up after itself now and in the future. Please support SB24-159, to phase out new permits and make sure oil and gas companies clean up after themselves! My support for this bill is based on research presented in Colorado Fiscal Institute's report on the economic impacts of oil and gas in Colorado.
Patricia Goudvis For themselves	I'm writing to encourage you to pass SB24-159. Climate and pollution are my number one issues. Colorado already has nearly 50,000 active wells that produce far more oil and gas than we need and we MUST transition as soon as possible away from fossil fuels, if we hope to have a planet our children and grandchildren can inhabit. Colorado's economy is ready for the clean energy transition. SB24-159 will create certainty for businesses and workers and make sure the industry cleans up after itself now and in the future. Everyone suffers from fossil fuel related pollution but lower income communities and people of color are disproportionately affected. We need to stop adding new wells in the near future and clean up the dead and dying wells which are already being orphaned in Colorado. Trust the science and evidence that continuing to extract and burn fossil fuels is a path to planetary disaster. We have alternatives, let's use them.
Stephen Whitaker For themselves	I have lived in Colorado for over 50 years and am very familiar with the mess that extractive companies leave when they are done. The polluting and dangerous remains from their activities include toxic tailing ponds, abandoned mines, burning coal seams, and forgotten and abandoned oil and gas wells. These dangerous and toxic sites are left for taxpayers to clean up. Many are still unmarked and unknown hazards to Coloradans.

	<p>This is just plain wrong. Those companies that are engaged in resource extraction should pay the full amount for returning their sites to their original natural, safe condition and removing all equipment used in the extractive and production process.</p> <p>SB24-159 does not address all the messes that extractive companies have and are creating, but it does go a long way in preventing the oil and gas industry from leaving toxic and hazardous wells for taxpayers to clean up. I support this legislation and look to our elected representatives to pass it out of committee. Doing so will protect current and future Coloradoans health and financial wellbeing.</p>
<p>Taylor King For themselves</p>	<p>My name is Taylor King and I am representing myself, as a lifelong Colorado resident. I am asking you to vote Yes on SB 159. Climate change is drastically impacting my life and I worry about the future of my children. This bill takes important steps towards solving this problem and I am grateful for the sponsors of SB 159.</p> <p>Industries like the one that directly impact the source of my livelihood, outdoor recreation, as well as agriculture are already suffering economical consequences due to climate change. According to the National Academy of Science, for each 1°C temperature rise crop yields decline by 7.4% for corn, 6% for wheat, 3.2% for rice, 3.1% for soy. Temperatures have already risen more than 2°C in 15 of our counties. Additionally, the oil and gas industry has already drilled over 120,000 wells and has nearly 50,000 in production. Oil and gas corporations export around 40% of the oil and 75% of the gas they extract in Colorado, so Coloradans get the pollution while these corporations get the profit.</p> <p>I represent one of the households directly affected by the Marshall Fire, the most destructive fire in Colorado history. The winds that day raged and I feared for the life of my pets left at home as I desperately tried to get home to rescue them. I saw the flames coming over the hill and before I knew it, we were enveloped in smoke and embers. Driving away from the massive smoke cloud that enveloped our town, I was so grateful that my family escaped while wondering if we would have a home to return to. This fire happened in the middle of winter and climate change is responsible for making any time of year fire season.</p>

	<p>We must take action to prevent further devastating losses to our state’s economy, land, and people as a result of climate change. As the 5th highest oil producer and the 8th highest natural gas producer in the country, Colorado has the chance to demonstrate real leadership through this bill – taking seriously the science-based need to stop moving forward with new fossil fuel projects in order to slow climate change and reduce the increasing pollution from oil and gas operations that over half of Colorado’s population is exposed to.</p> <p>I am counting on you to make the right choice for Coloradoans’ future which is why I implore you to vote yes on SB 159.</p> <p>Sincerely, Taylor King</p>
<p>Riley Ruff For themselves</p>	<p>According to the latest ozone State Implementation Plan that included all of the recent oil and gas regulations, Colorado continues to be unable to meet the EPA health standards for air quality. The oil and gas industry emits more than any other sector, even with these new regulations in place. For the health and safety of Colorado residents, as well as the environment, halting fracking operations is crucial. As a life-long resident of Colorado, the health and wellbeing of our residents and our natural environments is of the utmost priority. When Colorado continues to produce more oil and gas than we are able to use as a state, this lends itself very naturally to a transition away from extraction methods (like fracking) that continually endanger and disproportionately impact communities of Color. It is imperative that these at-risk communities are prioritized, and as our state government, there is a duty to reduce negative externalities and advocate for the most vulnerable populations. This bill would do that, and set up Colorado for a just and equitable future and transition away from extractive and harmful industries.</p>
<p>Adrienne Razavi For themselves</p>	<p>Dear lawmakers,</p> <p>I urge you to support SB24-159. Climate and pollution are my number one issues; I am a Millennial wondering what life will be like with the continued production and use of oil and gas. It is hard to live in such a beautiful place and be aware that without the passage of a</p>

	<p>bill like this, permitting for new fracking will only continue, wrecking our landscape and contributing to pollution that is already changing our seasons and health. I'm asking you to please make sure Colorado reduces our air pollution and helps to leave a world that is healthy for future generations. The Oil and Gas industry is the #1 cause of toxic and climate pollution in our state. We already have nearly 50,000 active wells in Colorado but the energy transition is well underway and we need to stop adding more, but the oil and gas industry will not stop, or even slow, of their own accord; they profit from business as usual, but we need to phase out future permitting to see a different kind of future. Colorado's economy is ready for the clean energy transition. We need SB24-159 to create certainty for businesses and workers, and to make sure the industry cleans up after itself now and in the future. Please support SB24-159, to phase out new permits and make sure oil and gas companies clean up after themselves.</p>
<p>Penn Richmann For themselves</p>	<p>Thank you Chair Roberts and members of the Committee. I am Penn Puskarich Richmann, the daughter of a dairy farmer, and I am sincerely requesting that you vote yes on SB 159 to save family farms and ranches from climate change.</p> <p>I grew up on a 360 acre dairy farm south of Pittsburgh. We had oil derricks on the farm and the natural gas heated our house. I remember one cold winter the water froze in the surface pipes that supplied gas to our house. So my brother spread hay along the pipe and lit the hay on fire. My job as a 10-year old girl was to keep the cattle away from the hay. It worked, but years later I realized how lucky we were that there was not a gas leak or else there would have been one heck of a barbeque.</p> <p>An oil company now owns my old farm. It tore down the family home and only the barn and silos remain. No, oil and gas revenue did not save my farm. We sold everything in the mid 80s. It was probably the worst thing that has ever happened to me. Seeing the cattle leave and the farming equipment auctioned off. I rarely talk about it since I usually get choked up.</p> <p>Every farm family has heard stories of difficulties, usually about extreme weather. But no generation has seen the strange and extreme weather whiplash that our Future Farmers of America will witness. No generation will need to be as smart, resilient, and stubborn as this generation. Climate change will churn up weather</p>

	<p>events more frequently with a severity not seen before. We must slow climate change and give our farmers a fighting change to adapt by passing SB 159. Senate Bill 159 significantly mitigates the impact that the oil and gas industry, Colorado's top climate polluter, has on our climate. The bill can buy farmers time to develop and implement new agricultural methods and technology to manage the challenges ahead.</p> <p>To a multi-generational farming family, oil and gas revenue is often a short-lived boon compared to decades of cultivating crops and raising livestock. Oil and gas companies may make the current generation rich, but the effects of climate change are forever. These effects will put extraordinary stresses on farming families fighting to survive. It is through their hard work that we can feed our family and nourish this nation. From the bottom of my heart I would give every cent I have to have my family farm back. But once it is gone, no amount of money can bring it back.</p> <p>Stop climate change from destroying family farms and ranches. Vote yes on SB 159.</p>
<p>Carrie Jordan Against themselves</p>	<p>Good afternoon. My testimony today is in opposition to this bill being proposed to ban drilling in Colorado. Oil & gas extraction is an essential part of our economy, employing thousands of workers directly in our state as well as supporting many secondary businesses. The amount of tax money that is put into our communities, schools, and state funding is irreplaceable at this point in today's current settings. Over the past 20 years the industry has made tremendous improvements to processes, safety for workers and the environment, and has become a leading champion for carbon neutrality in the future. The continuous assault from far left groups and legislators over the last 10 years is immensely frustrating to me and the thousands of others who depend on not only the industry for our livelihoods but also on the affordable, clean energy that it provides. Renewable energy availability increases every year but it is in no way able to completely provide the amount of energy that Colorado needs today or anywhere in the next 10 years. By wasting resources every year to try to ban and restrict an essential industry that already works very hard to not only meet but far exceed the ever elevating regulatory requirements the legislators are missing the opportunities to enact solutions to address the far more pressing problems of real Coloradoans like affordable housing, jobs, school funding and other real issues at hand.</p>

<p>Kristi Douglas For themselves</p>	<p>Dear Committee Members.</p> <p>I hereby submit this comment to express my ecstatic support for SB24-159. As a long-time Climate Crisis Acknowledger, this day is monumental.</p> <p>I come to you as a Commerce City Councilmember, first and foremost representing many, many of my constituents; however, as a Councilmember, I also come to you as an individual - independent of the Council as a body, as well.</p> <p>We, here in Commerce City, have managed to escape getting fracked for nearly 15 years now, however we still suffer the negative impacts of fracking and other petroleum operations -- as many in Adams County, Aurora, Thornton and Brighton welcome these industrial toxin-releasing operations believing that private profiting of those who seek support from our leadership, outweighs the long-term negative impacts that come with this kind of exploitation.</p> <p>As it stands, we drill for greed – and not for need.</p> <p>It’s time to “curb the enthusiasm” because the Climate Crisis is real. Let Colorado be the leader, as others will certainly follow.</p> <p>Kristi Douglas Councilmember Commerce City available by text @ 720-205-2627</p>
<p>Martin Sandberg Against themselves</p>	<p>Here are the complete comments that had to be cut to make it 90 seconds</p> <p>I’m Martin Sandberg, I’m a retired MSEE. I’m a long time Colorado resident and am very concerned about keeping our air clear! After all, we built a house in the foothills that is called “The Views” and its website is theviews.org! On that site, you can see some of Colorado’s magnificent mountain views like you’ve never seen them before. The time lapses reveal things that you can’t imagine!</p> <p>I think that we can all agree that we must protect Colorado’s clean air.</p> <p>As I read SB24-159, the first thing that came to mind was Gideon J. Tucker’s observation that no man’s life, liberty or property are safe while the legislature is in session!</p> <p>The next thing I noticed is that Oil and gas have an almost incredible upside that is completely ignored in Section 1. Not only does the oil</p>

	<p>and gas industry pay roughly a billion dollars a year in Colorado state and local taxes, but it also allows us to affordably heat our houses, ship our goods, and provide all the plastics that we need. Over 300,000 Coloradans work in the oil and gas industry when you count both direct and indirect jobs. Does this committee want to take responsibility for destruction of that magnitude?</p> <p>There are some really strange assumptions being made in this bill. Let's take a look at an example of one. My house is heated with a condensing boiler that is about 95% efficient. What would happen if I had to switch to electric heating, which this bill would force me to do? Wind and Solar require 100% backup during much of our winters, which are calm and cloudy for long periods. Batteries can't do this so conventional power plants would have to be used. The best of these are combined cycle natural gas plants which are about 60% efficient. Add in transformer and transmission losses and the power plant will be burning roughly twice as much fuel as I'm currently doing. How is this an improvement?</p> <p>With all the obvious errors and innumeracy in this bill, it simply must be rejected.</p> <p>It isn't necessary to take any dramatic action https://wattsupwiththat.com/2023/07/30/the-ipcc-says-no-climate-crisis/</p>
<p>Julie Lang For themselves</p>	<p>Colorado has the opportunity to be a state leader in the energy transformation. We have been doing some wonderful work, but being a major player in the oil and gas production leaves at the lagging tail of these efforts. The pollution, the greenhouse gas stream produced by these wells, including the more recently measured methane leaks, and the support of a carbon energy are all areas we NEED to avoid to mitigate climate change. These greenhouse gases are at the core of so many of today's issues, including health (both physical and mental), natural disasters and change at a rapid pace. As the leaders and policy makers we need you to help steer this big boat in the right direction. For the people of this state and the world, to mitigate unfair environmental impacts on marginalized communities, I URGE YOU TO VOTE YES on SB159. WE need to move away from this very dirty business that creates more problems, waste and empty wells. Thank you. Julie Lang Denver</p>
<p>Finn Jackson</p>	<p>My name is Finn Jackson. I urge the committee to support SB24-159.</p>

<p>For themselves</p>	<p>I have lived in the Rocky Mountain region my entire life. The negative effects of oil and gas extraction can be felt drastically after they're P&Aed. Though some wells are worse than others, all extraction processes have poor impacts on soil quality, and poor well reclamation can kill entire swathes of untouched, native plant cover and can take thousands of years to fully recover on its own, leaving acres of salty soils in the meantime. Effects can spread, which isn't great where suburbs, parks, farms, and oil wells all mingle closely.</p> <p>The drilling process is loud. Close proximity has a negative impact on personal health, but also hearing. I once spent 1-2 hours digging up weeds right next to a well being drilled. Even with earplugs, I had a piercing ring that lasted the whole day. Residents who live near oil and gas wells, especially ones being drilled, are actively having their hearing destroyed.</p> <p>This bill only phases out new permits by 2030-2032. It doesn't stop current wells from extracting or producing. It doesn't force current wells to be plugged and reclaimed. And it doesn't really do anything at all until 2028. Colorado's oil and gas industry, as it stands today, will be just as productive, only decreasing in the decades to come, but Colorado is already highly productive. I understand the critical role oil and gas plays in our state. I also understand that we need to start moving away from it if we want to maintain multiple facets of wellbeing in the future.</p> <p>No one will be left behind with its passage, so please - vote yes on SB24-159.</p>
<p>Kathleen Sullivan Kelley Against themselves</p>	<p>Please oppose Senate Bill 159. The legislation ignores the contribution of natural gas to the expansion of renewable energy production.</p> <p>In 2020 we entered into a contract for a large-scale industrial solar farm on several hundred acres of our ranch. Because our solar installation is considered "high altitude" it is what is called in industry vernacular "snow solar." In winter, energy production is less, both because of the changing azimuth (angle) of the sun and snow loads.</p>

While lithium batteries are posited as a bridge for the down-times, they are not necessarily the solution. We understand from Luke Danielson, President of Sustainable Development Strategies Group (whose organization helps negotiate mineral contracts for indigenous tribes globally) that some of the most affected are tribal properties in the Amazon meaning both people and resources face devastation. Lithium extraction is environmentally challenging particularly in zones like the Amazon.

Consider this: natural gas plants significantly enhance the energy production of solar farms and make them far more economically viable. The symbiotic pairing of locally extracted natural gas as supplemental energy at night and additionally during inclement weather. This potentially accelerates the expansion of solar farms. The layers of benefit include energy security, local jobs, and enhanced renewable development leading more quickly to climate solutions because of this pairing with a stable, relatively clean energy source.

Also consider, in just the last year, energy consumption has risen exponentially with the development of data centers and the sudden expansion of AI. (See Colorado Sun, 3/25) Its pressure on the grid is significant. Shall we slow its development when we need it most?

In a discussion recently with the developer of our industrial solar farm, they indicated to me that their largest customers are data giants like Google. With that in mind, I feel strongly that we must be particularly thoughtful in how we approach our future. Creative, critical, scientific thinking is essential. Not fear-driven, rigid ideologies.

Legislation like SB24-159 has chilling, unintended consequences. It will inhibit the growth of renewable energy, and certainly impact our fragile economy and our essential task of creating climate solutions. Please oppose SB24-159.

Sincerely,

Kathleen Sullivan Kelley

Former Colorado HD 57 Representative (1980)

Bear Track Basin, LLC and Josephine Basin, LLC

<p>John Newman Against themselves</p>	<p>To Whom It May Concern:</p> <p>I am a voter who is deeply concerned about the negative impact that SB 159 will have on both a local and global level. I served in the Army and deployed to Iraq and Kuwait. I was only in my 20s during those deployments but one of the darkest memories that is forever seared into my mind is the blatant disregard that these countries and their energy industries have for the environment. The refineries we worked near flared at will, sending dark toxic smoke into the air and the drilling pads were consistently worse. If we ban the production of energy from Colorado and even elsewhere in the US, we are offshoring our emissions and exponentially increasing the damage to the environment. The demand for oil and gas has not subsided and will not for the foreseeable future. While the long term goal of reducing emissions is a noble one, we are shooting ourselves in the foot in the near term. Its deeply concerning that we would consider such a myopic measure. This will only have negative consequences. If we are concerned about both the local impact (jobs, state revenue, reliable/clean energy) as well as the global impact (sending our money to support toxic energy production abroad), then this bill should be DOA. This bill has zero upside. There is nothing noble in this proposal. We are lying to ourselves and every voter if we say that this will yield a cleaner environment. If we truly care about the environment, then we will continue to support local, clean energy production here in Colorado. From what I have observed through diligent analysis, the energy industry has taken remarkable strides to reduce emissions. Let's support what we can control and that is oil and gas production throughout our State.</p> <p>Thank you for your thoughtful consideration.</p> <p>Best, John</p>
<p>Leslie Glustrom For themselves</p>	<p>Dear Members of Senate Ag and Natural Resources Committee--</p> <p>This may feel counterintuitive, but</p>

	<p>PLEASE VOTE YES ON SB24-159 TO HELP OIL AND GAS WORKERS AND COMMUNITIES</p> <p>Yes--please VOTE YES to help oil and gas workers and communities.</p> <p>A "No" vote doesn't help them face the reality that the oil and gas industry will be phasing out in the coming decade or two--and this is the time to start planning.</p> <p>DENIAL does not help you prepare....</p> <p>All good parents know that sometimes TOUGH LOVE means telling your children what they NEED to hear--not what they want to hear...</p> <p>We will be largely moving beyond oil and gas in the next couple of decades</p> <p>NOW IS THE TIME FOR PREPARATION--NOT DENIAL....</p> <p>I lived through all the politicians that "protected" the auto workers by not allowing improved mileage standards--and so instead of preparing for the future, they went their merry ways--until life was no longer so merry...</p> <p>PLEASE, PLEASE VOTE YES ON SB24-159 BECAUSE DOING SO WILL HELP OIL AND GAS WORKERS</p> <p>A MANAGED TRANSITION IS MUCH BETTER THAN A CHAOTIC ONE!!</p> <p>PLEASE HELP OIL AND GAS WORKERS BY TELLING THEM THE TRUTH ABOUT THE FUTURE OF THEIR INDUSTRY AND HELP THEM TO PREPARE FOR THAT FUTURE.</p> <p>PLEASE VOTE YES ON SB24-159.</p> <p>Thank you</p>
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	<p>Leslie Glustrom</p>
<p>Marsha Barancik For themselves</p>	<p>Reduce fracking permits for community and economic health</p> <p>SB24-159: Modifications to Energy and Carbon Management Processes or the "The Phase Out and CleanUp Bill" is one of many bills needed to manage our state's significant fracking footprint.</p> <p>Fracking fractures Colorado's destination state status as it impedes the economic and physical health of our communities. Proximity to more than 50,000 active wells as well as expired fracking operations (1,000 orphan wells) — puts the communities that sustain our state's economy at risk.</p> <p>Healthy Coloradan workers and their families drive our economy. Communities lose resident families and workers, due to fracking-induced health issues and concerns about exposure to land, water and air pollutants. In turn, employers across sectors are poised to lose access to the workers sustaining them.</p> <p>More than half of Colorado's 5.8 million residents live in areas exposed to pollution from oil and gas operations. In 2023 alone, more than 1,200 spills occurred in Colorado. All Coloradans and businesses, particularly in communities disproportionately impacted by fracking-induced pollution, need to bank on a trajectory for entirely phasing out fracking. Drilling permits reductions framed in SB24-159 are an initial and essential step.</p>
<p>Gaia Mika For themselves</p>	<p>Please support SB24-159. This bill will move us toward the low carbon future that is needed to protect human health and respond to the climate emergency which is the most serious issue humans are facing. The bill enables existing wells to continue producing and will help workers and communities make the transition. It will also shift the cost of shutting down abandoned wells from us, the tax payers, to prior owners - many states already do this.</p> <p>Thank you,</p>

<p>Katy D For themselves</p>	<p>I am ready for the clean energy transition. I strongly support SB24-159, which aims to phase out new drilling for oil and gas and make sure polluting companies pay for cleanups. The Oil and Gas industry is the #1 cause of toxic and climate pollution in our state. Meanwhile we all have to suffer from this pollution and lower income communities and people of color are disproportionately affected by the pollution. We need to stop adding new wells in the near future, and clean up the dead and dying wells which are already being orphaned in Colorado. Colorado causes 1.36 billion dollars in damage each year and it's time the Oil and Gas industry pays for this damage and owns their part of the disasters that are being caused by climate change. The climate disasters here have cost the state 20-50 billion dollars. I want air pollution reduced now so that future generations can know what it's like to enjoy the outdoors without having to check air quality apps or succumb to health hazards or endure chronic illness due to pollution caused by Oil and Gas industry.</p>
<p>Jane Perkins For themselves</p>	<p>I am Jane Perkins, Loveland, CO. Please vote yes on SB 159.</p> <p>I write to you today as a human being, a mother and grandmother, a lover of nature. I speak for millions of other human beings, for parents and grandparents concerned for their children and grandchildren's dire-looking futures. I speak for those who have no voice – wildlife, our air and waters, our lands being systematically destroyed by climate change. These living beings of Nature may not have a "voice" we can hear but they are speaking massive volumes right now. And I speak for a million life species going extinct before our very eyes due to the burning of fossil fuels.</p> <p>Pollution from O&G production has impacted the health of Coloradans and human beings worldwide for decades. O&G wells release massive amounts of air, water, soil, climate pollution. Four million Coloradoans are at risk of heart and lung disease from ground level ozone. Cancer risk of 3.7 million Coloradans is higher than the EPA level of concern - directly due to toxic air pollution from O&G operations. O&G industry is Colorado's top climate polluter, and climate change is the number one public health threat.</p> <p>THIS DATA ALONE SHOULD MAKE EVERY ONE OF US SIT UP AND PAY HEED!</p> <p>I AM a lover of nature and our incredible planet Earth, I believe the FACT AND SCIENCE of the climate change emergency. Our Earth is being blatantly, greedily, and horrifically destroyed directly by the number one contributor to climate change and global warming – the burning of fossil fuels.</p>

	<p>Here are four major ways that CO residents are seeing the impacts of climate change right now.</p> <p>1) INCREASES IN HEAT - increased energy grid system stress, and increased illness and death for those vulnerable to illness and death from heat stress.</p> <p>2) DECLINING SNOWPACK AND SNOWMELT = declining water supplies in Colorado's river basins.</p> <p>3) SEVERE DROUGHT –caused by global warming, directly caused by the burning of fossil fuels.</p> <p>4) INCREASED WILDFIRES from the climate crisis FUELED DIRECTLY by fossil fuels. And the toxic smoke we're forced to breathe when wildfires burn - toxic particulates tiny enough to reside within our cells, causing lung, cardiac, cancer and other disease.</p> <p>Millions around the globe want a phase out of the burning of fossil fuels, and those in Nature have no voice. I think about climate change and its effect on our world every single day.</p> <p>Thank you for your consideration, and please vote in favor of SB-159.</p> <p>Sincerely, Jane Perkins</p>
<p>Sarah Burke For themselves</p>	<p>My name is Sarah Burke, I am 24 years old and have lived in Colorado my whole life. I grew up in Summit County. I spent my winters snowshoeing by my elementary school, going to ski school on the weekends, and ice skating on the ponds. In the summer we would play and hike in the forest behind my house and watch the boats on Lake Dillon. I thought that Summit County was perfect and that nothing could ruin it. Then, as the summers got hotter and dryer, wildfires became more frequent and destructive. In 2018, the Buffalo Mountain Wildfire burned 100 yards from my home. After being evacuated, we had to watch the fire burn, and hope that we would have a home to return to. The fire did not claim my home, but the beautiful dense forests where we used to play were completely singed, ruined. Although I did not grow up seeing fracking wells, I saw the impacts of fracking unfold in my own backyard. The increase in wildfires, the winters seeing less and less snow, and Lake Dillon's water levels falling each year. In 2022, I moved to Fort Collins and learned that my new city had the 15th worst air quality in the US. The</p>

	<p>more I learn about the environmental and health impacts of fracking, the more I fear for my future. This bill is the first thing in a while that has made me feel hopeful. You now have the opportunity to vote in the best interest of Coloradans. Politicians continue to vote to protect an industry that is poisoning us and that is not as lucrative for our state as it claims to be. When you vote today, think about not only me and my future but also your kids, and grandkids, think about the life they will have in 50 years, in 100 years. If you kill this bill today in committee, you send a message to Coloradans that you value a toxic industry over the health, safety, and well-being of the people you swore to represent.</p>
<p>Darrell Nordstrom For themselves</p>	<p>REGARDING SB24-159 Mod to Energy & Carbon Management Processes</p> <p>I, Kirk Nordstrom, am writing this testimony regarding senate bill SB24-159 as a private citizen who is deeply concerned about global warming, climate change, and all the consequences negatively affecting our planet. These problems were known by oil and gas industries since the 1960s [documented], nevertheless the same industries spent many millions trying to persuade the public that climate change was either a hoax or questionable at best. Meanwhile the world's experts on climate change have been issuing warnings for decades that life as we know it is in peril if we continue to emit fossil fuel combustion gases at the current rates. Now those deleterious consequences are clearly happening, yet our governments (State and Federal) are not acting fast enough to curb the rise in carbon dioxide emissions. It is a long and slow political process which must hasten and unfortunately fight the oil and gas industries who have enormous wealth and power to prevent these regulations from protecting the common citizen. Oil and gas development must be phased out. Economics even dictates that it is not supportable in the long run let alone sustainable. Please vote for what is morally, economically, environmentally, socially, and sustainably right.</p>
<p>Evi Klett For themselves</p>	<p>Dear Members of the Committee, I urge you to vote yes on SB-159.</p> <p>We are living in the age of the Anthropocene where the chickens of the human industrial project are coming home to roost in the form of extreme weather, temperature, and pollution. Drought is now a fixture in Canada and the American West. The Colorado River is over allocated and being overdrawn. Red flag days are on the increase</p>

leading to catastrophic fires. In 2021 the Marshall Fire burned 1,000 homes on a late Dec afternoon. A similar scenario could easily happen in SW Denver where I live. High winds, super dry conditions, and a spark could set my neighborhood and home on fire.

The science is clear. Our atmospheric changes are being caused by the burning of fossil fuels. If we want to continue living we need to decrease our extraction and combustion of these materials. It's 2024!

Dying due to our fossil fuel addictions is not inevitable. We can, in concert with others, shift our human endeavors away from destruction and towards regeneration. SB 159 is a proactive attempt to do just that.

1. It sets a clear end date, 2030, for new well permitting. The currently active 50,000 oil and gas wells in Colorado, plus all additional wells permitted before 2030, will still continue to produce for decades. This bill begins the necessary work of weaning us off of fossil fuels without the economic shock of going cold turkey.

2. It provides mechanisms to help fossil fuel workers transition to livelihoods that ensure a healthy livable planet for all.

3. It holds the correct entity, the oil and gas industry, responsible for the cost of capping orphan wells. It is not fair that an industry that profits from our state's resources leaves us with costly clean-up problems and bad air quality. In this bill liability provisions are placed on the industry not on tax payers or mineral owners.

In conclusion, I remind you that government can regulate the use of private property in the interests of public health, safety, and welfare. The longer we continue to invest in fossil fuel extraction and combustion the more intense the degradation of our environment and our health. SB 159 is a proactive bill to responsibly manage our transition away from fossil fuels on behalf of communities, oil and gas workers, and our collective future here at home on planet Earth. Without a healthy biosphere we're cooked. Please shift our trajectory in a positive direction by voting yes on SB 159.

Sincerely,

	Evi Klett
<p>Shirley White For themselves</p>	<p>SB24-159, "Mods to Energy and Carbon Management Processes," a.k.a. the Phase Out & Clean Up bill, will phase out the approval of new oil and gas permits by 2030, This will both help and show our willingness to seek solutions for reducing our dependence on fossil fuels for our energy needs. It will also help to reduce high levels of pollution and ground level ozone along the front range Prioritizing permit reductions in disproportionately impacted communities first, such as Commerce City and surrounding areas, will reduce incidence of respiratory diseases such as childhood asthma. Finding ways of holding oil and gas operators who benefit from these operations responsible for the cleanup costs is essential, and making profits from their polluting industries and then declaring bankruptcy by clearing their profits through financial manipulations must finally be effectively addressed to eliminate this maneuver. It would not affect production from current wells. It also has provisions for follow up on the study required by HB23-1074 to determine how to support oil and gas workers and communities impacted by the transition away from oil & gas expansion. Caring for the workers and communities impacted by limits placed upon fossil fuel extractions will go a long way in gaining suport for necessary adaptions of industry to the demands unregulated fossil fuels have visited upon world. Regulation is essential if we are to meet net zero carbon by 2050, which is no longer the far distant future. It is coming toward us quickly, and we are already feeling its affects in increased consequences relative to the pollution we have allowed.</p>
<p>Jeany Rush Against themselves</p>	<p>TO: SENATE AGRICULTURE & NATURAL RESOURCES RE: SB24-159 MOD TO ENERGY & CARBON MANAGEMENT PROCESSES 3-28-24 FROM: JEANY RUSH COLORADO SPRINGS CONCERNED CONSTITUENT VOTE: NO 1 While western nations are spending time and money to remake their entire energy systems to comply with FAUX climate policies, the two most populous countries — China and India — are busy building more coal plants to guarantee affordable and reliable energy to their people and businesses for decades to come. ALSO CREATING THE MOST EMISSIONS, OR POLLUTANTS ON THE GLOBE. NOT THE USA. 2 Both nations already use more coal than the United States, which has not seen a coal plant constructed for 10 years; China uses 9 times as much coal as the United States.</p>

	<p>THESE NATIONS ARE MANUFACTURING THE RENEWAL MATERIALS AND SELLING TO US AT GREAT COST. HOW IS THIS RELEVANT!</p> <p>While you create bills to control the only rational fossil fuel energy generation in our nation, which means oil, gas, and coal, you are attempting to justify environmental reasons. Well currently, energy is being usurped and created to the tune of trillions \$\$ for minimal gains on energy production, needs, by solar & wind, not having real gain. Lands are being stolen, deceitfully , fines for everything from lightbulbs to stoves, and the true environmental damages, impacts of solar and wind are ignored. where are the fines for kids mining lithium etc., in Africa & China? Where are the fines for the disposition of solar and wind parts when done.? Subsidies for alternatives, which will not be responsible, dependable! EV batteries, vehicles, still need fueled by Electricity.</p> <p>CO2 is the foundation of life. It is .04% of the actual atmosphere. It does not need managed by people who are using Hoax Climate Change non science to enslave us further by controlling our every move. I am for responsible operations. But hundreds of thousands jobs in Colorado are at stake. Billions of Dollars in contributions by oil and gas to our state. If you lower carbon much more, we will all die (150PPM) and we are at approx. 400PPM. These bills are power grabs, and feeding the wrong companies. This is insanity and it is actually criminal. PS the real scientists show coverup of truth: Earth's temperature has not risen in 15 years!</p> <p>We do not need carbon management; we need legislative management!</p>
<p>Kay Lee Against themselves</p>	<p>I'm retired and the O&G industry is the source of my income. We all want Colorado to have affordable, reliable and clean energy. One of the premises behind this bill is Gov. Polis goal of 100% clean energy by 2040. It is a lofty goal but one of my experiences led me to question its attainability.</p> <p>Several years ago, I installed solar panels on my home. About a week later, I got a message that they were not working. I panicked and called the solar company. They said, " Did it snow?" This happens every time it snows. It made me realize that the sun doesn't always shine and the wind doesn't always blow. We need a plan B to fill in those gaps in the clean energy plan. Currently, natural gas does a pretty good job of doing that. But what are we going to do in the future without it?</p> <p>Another premise behind this bill is that the impact on the economy is not something to worry about and the jobs lost are only in the oil</p>

	<p>sector and easily replaceable. I strongly disagree!!! In the mid 1980's two things happened in Colorado:</p> <p>The price of oil dropped to \$7 per barrel and And Colorado wasn't business friendly.</p> <p>The oil companies needed to cut costs to survive. They laid off workers and most of the workers who kept their jobs were moved to states who were friendlier to Oil and gas.</p> <p>I lost my job and my late husband's company told us his job was now in California. It took three years for me to go back to work in another field at half of the salary. The emotional toll was equally devastating. I think the only reason our marriage survived was our mutual love of our infant son.</p> <p>This devastated Colorado's economy. Not only oil workers lost their jobs. It trickled down. My baby sitter her job, realtors couldn't make sales. Every industry cut back. Nobody could find new jobs. Farmers couldn't rely on the income from mineral rights to tide them over in the lean years. Some of them went bankrupt. People couldn't sell their houses and gave them back to the bank. One friends who rented couldn't even give the keys back because both the owner and the bank disappeared. Property values plummeted as did tax revenue. Office buildings were empty. Denver was like a ghost town.</p> <p>Please learn from history and think of the unintended consequences of this bill and vote NO</p>
<p>Tom Rhodes For themselves</p>	<p>I am writing in support of SB 24-159. With 50,000+ active Oil & Gas wells in Colorado we already have more than enough petrofuels to support our state's needs, and the US is already an exporter of Oil & Gas.</p>

	<p>At the same time, our air quality continues to decline, in large part to the Oil & Gas industry. SB 24-159 will not curtail existing O&G production, but it will help to ensure that reserves are tapped in a way that is safe for human health and the environment.</p> <p>Please support senate bill 24-159. Thank you.</p>
<p>Carol Baker Against themselves</p>	<p>Senators, thank you for your work here at the Capitol as you study the merits of legislation. As legislators you know how to write laws to solve problems, but just because you CAN, doesn't mean you SHOULD.</p> <p>I am Carol Baker, I have been a resident of Aurora since 2002. I am NOT employed by the oil and gas industry. I am a consumer of energy. Along with many other travelling health care workers, I was recruited as a Registered Pharmacist to small towns, like Trinidad and Lamar, CO. I felt the ups and downs of the seasons of life there. As I adjusted to working away from Aurora, I considered the resources I had at the time. Driving was just part of the job. With my SUV I had a 'can-do' attitude.</p> <p>Agriculture and natural resources bring challenges as old as time. Colorado is unique. For generations people have been loving stewards of the land, adjusting to changes along the way. I am pleased people in Colorado have set high standards for limiting adverse effects on our people as we obtain resources for energy.</p> <p>After looking at other states and other nations for government mandates on limiting an industry, I really expect the best solutions may come from those closest to the resources in question. As legislators you know how write laws to solve problems, but just because you can doesn't mean you should.</p>



March 26, 2024

Dear Bill Sponsors and Members of the Senate Agriculture and Natural Resources Committee:

The Colorado Renewable Energy Society, a statewide organization representing individuals and businesses supportive of advancing renewable energy technologies for Colorado, urges you to vote yes on SB24-159, concerning modifications to energy and carbon management in Colorado to further protect public health.

SB24-159 helps Colorado align with the science on climate change¹ and would help our state manage the transition beyond fossil fuels in a way that reduces economic disruption and helps protect public health and safety and the environment from orphan wells while reducing the liability for taxpayers.

Colorado has hundreds of orphan wells that need plugging and each well can cost up to \$100,000 per well. This bill will help protect taxpayers from bearing the responsibility that rightly belongs with the present and past operators that profited from these wells.

This bill will also help advance Colorado's efforts to help workers and communities navigate the transition away from fossil fuels—provisions that CRES strongly supports.

CRES understands that economic transitions are never easy, but CRES believes it is better to manage the transition rather than to let it proceed in a haphazard fashion.

We appreciate your service and hope you will support this important bill.

Sincerely,

Vince Calvano for the Colorado Renewable Energy Society

¹ See for example [IPCC_AR6_WGIII_SummaryForPolicymakers.pdf](#)

Thank you Chair Roberts and members of the Committee. I am Natalie Pierce. I am here representing myself. Please vote yes on SB 159. We are currently facing a desperate crisis which deserves to be treated as an emergency. If we continue to produce and use oil at the current rate and don't make significant reductions, our land, children, and communities will suffer. This bill may seem bold or extreme, but please remember to see it in light of all of the wildfires, floods, droughts, heatwaves, loss of biodiversity, and human lives lost. In light of this crisis, this bill is the bare minimum. Thank you to senator Priola and Senator Lewis for sponsoring this important bill.

There are many reasons I am passionate about this, but like many people, it took personal experience to spur me into action. My husband was raised in Lahaina on Maui, Hawaii. As you likely know, Lahaina was burned down on August 8th of last year. There have been many wildfires on the Island throughout the years, but this one was historically destructive and would not have caused so much damage if it weren't for climate change, if it weren't for our over production and consumption of oil, if it weren't for my neighbors in Colorado producing oil and not taking responsibility. I will never experience the beauty of Lahaina and having my husband show me his old stomping grounds. My people destroyed the homelands of my husband's people. I can't stand for it anymore.

If you're worried about the money that we'll lose due to cutting down production, please consider the 5.5 Billion dollars in damage caused by the Lahaina wildfires. Or the \$2 Billion caused by the Marshall Fires. It costs us more to clean up than it costs to prevent the issues and protect our people in the first place.

This bill phases out permits starting in 2030. This means that current production and even future wells will be producing for at least the next 70 years. This gives us time to creatively secure funding for the areas of our lives that currently are funded by fossil fuel production. But we need you to take action by passing this bill NOW.

ENVIRONMENTAL RESEARCH
LETTERS

PERSPECTIVE

Applying the hierarchy of controls to oil and gas development

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1. Introduction

The growth in the oil and gas development (OGD) industry has placed millions of United States (US) residents in the path of multiple hazards associated with OGD operations. In 2020, nearly 1000 000 oil and gas wells were in operation (United States Energy Information Administration (USEIA) 2022), and a 2017 analysis estimated that 17.6 million US residents lived within 1600 m (1 mile) of an active oil or gas well (Czolowski *et al* 2017). Evidence continues to mount that OGD contributes to air pollution, water contamination, noise, psychosocial stress, and health risks (Johnston *et al* 2021, Deziel *et al* 2022a). Policy makers, public health scientists, regulatory agencies, community leaders, industry, and the public continue to grapple with how to best protect communities affected by OGD hazards. In this commentary we offer a hierarchy of controls framework for weighing which approaches or combination of approaches would most effectively reduce the public health impacts of the OGD industry, with particular consideration of nearby communities.

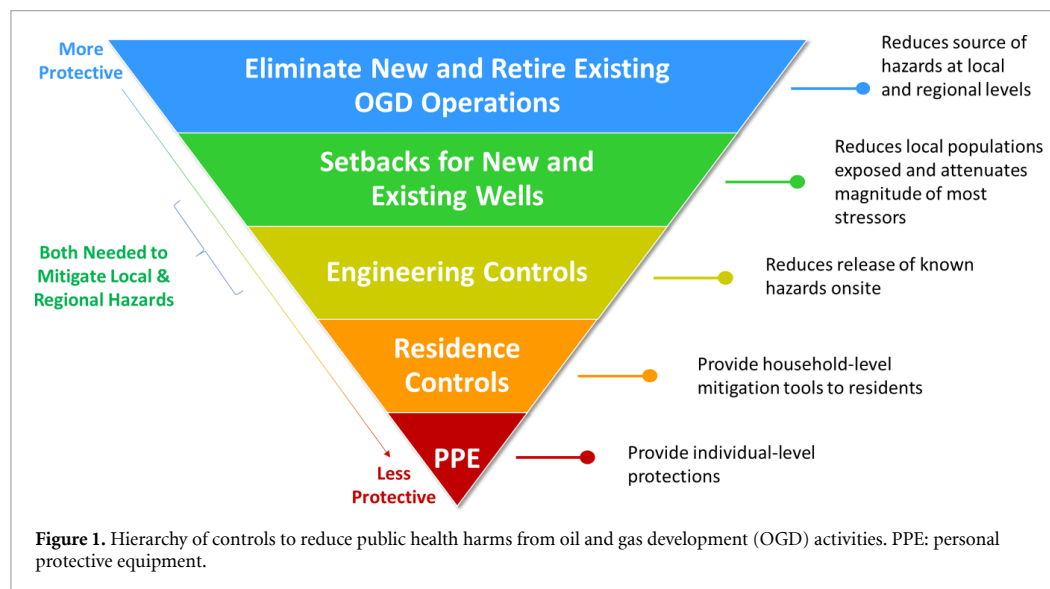
2. The hierarchy of controls

The concept of hierarchy of controls originated from the fields of occupational health and industrial hygiene to prioritize mitigation strategies from the most to the least effective at reducing hazards to workers (National Institute of Occupational Safety and Health (NIOSH) 2015). This hierarchy is based on the premise that the best way to control a hazard is

to eliminate it, and the least effective is to rely on individuals to wear protective gear. In practice, regulators and risk managers can increase protections by employing a layered or ‘defense in depth’ approach incorporating multiple actions, rather than selecting a single strategy (Chierici *et al* 2016).

The levels from the original occupational health framework (from the most to least protective) are (a) elimination (removal of the harmful substance or process altogether); (b) substitution (replacement with a less hazardous alternative); (c) engineering controls (the hazard remains but technology is used to limit its release or intensity); (d) administrative controls (policies that try to alter behavior to limit contact with a hazard, such as signage or limiting time spent in a hazardous area); and (e) personal protective equipment (PPE) (e.g. requiring individuals to wear clothing or equipment, such as masks, to create a barrier between the person and the hazard) (NIOSH 2015).

Extending this framework to environmental and other public health hazards offers great utility for guiding policy makers and communicating risk management strategies. In figure 1, we adapt the hierarchy of controls to reduce human health hazards, risks, and impacts from OGD activities. In contrast to the original framework, which was designed for specific hazards in workplaces, adaptation of this hierarchy to OGD reveals important distinctions when managing a complex multi-hazard source that poses threats to community members. Below, we describe the controls deployed at each level of protection in the hierarchy.



2.1. Eliminate new wells and phase out existing oil and gas wells

At the top of the inverted pyramid of figure 1 is the most health protective strategy: to stop development of new oil and gas wells and phase out existing OGD activities and infrastructure with proper well plugging and environmental remediation. Placing a halt on new oil and gas wells is classified as elimination because it completely removes the hazard. Properly plugging and remediating legacy wells and ancillary infrastructure is considered substitution because the idled wells remain, but in a modified form to enhance safety.

Although most effective at protecting health, complete elimination represents a systemic shift from the status quo with substantial political, socioeconomic, and logistical ramifications. Despite these challenges, examples of elimination are occurring throughout the US. Unconventional OGD (i.e. hydraulic fracturing or ‘fracking’) has been eliminated in Vermont, Maryland, New York, and Washington, states which vary in available reserves. The Delaware River Basin (DRB) Commission prohibited fracking in the DRB region, which covers parts of New York, Pennsylvania, New Jersey and Delaware, in order to protect drinking water (Delaware River Basin Commission (DRBC) 2021). Because these bans are specific to fracking, they do not eliminate conventional wells or orphaned and abandoned wells. However, some municipalities are moving towards complete OGD elimination, including Los Angeles, which has approved a ban of all new conventional and unconventional oil and gas wells and a phase-out of existing wells (Los Angeles Times 2022). In addition, the bipartisan infrastructure bill passed in November 2021 allocated \$4.7 billion to

plug abandoned oil and gas wells across the nation (Department of Interior 2021).

2.2. Setbacks for new and existing wells

Setbacks can include the restriction of new wells and phase out of existing wells and ancillary infrastructure within health science-informed distances from sensitive receptors. Sensitive receptors include homes, schools, and other places where people live, work, and play. The utility of setbacks is based on the premise that the multiple hazards associated with OGD operations attenuate with distance, such as noise (Lamancusa 2000), odors, and health-damaging air pollutants (Turner 2020, Gonzalez *et al* 2022), and impacts to aquifers that are used for drinking water and agricultural irrigation (Domenico and Robbins 1985, Garcia-Gonzales *et al* 2019, Soriano *et al* 2020). In this application, setbacks can be considered a combination of elimination and administrative controls. Setbacks are less effective at removing exposure pathways than complete elimination because they allow OGD activities to continue. Similar to administrative controls in the occupational setting, which can limit the amount of time a worker spends in a hazardous environment (i.e. shortened shifts), people may still spend time in the setback area but less time than they would if they resided or attended school within the setback zone. To maximize effectiveness, setbacks should apply to both the OGD site and to new construction of housing or schools, the latter of which could be constructed near existing OGD wells (also referred to as a reverse setback). Additionally, exposure and health data to inform local and regional setback distance choice is limited. Because hazards attenuate at different functions of distance, it is challenging to establish

a universal setback that optimally addresses all hazards. Furthermore, because setbacks do not eliminate OGD activities, regional hazards remain. For example, setbacks do not protect against the release of fine particulate matter (PM_{2.5}), nitrogen dioxide (NO₂), and volatile organic compounds (Gonzalez *et al* 2022), all of which contribute to formation of secondary pollutants such as ozone or secondary particulate matter at locations far from OGD operations. Setbacks also do not prevent the release of methane or other greenhouse gases that contribute to climate change, which indirectly introduces human health risks at local to global scales. Finally, increasing distance between OGD activities and human residential communities could place OGD infrastructure closer to wildlife communities, thereby shifting the burden to ecological rather than human health impacts (Deziel *et al* 2022b). To date, 23 states have adopted or are considering setbacks that vary widely and range from 100 ft (e.g. Arkansas and New York) to 3200 ft (California) (Ericson *et al* 2020). These distances often reflect a compromise among multiple stakeholders and include both economic and public health considerations, and therefore do not generally protect public health adequately (Haley *et al* 2016).

2.3. Engineering controls

In this framework, engineering controls include deployment of technologies to capture or reduce hazards at the source, monitoring to rapidly detect leaks, and the timely repairing of new and existing wells and ancillary infrastructure. Engineering controls are typically ranked higher in the hierarchy because they can control the hazard at the source. However, in the case of OGD, we ranked engineering controls lower in the pyramid because OGD is a complex source of many potential hazards. Consequently, reliance solely on engineering controls to manage risk requires knowledge of all the hazards, availability and implementation of methods for controlling the hazards, and technologies for monitoring the effectiveness of the controls. Engineering controls could include technologies such as noise and air pollution emission mitigation controls on OGD infrastructure (e.g. sound walls, capture of emissions), particularly for those oil and gas wells nearest to residential sites and schools, and for processes associated with the highest emissions or leaks.

Leak detection and repair (LDAR) technologies have advanced in recent years (e.g. optical gas imaging) and can be effective at identifying points of air emissions releases of methane and other pollutants (Ravikumar *et al* 2020). Control for greenhouse gases such as methane may concurrently reduce co-emitted toxic or malodorous chemicals and vice versa. An example was the observed co-benefit of methane emission reduction after controlling for olfactory compounds in Alberta, Canada (Lavoie *et al* 2022). However, not all infrastructure that emits

health-damaging air pollutants is methane rich and as such, LDAR focused on methane may not effectively control emissions of air toxics. Further, engineering controls can fail, and such solutions may not be available or economically feasible to handle all the complex hazards associated with OGD. Further, while the epidemiological literature clearly demonstrates that OGD is associated with multiple adverse health outcomes, such as adverse birth outcomes, respiratory disease, and mortality, the hazards and exposure pathways that contribute to these outcomes remain unclear (Li *et al* 2022, Deziel *et al* 2022a). Consequently, the effectiveness of mitigating health risks through engineering controls alone may be limited if the technologies do not control for uncharacterized hazards or exposure pathways.

2.4. Residential controls

Residential controls entail providing households with technologies and approaches to reduce hazardous exposures at home or other sensitive receptor areas, such as schools. Such controls can include water filters, light-blocking shades, sound-blocking windowpanes, air filters, and improved ventilation systems. These strategies are situated in the hierarchy between engineering controls and PPE. These protections, if used and maintained properly, may be effective at removing or reducing certain hazards indoors, where people spend a lot of time. However, this approach does not eliminate OGD hazards at the source, instead placing the burden on residents to use and maintain their own equipment. Furthermore, a complex array of devices would be needed to address the numerous known and potential hazards associated with OGD that could penetrate the home and other indoor environments. Like setbacks, residential controls do not address release of pollutants contributing to poorer regional environmental quality or climate change.

2.5. PPE

Use of PPE involves the provision of devices to reduce an individual's exposure, such as respiratory masks, ear plugs, and eye masks. PPE is the last layer of defense because it does not control the hazard. If the PPE fails, is in poor condition, worn improperly, or not worn consistently, individuals may be exposed. There is no PPE that can feasibly protect individuals against the full range of potential hazards associated with OGD. Additionally, like setbacks and residential controls, PPE does not address regional pollutant and climate change hazards.

3. Recommendations

In table 1 we summarize the advantages and disadvantages of each control type. Based on the hierarchy of controls, the most effective strategy for protecting communities from the hazards of OGD would be to

Table 1. Advantages and disadvantages of oil and gas development (OGD) control strategies from an environmental public health perspective.

Control Strategy	Description	Advantage	Disadvantage
Elimination	Eliminate new wells, properly plug existing wells, and remediate ancillary infrastructure.	Eliminates the source of nearly all environmental stressors (e.g. air and water pollutants, noise); protects local and regional populations; largest reduction in carbon emissions	May require a long-term approach due to economic, legal, political dynamics and energy reliability considerations, the need to address both conventional and unconventional wells, and the unknown location of many abandoned wells.
Setbacks	Establish a protective buffer zone between OGD hazards and sensitive receptors.	Reduces risk of exposures to populations living near OGD sites; environmental stressors are generally attenuated with increasing distance.	Setbacks alone without coupled engineered mitigation controls allow continued release of hazards. There is no universal setback that would adequately address regional air quality issues and emissions of climate-warming gases from OGD.
Engineering controls	Reduce or eliminate release of specific environmental hazards on site.	Reduces or eliminates certain hazards and therefore can have local and regional environmental public health benefits.	Tends to be disproportionately focused on air pollutant emissions and noise, and thus fails to address other pathways of exposure, including via water resources. Often not feasible to apply engineering solutions to multiple, complex hazards each requiring different control technologies (e.g. noise, air and water impacts, odors, light pollution) and lacks the important factor of safety provided by a setback when engineering controls fail.
Residence controls	Households deploy devices and strategies to reduce exposure to indoor environmental hazards at the household/school-level (e.g. water filter, light-blocking shades, air filters).	Reduces intensity of certain hazards to nearby communities at the household level.	Places burden on individuals and households to use and maintain devices properly to maximize effectiveness. Not feasible to apply devices to address numerous, complex stressors. Does not adequately address impacts of ambient air pollutant and greenhouse gas emissions from OGD on regional air quality and the climate.
Personal protective equipment	Individuals wear protective equipment to reduce exposure to environmental hazards (e.g. respiratory masks, ear plugs, eye masks).	Reduces intensity of exposure of certain hazards to nearby individuals.	Places burden on individuals to use PPE consistently and properly. May not be feasible for understudied stressors or certain environmental toxicants. Does not address impacts of air pollutant and greenhouse gas emissions from OGD on regional air quality and the climate.

eliminate all new OGD and ensure the proper plugging, decommissioning, and remediation of existing oil and gas infrastructure. However, complete elimination poses near-term challenges due to socio-economic, energy reliability, and political considerations and therefore may require a long-term approach. In the near term, reasonably protective strategies include the layering of setbacks and engineering controls, because neither alone adequately protects populations from OGD hazards and risks. We encourage the integrated deployment of these approaches to align with the best available science and technology. Additionally, evidence-based decision-making could be improved by new research designed to elucidate

the relative importance of OGD-related hazards or exposure pathways and how to mitigate them.

OGD presents a challenge for regulators due to its many hazards with varying spatiotemporal scales, dispersion patterns, and monitoring and mitigation approaches. In this application, we reached two conclusions regarding the management of risks from OGD: (a) that our modified hierarchy of controls is a useful decision-making framework that could readily be adapted to other environmental hazards; and (b) that the application of near-term and long-term approaches in this hierarchy is needed to address OGD hazards more adequately and better protect community health.

Data availability statement

No new data were created or analyzed in this study.

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Ambient Nonmethane Hydrocarbon Levels Along Colorado's Northern Front Range: Acute and Chronic Health Risks

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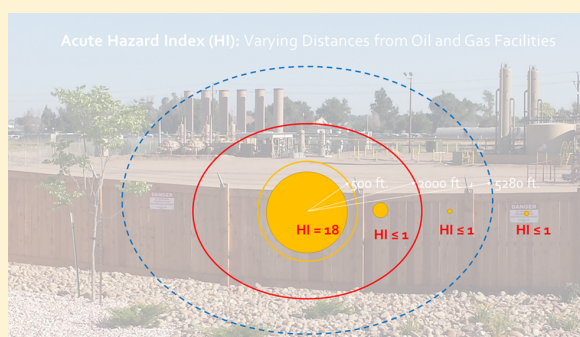
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Supporting Information

ABSTRACT: Oil and gas (O&G) facilities emit air pollutants that are potentially a major health risk for nearby populations. We characterized prenatal through adult health risks for acute (1 h) and chronic (30 year) residential inhalation exposure scenarios to nonmethane hydrocarbons (NMHCs) for these populations. We used ambient air sample results to estimate and compare risks for four residential scenarios. We found that air pollutant concentrations increased with proximity to an O&G facility, as did health risks. Acute hazard indices for neurological (18), hematological (15), and developmental (15) health effects indicate that populations living within 152 m of an O&G facility could experience these health effects from inhalation exposures to benzene and alkanes. Lifetime excess cancer risks exceeded 1 in a million for all scenarios. The cancer risk estimate of 8.3 per 10 000 for populations living within 152 m of an O&G facility exceeded the United States Environmental Protection Agency's 1 in 10 000 upper threshold. These findings indicate that state and federal regulatory policies may not be protective of health for populations residing near O&G facilities. Health risk assessment results can be used for informing policies and studies aimed at reducing and understanding health effects associated with air pollutants emitted from O&G facilities.



INTRODUCTION

Horizontal drilling and high-volume hydraulic fracturing have resulted in a dramatic increase in the number of oil and gas (O&G) wells located on a single pad.^{1,2} It is now common for O&G well sites to contain 20 to 40 wells, related infrastructure, and tank batteries to store and/or pipelines to transport petroleum products and exploration and production (E&P) waste.³ Additional equipment and facilities, such as gathering lines, compressor stations, and E&P waste disposal sites may also be located in areas of intensive O&G development.⁴

In the Denver Julesberg Basin (DJB) on the Colorado Northern Front Range (CNFR), the O&G industry is rapidly expanding at the same time that housing construction is increasing to accommodate a rapidly growing population.⁵ As a result, 19% of the population (~356 000 people) in the DJB live within 1600 m of an active O&G well site.⁵ Between 2000 and 2012, the number of people living within 1600 m of an

O&G well site grew almost 3 times faster than the population living further away.⁵

Colorado mandated regulatory exclusion zones around residential structures in which the drilling of O&G wells is discouraged are referred to as setback distances. Colorado setback distances were historically as short as 150 feet (46 m) and are currently at 500 feet (152 m).⁶ Additionally, setback distances of 1000 feet (305 m) apply to high occupancy buildings serving 50 or more people (e.g., schools and hospitals) as well as operating child care centers for 5 or more children.⁶ While the setback distances are intended to protect the general public's safety and welfare from environmental and nuisance impacts resulting from O&G develop-

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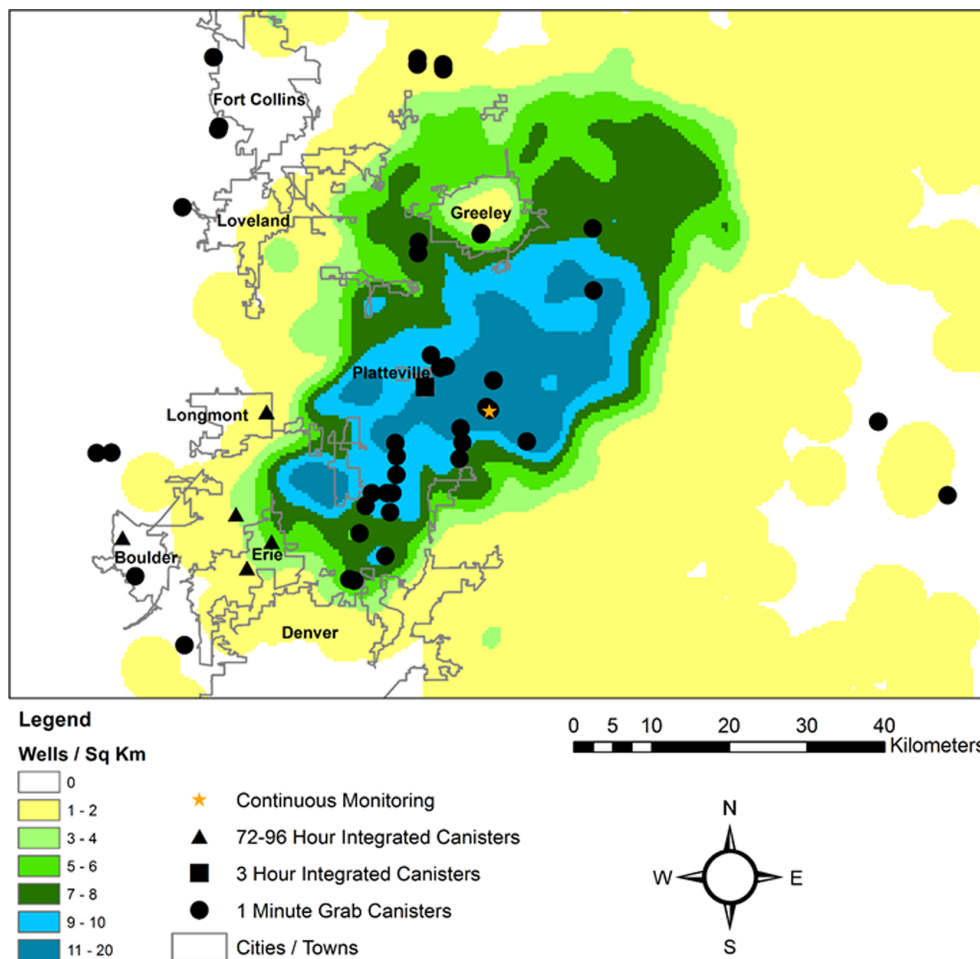


Figure 1. Colorado Northern Front Range: sample locations³⁷⁻³⁹ and oil and gas well density.³⁶

ment, they are not intended to address potential human health impacts associated with O&G development air emissions.⁷

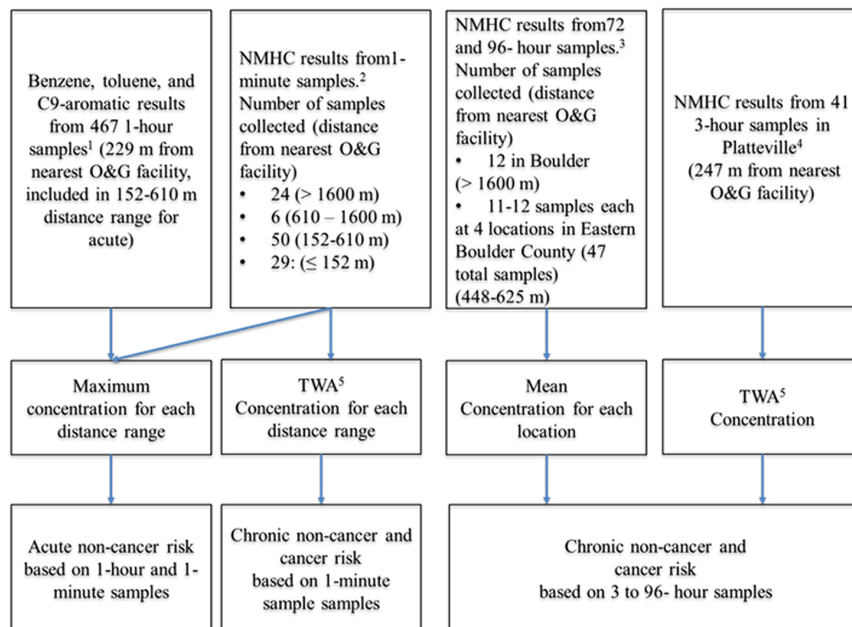
Air pollution is one of the major potential health risks for populations living near O&G sites.^{4,8} O&G sites directly emit nonmethane hydrocarbons (NMHCs) into the air,⁹⁻¹¹ and several studies have identified O&G facilities as major contributors to ambient NMHC levels along the CNFR.¹²⁻¹⁷ Some of these NMHCs such as benzene, toluene, ethylbenzene, and xylenes (BTEX) are defined as hazardous air pollutants.¹⁸ Because of higher atmospheric stability at night, nighttime emissions do not disperse as much as during the daytime, and average nighttime benzene levels are approximately twice daytime levels.¹⁵

Recent Colorado studies observed that infants with congenital heart defects and children diagnosed with leukemia are more likely to live in the densest areas of O&G wells.^{19,20} Studies in Pennsylvania and Texas have observed associations between proximity to O&G wells and fetal death, low birthweight, preterm birth, asthma, fatigue, migraines, and chronic rhinosinusitis.²¹⁻²⁵

The few previous human health risk assessments conducted in areas with O&G development have used results from ambient air samples to predict the risk for both noncancer and cancer health effects in the surrounding population.^{8,26,27} Risks for noncancer health effects have been expressed as semi-

quantitative hazard indices (HI), and cancer risks have expressed as risk in excess of the baseline lifetime cancer risk for Americans of 44 per 100 (lifetime excess cancer risk).²⁸ The previous assessments indicate the potential for short-term respiratory, neurological, hematological, and developmental effects and elevated estimated lifetime excess cancer risk for populations living within approximately 800 m of O&G well pads,⁸ while the potential for chronic noncancer health effects and lifetime excess cancer risk are lower for populations living further from O&G sites.^{8,26,29,30} One important shortcoming of previous risk assessments is that they did not consider short-term and repeated nighttime peak exposures. They did not explicitly address childhood exposures or incorporate findings from the most recent studies on health effects associated with ambient benzene exposure. Additionally, data sets supporting most of the previous risk assessments were not sufficient for assessment of short-term exposures to air pollution O&G facilities or the variance in health risks with differing setback distances from O&G facilities.

The goal of this analysis is to characterize prenatal through adult noncancer and cancer health risks from both short-term (acute) and long-term (chronic) residential exposures to NMHCs measured in CNFR O&G development areas and how health risks vary with proximity to O&G facilities.



For each sample type this figure depicts the chemical measurement results used, number of samples collected, and the distance of the sampling location from the nearest oil and gas (O&G) facility (single and multi- well sites, tank batteries, extraction and production waste disposal sites, gathering lines, and O&G processing facilities).
 NMHC: non-methane hydrocarbon

¹ DISCOVER AQ Field Sampling Campaign: The nearest O&G facility is a multi-well pad. Sample collected every minute between July 17 and August 8, 2014 (n = 28,009 total measurements). Benzene, toluene, and C9 aromatic results determined by proton-transfer-reaction quadrupole mass spectrometry. The 1-hour results are the mean of 60 consecutive 1-s readings.¹⁵

² DISCOVER AQ Field Sampling Campaign: Samples collected between July 17 and August 13, 2014 primarily during daylight hours 6:00 and 21:00 hours (2 samples were collected in the 2:00 hour) at 3 to 14,870 meters from single and multi- well sites, tank batteries, extraction and production waste disposal sites, gathering lines, and O&G processing facilities. NMHC results determined by gas chromatography with flame ionization and quadrupole mass spectrometer detectors. 1-minute canister samples.^{15,33}

³ 2014 Boulder County Air Study: Samples were collected between May 23 and August 27, 2014: 12 sample at a single location in Boulder (> 1600 meters from an O&G facility) and 11-12 samples at each of four Erie locations (448 to 625 meters from multiple O&G well pad). NMHC results determined by gas chromatography with flame ionization and quadrupole mass spectrometer detectors. 72-96-hour integrated canister samples.³⁷

⁴ Colorado Department of Public Health and Environment (CDPHE) Platteville Air Monitoring Site: Nearest O&G facility is a multiple O&G well pad. Samples collected at a single location between 6:00 to 9:00 am (27 samples) and 1:00 to 4:00 pm (14 samples) from June 1 to August 31 2014. NMHC results determined by gas chromatography with flame ionization detector. 3-hour-integrated canister samples.^{16, 33}

⁵ Time Weighted Average: TWA mean = ((mean concentration x 12 hours x 2.34) + (mean concentration x 12 hours))/24 hour.

Figure 2. Samples collected along Colorado’s Northern Front Range in summer 2014 used to develop exposure and risk estimates.

METHODS

We used California’s Office of Environmental Health Hazard Assessment (OEHHA) Risk Assessment Guidelines to estimate acute and chronic noncancer hazards and cancer risks for exposures to NMHCs, including BTEX, in residential exposure scenarios.³¹ California’s OEHHA guidance addresses developmental outcomes not fully covered in standard United States Environmental Protection Agency’s (USEPA) risk guidance.^{32,33} Specifically, OEHHA guidance has incorporated recent research findings on the developmental toxicity of ambient level benzene into their toxicity factors as well as a lifespan beginning in the third trimester of pregnancy into their cancer risk assessment.^{31,34,35}

Data Sources. We characterized risks for residential populations based on proximity to the nearest O&G facility, as recorded in the Colorado Oil and Gas Information System.³⁶ All samples included in this risk assessment were collected at

plausible residential locations (i.e., at a distance greater than Colorado’s historic 150 foot (46 m) setback distance from the nearest O&G facility) using NMHC measurement results from one of three CNFR studies conducted in the summer of 2014 (Figure 1, Figure 2, Supporting Information):

Study 1: 1-min canister samples (hereafter 1-min samples) and continuous air monitoring (1-s time resolution readings every minute: 60 consecutive minutes averaged to represent 1 h of exposure, hereafter 1-h samples) from the 2014 DISCOVER-AQ (Deriving Information on Surface conditions from Column and VERTically resolved observations relevant to Air Quality) field campaign.³⁷ The 1-min samples collected during the DISCOVER-AQ study targeted O&G, power generation, agricultural facilities, and high vehicle traffic areas. In situ methane, carbon dioxide, and carbon monoxide measurements were used to identify plume and background locations. In addition to residential plausibility-based setback distances, we

reviewed Google Earth satellite images dated between June 2 and October 6, 2014 to determine if the sample location was appropriate for evaluating residential exposures. On the basis of these reviews, we excluded results from seven 1-min samples that had been collected at locations adjacent to large O&G processing plants or propane tank facilities because these locations were not plausible residential locations (Supporting Information Table S1). The 1-h samples were collected at a fixed site located in a rural area at 229 m from the nearest O&G facility.

Study 2: 72–96-h integrated canister samples (hereafter 72–96-h samples) collected for the 2014 Boulder County air quality monitoring study.³⁸ All sites were located in residential areas. The site in western Boulder was selected as a reference site (i.e., with minimal O&G development influence) and was located on the grounds of the Boulder County Public Health offices near a busy intersection. Results from this location are subjected to urban and traffic influences and thus provide a representative urban signature. Twelve summa canister samples were collected at the Boulder site. The sites in Eastern Boulder County, along the border between Boulder and Weld County, were selected to assess the geographical gradients of NMHCs resulting from dense O&G development. The Eastern Boulder County sites were public facilities (a school, park, church, and fire station) located in residential areas, and other obvious sources of NMHCs were avoided. A total of 47 summa canister samples were collected from 4 sites in Eastern Boulder County (11–12 samples at each site).

Study 3: 41 3-h integrated canister samples (hereafter 3-h samples) collected by the Colorado Department of Public Health and Environment (CDPHE) at a single site in a residential area of Platteville, CO located 247 m from the nearest O&G facility.³⁹

Data Assessment. Field measurement results were grouped by exposure scenario and sample type, as indicated in Figure 2. Because the underlying measurements were not normally distributed, all data were log transformed prior to statistical analysis. We evaluated the remaining measurements from the 1-min samples as well as the 1-h, 3-h, and 72–96-h samples for outliers using Q-Q plots.³⁹ No results were removed based on the outlier analysis. For results below the limit of detection, we substituted the limit of detection for statistical evaluations and calculations of mean concentrations.⁴⁰ Supporting Information Tables S2–S4 contain summary statistics and limits of detection for NMHCs included in the risk assessment.

We used analysis of variance (ANOVA) to compare means of specific NMHC concentrations between the four scenarios described below. We evaluated differences between mean NMHC concentrations with post hoc Tukey's studentized range (HSD) tests. Results were considered statistically different at an α of 0.05. All statistical analyses were conducted using SAS software version 9.3 (Cary, NC).⁴⁰

Exposure Assessment. Acute and chronic exposure estimates were developed for four scenarios based on Colorado regulatory setback distances between O&G wells and residential facilities of 152 m⁶ and literature reference points of 1600 m:^{5,41}

- (1) No O&G facilities within 1600 m.
- (2) Nearest O&G facility within 610–1600 m.
- (3) Nearest O&G facility within 152 to 610 m.
- (4) Nearest O&G facility within 152 m.

The nearest O&G facility from each sample location included well pads, tank batteries, E&P waste disposal sites, gathering lines, and processing facilities.

To estimate acute and chronic noncancer health hazards and cancer risks, we considered short and long-term exposures to NMHCs. For acute exposure, we used the maximum measured concentration of each NMHC from the 1-min samples to estimate the maximum 1-h ambient air concentration for all scenarios and compounds, except for benzene, toluene, and C9 aromatics in the 152–610 m scenario. For the 152–610 m acute scenario, we used maximum 1-h sample results for benzene, toluene, and C9 aromatics that were available only for this scenario. For chronic hazards and cancer risks, time-weighted average (TWA) mean (1-min and 3-h samples) over 24 h and mean (72–96-h samples) ambient NMHC concentrations were used to represent the average concentration and calculate a daily intake dose for each NMHC according to OEHHA Guidance (Supporting Information).³¹ We calculated a TWA mean for the 1-min and 3-h samples because these samples were mostly collected in the daytime and do not represent nighttime concentrations. Continuous sampling results at the Platteville location indicate that the average mean benzene concentration from 19:00 in the evening to 7:00 the following morning is 2.34 times higher than between 7:00 and 19:00 h.¹⁵ On the basis of these observations, eq 1 was used to calculate the TWA mean:

$$\text{TWA mean} = \frac{(\text{mean concentration} \times 12 \text{ h} \times 2.34) + (\text{mean concentration} \times 12 \text{ h})}{24 \text{ h}} \quad (1)$$

Toxicity Assessment and Risk Characterization. For noncarcinogens, we expressed inhalation toxicity health-based factors as a reference concentration (RfC) in units of $\mu\text{g}/\text{m}^3$ (Supporting Information Table S5). We used OEHHA chronic reference exposure levels (REL) to evaluate long-term exposures of 8 or more years (OEHHA 2015).³¹ If an OEHHA chronic REL was not available, we used the USEPA's risk screening level (RSL) for ambient air.⁴² The OEHHA chronic RELs and EPA chronic RSLs are applicable to 24-h per day exposures over 10 to $\geq 12\%$ of a 70-year lifespan (i.e., 7 to 8 years of exposure).^{31,34,42} We used OEHHA acute RELs to evaluate acute 1-h exposures.³¹ If an acute OEHHA REL was not available, we used the ATSDR's acute MRLs.⁴³ If RELs, RSL, or MRL were not available, RfCs were obtained from (in order of preference) EPA's Integrated Risk Information System (IRIS) subchronic RfCs,⁴⁴ EPA's subchronic Provisional Peer-Reviewed Toxicity Values (PPRTV),⁴⁵ or Health Effects Assessment Summary Tables.⁴⁶ We used surrogate RfCs according to EPA guidance for C₅ to C₈ alkanes and C₉ aromatic hydrocarbons, which do not have a chemical-specific toxicity value.⁴⁵ We derived semiquantitative noncancer hazard quotients (HQs), defined as the ratio between the estimated exposure concentration and RfC.^{31,32} We summed HQs for specific NMHCs to calculate the HI. We also separated the HQs specific to neurological, respiratory, hematological, and developmental effects and calculated a separate end point-specific HI for each of health effect. HQ's and HI's > 1 indicate that the estimated exposure exceeds the threshold exposure and the possibility of adverse health effects.³² Because the HI is semiquantitative metric, it does not imply a multiplier. For example, an HI of 4 is not twice the risk of an HI of 2.

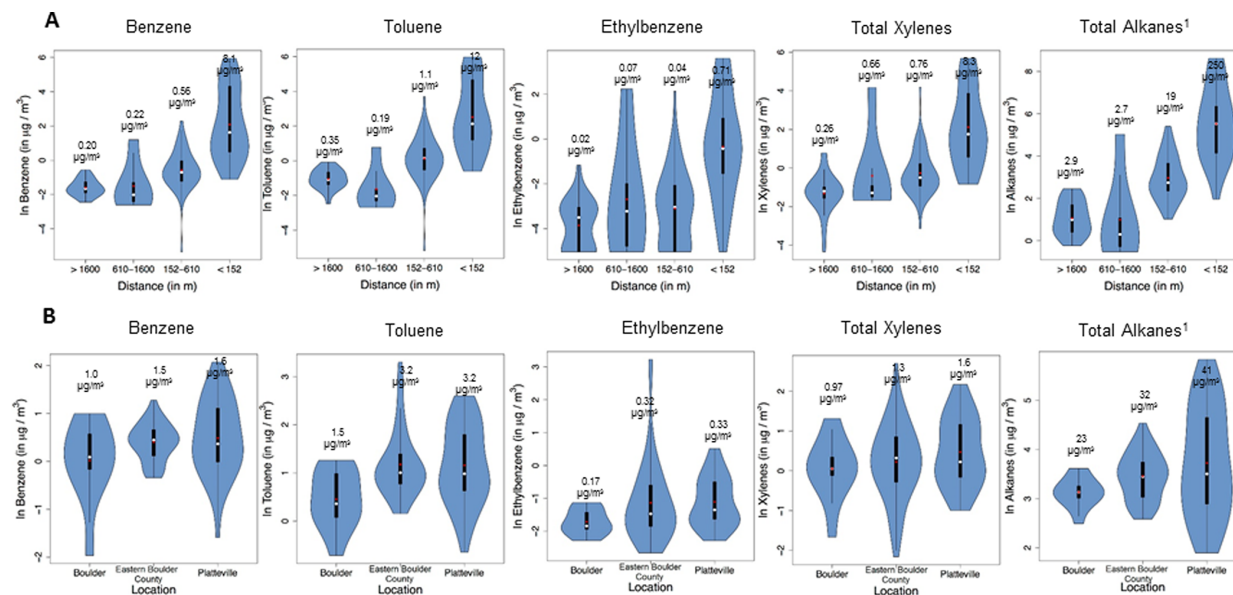


Figure 3. (A) Distributions and means of selected hydrocarbon concentrations from 1-min samples by distance from the nearest oil and gas facility. (B) Distributions and means of selected hydrocarbon concentrations from 3 to 96 h samples by distance from the nearest oil and gas facility.

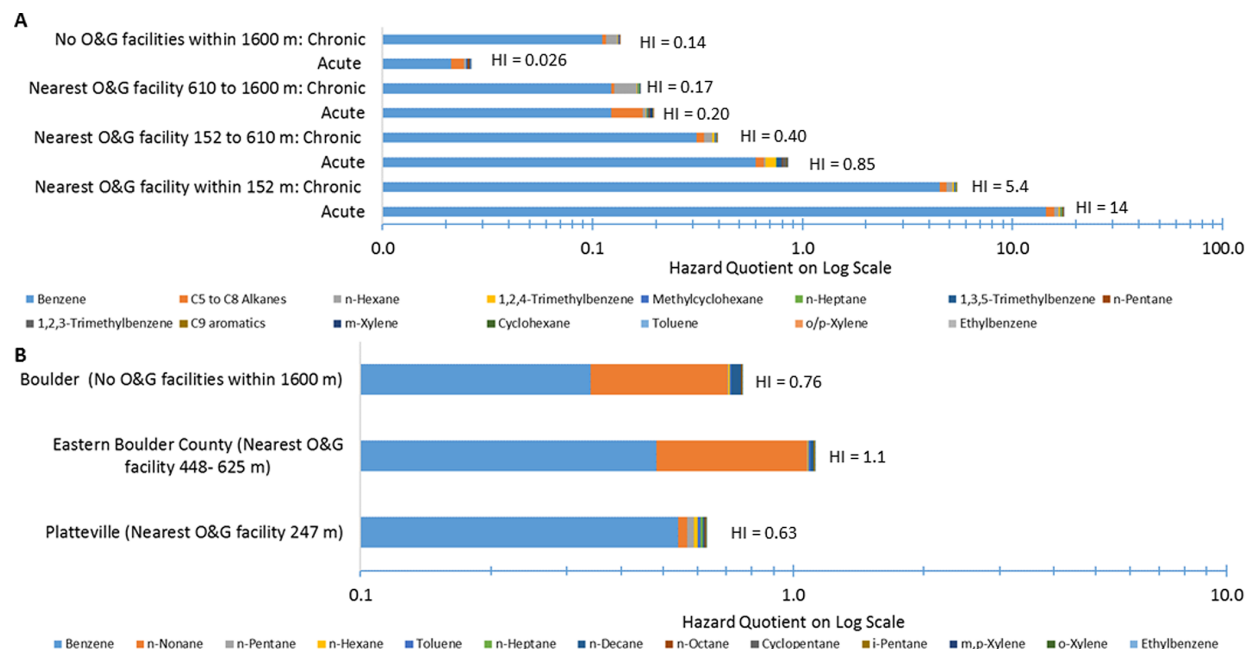


Figure 4. (A) Chronic and acute hazard quotients and hazard indices for residents living >1600, 610–1600, 152–610, and within 152 m from an oil and gas facility based on 1-min and 1-h sample results. (B) Chronic hazard quotients and hazard indices for residents living in Boulder, Eastern Boulder County, and Platteville based on 3-, 72-, and 96-h sample results.

For carcinogens, we expressed inhalation toxicity measurements as OEHHA inhalation cancer potency factors (CPFs) summarized in units of $(\text{mg}/\text{kg}\cdot\text{day})^{-1}$.³¹ The lifetime excess cancer risk for each carcinogenic NMHC was derived per OEHHA guidance (Supporting Information).³¹ We summed individual lifetime excess cancer risks for each NMHC to estimate cumulative lifetime excess risk. Risks are expressed as excess cancers over a lifetime per 1 million population based on

exposure over 30 years, per OEHHA guidance,³⁴ which is consistent with the USEPA reasonable maximum exposure.³²

To estimate the population cancer risk for residential scenarios of less than 1600 m, we adjusted the cumulative lifetime excess cancer risk by subtracting the risk for populations with no O&G facilities within 1600 m of their home from the risk for populations living in closer proximity to facilities. We derived 2014 population estimates by adjusting the DJB 2012 population estimates at specific distances from

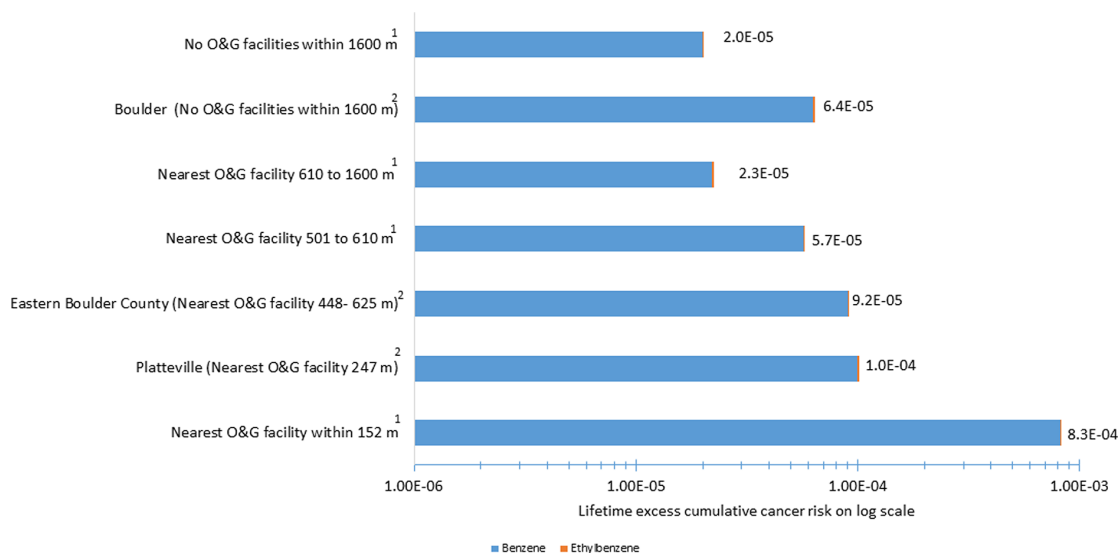


Figure 5. Lifetime excess cancer risks (30 year exposure duration) for residents >1600, 610–1600, 152–610, and within 152 m from an oil and gas facility based on 1-min sample results.

O&G wells for 2 years of population growth based on the average annual rate of growth between 2000 and 2012.⁵ We then estimated the population risk for each scenario by multiplying the adjusted cumulative lifetime excess cancer risk by the estimated 2014 population estimate.³¹

RESULTS AND DISCUSSION

For the 1-min samples (Figure 3), mean ambient BTEX and total alkane concentrations increased as the distance of the sample collection from the nearest O&G facility decreased ($p < 0.001$). The mean ambient benzene, toluene, ethylbenzene, total xylene and total alkane concentrations from the 1-min samples collected within 152 m of the nearest O&G facility were 41, 34, 35, 32, and 86 times higher, respectively, than the mean from 1-min samples collected further than 1600 m from the nearest O&G facility ($p < 0.05$, Figure 3). Supporting Information Table S6 presents the ANOVA results comparing selected NMHC mean concentrations as a function of distance to O&G facility.

For the 3-, 72-, and 96-h samples (Figure 3b and Table S6b), the TWA mean concentration from the 3-h samples collected in Platteville (247 m from nearest O&G facility) was compared to the mean concentration from the 72- and 96-h samples collected in Boulder (>1600 m from nearest O&G facility) and Eastern Boulder County (448–625 m from nearest O&G facility). Mean ambient benzene, ethylbenzene, and total xylene concentrations did not vary significantly between locations, although the lowest mean concentrations occurred in samples collected in Boulder. Mean ambient toluene concentrations in Platteville and Eastern Boulder County were twice the mean concentration in Boulder ($p < 0.05$). Mean ambient total alkane concentrations in Platteville were 1.3 and 1.8 times greater than those in Eastern Boulder County and Boulder ($p < 0.05$) (Figure 3b).

Noncancer Hazards. Figure 4a presents acute and chronic noncancer HQ and HI estimates based on maximum 1-min and 1-h sample results, and TWA mean 1-min sample results, respectively (Supporting Information Tables S7). Acute and chronic HQs and HIs increased with decreasing distance to the

nearest O&G facility. Acute HIs for nervous system (18), blood system (15), and developmental effects (15) were >1 for residents living within 152 m of an O&G facility, and benzene and alkanes contributed more than 80 and 13%, respectively, to these end point specific HIs. Acute respiratory HIs were <1 for all scenarios. Chronic HIs for blood system (4) and developmental effects (4) were >1 for residents living within 152 m of an O&G facility, and benzene contributed to 84% of the HI (Supporting Information Tables S7). Acute and chronic HIs for all effects were <1 at distances greater than 152 m from O&G facilities.

Figure 4 b presents chronic HQ and HI estimates based on TWA mean 3-h (Platteville) and mean 72–96 h (Boulder and Erie) sample results (Supporting Information Table S8). Total chronic HIs were highest in Eastern Boulder County, where the total HI was 1.1, followed by Boulder, and then Platteville. Nervous system, respiratory system, blood system, and developmental HIs were <1 for all locations.

The chronic HIs based on 72–96-h samples are 2–10 times greater than those reported for residential exposures to NMHC in O&G areas in previous risk assessments^{8,26,27} primarily because the OEHHA chronic REL for benzene ($3 \mu\text{g}/\text{m}^3$) is 10 times less than the USEPA's chronic RfC ($30 \mu\text{g}/\text{m}^3$). The OEHHA chronic benzene REL³⁴ considers several studies published after USEPA's 2002 benzene assessment,⁴⁷ which found increased efficiency of benzene metabolism at low doses,^{48–51} decreased peripheral blood cell counts at low doses ($800\text{--}1860 \mu\text{g}/\text{m}^3$) with no apparent threshold,^{52–54} and large population variation in the response of metabolic enzymes involved in benzene activation and detoxification.⁵⁵

Lifetime Excess Cancer Risk Estimates. Figure 5 presents lifetime excess cancer risks based on daily inhalation intake dose estimates calculated from 1-min, 3-h, and 72–96-h sample results (Supporting Information Tables S9 and S10). All cumulative lifetime excess cancer risks exceeded USEPA's de minimus benchmark of 1 in a million⁵⁸ with benzene representing more than 95% of the total risk estimate for all scenarios. The cumulative lifetime excess cancer risk increased with decreasing distance to the nearest O&G facility. For

residents living within 152 m of an O&G facility, the risk exceeded the USEPA upper bound risk level of 1 in 10 000⁵⁶ with an overall risk of 8.3 per 10 000 (Supporting Information Table S9). The cumulative lifetime excess cancer risk was higher in Eastern Boulder County and Platteville than in Boulder and reached the USEPA's upper bound risk level of 1 in 10 000 in Platteville (nearest O&G facility 247 m) based on the 3-, 72-, and 96-h sample results (Supporting Information Table S10). For similar scenarios, the cumulative lifetime excess cancer risks based on mean 72–96-h sample results are greater than risks based on TWA mean 1-min and 3-h sample results.

These lifetime excess cancer risk estimates are 10–100 times greater than those reported in previous risk assessments in O&G development areas that used USEPA guidance.^{8,26,27} This is partly because the OEHHHA inhalation benzene CPF (0.1 (mg/kg-day)⁻¹ is 4 times higher than USEPA's benzene slope factor (0.027 (mg/kg-day)⁻¹).^{31,44} The OEHHHA approach addresses methodological shortcomings in the derivation of USEPA's current slope factor, which was calculated with a linear extrapolation model that assumes excess risk is proportional to the lifetime average exposure, is the same for all ages, and does not explicitly address the impact of episodic exposure peaks.⁵⁷ OEHHHA's inhalation CPF was calculated using a weighted cumulative exposure/relative risk procedure that assumes with continuous exposure, age-specific cancer incidence continues to increase as a power function of the elapsed time since the initial exposure.³⁵ Additionally, OEHHHA includes prenatal exposures in the calculation of lifetime excess cancer risk based on recent studies indicating increased susceptibility to benzene in early life.³⁵ Even using USEPA's current slope factor, which would reduce the lifetime excess cancer risk from benzene for residents living within 152 m of an O&G facility to 2.2 in 10 000, our results remain above USEPA's 1 in 10 000 upper bound for remedial action.

Overall Strengths and Limitations. We assessed acute and chronic health risks from air pollution associated with O&G operations using data collected in close proximity to O&G facilities and realistic residential scenarios tied to regulatory setback distances and literature reference points. This approach allowed us to incorporate proximity, spatial variability, and temporally relevant sampling durations into our exposure scenarios. The consistent application of exposure and toxicity parameters for all four scenarios allows for the comparison of hazards and risks between the scenarios. We found increasing (1) hematological and developmental HIs and (2) cumulative lifetime excess cancer risks with decreasing distance to the nearest O&G facility. These results are consistent with findings from observational epidemiological studies that indicate an increased likelihood of adverse birth outcomes and childhood acute lymphocytic leukemia with increasing proximity to O&G wells.^{19–21,23,24} The weight of evidence increasingly suggests that plausible outcomes to explore in future epidemiological studies of exposure to O&G-related pollutants include: neural tube defects,⁵⁸ changes in blood cell and platelet counts and aberrant nucleic acid methylation patterns,^{59–61} and increased levels of 8-hydroxydeoxyguanosine, a biomarker of short-term nucleic acid damage.^{62–64}

However, the uncertainties in our risk assessment are substantial, and the results are best suited for scoping policy and future studies. Some of our assumptions are inherent in the risk assessment process (Table 1), while others are more specific to this study. Exposure to benzene had the largest

Table 1. Assumptions Adherent in Risk Assessment Process That Lead to Uncertainty

assumption	description
1	Maximum concentrations from 1-min samples to estimate acute exposure levels.
2	Chronic reference exposure levels and risk screening levels assume 24 h per day exposures, 365 and 350 days per year, respectively, for more than 7 years.
3	Multiple uncertainty factors applied in derivation of the reference concentrations.
4	The lifetime excess cancer risk assumed that residents spend 72–85% of their time at home over a 30 year period.
5	Reference concentrations that were mostly derived from occupational studies on adults or animal toxicity studies may not adequately represent the current understanding of developmental and reproductive effects.

contribution our predicted health risks. While there is extensive evidence that occupational benzene exposure is linked to leukemia, the evidence in nonoccupational populations is less robust. Nonetheless, the body of literature suggesting that exposures to ambient levels of benzene are associated with incidence of childhood leukemia is increasing. Additionally, recent studies that were included in the derivation of the RELs for toluene in this risk assessment suggest that low dose toluene exposure can alter fetal and adult testosterone levels.^{65–67} Reductions in testosterone and mRNA 3B-hydroxysteroid dehydrogenase levels were observed in male fetal rats at low toluene exposures.⁶⁵ Using the lowest observed adverse effect level of 3400 $\mu\text{g}/\text{m}^3$ from that study results in chronic and acute toxicity values of approximately 300 and 30 000 times lower, respectively, than current toxicity values, resulting in a corresponding increase of acute and chronic toluene HQs > 1 for the <610 m exposure scenarios.

Ideally, chronic HIs and cancer risk are estimated from a large number of air samples that represent 24-h exposure. In the summer of 2014, only the 72- to 96-h samples collected in Boulder and Eastern Boulder County captured full 24-h exposure periods. Because 24-h data was not available to estimate chronic HIs and cancer risks for populations living in close proximity to O&G facilities (i.e., 305 m),⁵ we used 3-h and 1-min measurements as they were the best available to estimate 24-h exposures for this scenario. However, the 1-min and 3-h samples were collected mostly during the daytime and do not represent the contribution of what are likely higher nighttime ambient NMHC concentrations,¹⁵ even after the TWA adjustment. This is likely the reason our chronic cumulative HIs and cancer risks based on mean 72–96-h sample results are greater than those based on TWA mean 1-min and 3-h sample results for similar scenarios. This also indicates that the HIs and cancer risks calculated from the 3-h and 1-min samples are likely not overestimated because they are an empirical estimate of local short-term concentrations of these compounds.

Our findings are based on ambient air samples collected in the summer of 2014 that may not capture temporal variations in NMHC concentrations associated with O&G activities. For example, NMHC concentrations likely differ by season and will vary in the future as O&G emission control technology evolves. Existing studies suggest that winter levels of these pollutants are higher because longer nights and cold daytime temperatures keep the atmospheric boundary layer lower than that in summer and thus increase NMHC concentrations near the surface.^{12,68}

Finally, exposure to other air pollutants, drinking water contaminants, and nonchemical stressors (e.g., noise) associated with upstream O&G operations could further contribute to the health risks estimated in this study. For example, alkanes emitted from O&G operations contribute to approximately 20% of summertime photochemical ozone production along the CNFR,⁶⁹ and each 10 ppb increase in ozone may result in a 2% increase in mortality.⁷⁰ Ozone levels in several CNFR cities exceed National Ambient Air Quality standards.⁷¹

To better understand health risks from air pollution originating from O&G operations, systematic ongoing sampling of NMHCs (especially BTEX), source tracers, and other air pollutants such as formaldehyde, acetaldehyde, and polycyclic aromatic hydrocarbons^{72,73} associated with O&G activities is needed. Future research should focus on providing measured and modeled exposure estimates of key risk drivers (e.g., BTEX) for populations living near O&G operations.⁷⁴

■ POLICY IMPLICATIONS

Our results indicate that State regulatory setback distances (the minimum distance an O&G wellhead may be located from a home) and reverse setback distances (the minimum distance a home may be located from an O&G wellhead) and related municipal codes may not protect nearby residents from health effects resulting from air pollutants emitted from these facilities. Setback distances between homes and other types of O&G facilities (e.g., tank batteries, waste disposal sites, gathering lines, compressor stations, etc.) have not been specified,⁶ and very few municipal codes regulate the siting of homes near existing O&G well sites.^{5,75,76} We found that Colorado populations within 152 m of an O&G facility are more likely to experience neurological, hematological, and developmental health effects from acute inhalation exposures to benzene and alkanes. We also estimated cumulative lifetime excess cancer risks for populations living within 610 m of an O&G facility exceed USEPA's upper threshold of 1 in 10 000.

Sources of air pollutants other than O&G facilities (e.g., non O&G related traffic) likely partially contributed to the health risks for all exposure scenarios. Nonetheless, our results indicate that air pollutants from O&G facilities increasingly contribute to the health risks as the distance from the nearest O&G facility decreases. For the more than 380 000 people along the CNFR estimated to be living within 1600 m of an O&G well in 2014, we estimate an additional 17 to 27 cases of cancer over a lifetime (70 years). We estimate that more than 50% of these additional cancers may occur in the population living within 152 m of an O&G facility (Supporting Information Table S11).

Our results could be useful in justifying and further scoping of Colorado regulations on air emissions from O&G facilities. In 2014, the Colorado Air Quality Control Commission fully adopted EPA's Standards of Performance for Crude Oil and Natural Gas Production, Transmission, and Distribution (NSPS OOOO) (40 C.F.R. Part 60, Subpart OOOO) into Colorado Regulation Number 6 and adopted complementary O&G emission control measures in Colorado Regulation Number 7.^{77,78} EPA's NSPS OOOO stipulates that hydraulic fracturing and well completion operations begun on or after January 1, 2015 and storage tanks must use control measures to reduce VOC emissions.⁷⁷ In 2016, the Colorado Department of Public Health and Environment's Air Pollution Control Division implemented Regulation 7, which requires O&G operators to find and repair leaks and install devices to capture at least 95%

of VOC emissions from new and existing wells, storage tanks, compressor stations, and glycol dehydrators.⁷⁸ Colorado's revised Regulations 6 and 7 aim to reduce ozone precursor and methane emissions from larger and newer O&G facilities and could eliminate 93 500 tons of VOCs per year.⁷⁸ Our results provide further justification for implementation of these regulations because such regulations could also reduce emissions of hazardous air pollutants such as benzene that drive our risk estimates.

However, our risk results include both older and smaller O&G facilities, and other studies indicate that older and smaller O&G facilities could emit significant levels of air pollutants that are important contributors to health risk. Because Colorado Regulations 6 and 7 are less stringent for older wells, controls on small emitters (<6 tons VOCs per year), and temporary frac tanks,⁷⁸ they may not be sufficiently protective for residents living near these facilities. The NSPS OOOO is applicable only to wells built or modified starting in 2015; the current United States administration is seeking delay of implementation, and the O&G industry is challenging the federal regulation in court.^{77,79} A study in the Marcellus shale found that older well sites generally had much high production normalized methane emission rates than newer multiwell sites because of a range of issues, including a lack of maintenance.⁸⁰ Small emitters outside the nonattainment area for ozone are required under Regulation 7 to conduct monthly audio, visual, and olfactory (AVO) inspections, and they are currently required to conduct only one inspection with an approved instrument monitoring method (e.g., an infrared [IR] camera capable of detecting hydrocarbon and VOC emissions) over the lifetime of the facility.⁸¹ Additionally, the regulations exempt storage tanks from emission inspections and small emitters from emission's management plans.⁸¹ A recent analysis conducted with an infrared camera in Boulder County, CO detected gas leaks at 65% of 145 inspected O&G sites, most of which were small emitters developed prior to 2011. Ninety-two percent of the detected gas leaks were at storage tanks, separators, or wellheads, and at least 31% involved pneumatic devices or equipment associated with them.⁸² Several studies have implicated storage tanks, thief hatches, and pneumatic devices as major sources of VOC emissions from O&G facilities.^{12,15,83–85} The Boulder County analysis found that only 2.5% of AVO inspections identified a gas leak, compared to 66% of inspections using an IR camera, indicating that in this program monthly AVO inspections are not effective in detecting VOC emissions from leaking equipment.⁸² Intermittent and continuous bleed pneumatic devices may be a significant source of emissions even when operating properly.⁸⁶ Zero-bleed pneumatic devices could also significantly reduce emissions.⁸⁶ Ultimately, this means that the large number of old, low producing, and insufficiently inspected O&G operations could be a significant source of air pollutant emissions and related health risks.

While the magnitude of air pollutant emissions may vary by region, these results also have implications for policies in other O&G regions where homes are located near O&G facilities^{75,76} and NMHCs have been measured. Studies in regions of dense O&G development in the Uintah basin, Marcellus Shale, Barnett Shale, and Eagle Ford Shale have documented elevated levels of NMHCs^{11,27,87,88} as well as increased risks for several adverse health effects.^{21–25} Risk assessments using air sampling results specific to these regions could be useful for informing

policies aimed at reducing health risks associated with O&G facilities for nearby populations.

This study provides further evidence that populations living nearest to O&G facilities bear the greatest risk of acute and chronic health risk from exposures to NMHC air pollutants emitted from upstream O&G facilities. Therefore, this analysis supports and highlights the importance of policies aimed at reducing or eliminating air emissions from O&G equipment and facilities, particularly those near homes, and effective monitoring of emissions from these facilities.

■ ASSOCIATED CONTENT

5 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b05983.

Details on sample collection and analysis, OEHHA Dose and Risk Equations for carcinogens, and tables including descriptive statistics and risk assessments (PDF)

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Notes

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Community Noise and Air Pollution Exposure During the Development of a Multi-Well Oil and Gas Pad

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ABSTRACT: Unconventional oil and gas development (UOGD) in the United States is increasingly being conducted on multiwell pads (MWP) and in residential areas. We measured air pollution, noise, and truck traffic during four distinct phases of UOGD: drilling, hydraulic fracturing, flowback, and production. We monitored particulate matter (PM_{2.5}), black carbon (BC), A-weighted (dBA), and C-weighted (dBC) noise using real-time instruments on 1 and 5 min time scales, and truck traffic for 4–7 days per phase at a large 22-well pad sited in a residential area of Weld County, Colorado. Hydraulic fracturing, which requires frequent truck trips to move supplies and diesel engines to power the process, had the highest median air pollution levels of PM_{2.5} and BC and experienced the greatest number of heavy trucks per hour compared to other phases. Median air pollution was lowest during drilling at this MWP, possibly because an electric drill rig was used. The equivalent continuous noise level (L_{eq}) exceeded guidelines of 50 dBA and 65 dBC for A-weighted and C-weighted noise, respectively, during all development phases. Our data show that these multiple stressors are present around the clock at these sites, and this work provides baseline measurements on likely human exposure levels near similarly sized MWPs.



INTRODUCTION

Extensive adoption of advanced petroleum extraction technologies, such as horizontal drilling and hydraulic fracturing, provide an economically viable means of developing previously inaccessible unconventional oil and natural gas resources (i.e., shale oil and gas).¹ These technologies have also allowed operators to concentrate unconventional oil and gas development (UOGD) surface infrastructure (e.g., drill rigs, tanks, etc.) at increasingly large distances from the target mineral resource by using below ground laterals up to 3 km (1.9 miles) long at depths of up to 3 km (1.9 miles).² As a consequence multiple wells are now being drilled on one surface location, known as multiwell pads (MWPs).³ Larger MWPs can include 20–40 wells^{4–6} and each MWP can cover a surface area >40,000 m².⁷

Development of MWPs involves four phases (drilling, hydraulic fracturing, flowback, and production) some of which may occur concurrently.⁸ For example, new wells may be drilled while existing wells are in production. Limited data on phase-specific emissions suggest that air pollutant emissions vary by phase.^{9,10} Diesel emissions from trucks and heavy equipment and chemicals in drilling muds used during the drilling of the wells can increase air pollutant levels in the drilling phase.^{11,12} Similarly, diesel emissions from the numerous truck trips to transport water, sand, and chemicals and engines used to power the process can increase air pollutant levels during hydraulic fracturing.¹³ Following hydraulic fracturing, flowback involves the return of injected

liquids, produced water, and hydrocarbons to the surface. Flowback has been associated with some of the largest air emissions of volatile organic compounds (VOCs).¹⁴ Shortly after the well is completed, it goes into production, where fugitive emissions from tanks and other equipment are likely the dominant source of air pollutant emissions.¹⁵ Air pollutants associated with UOGD have been suggested as the basis for health effects such as fatigue, migraines, chronic rhinosinusitis, asthma, adverse birth outcomes, congenital heart defects, and acute lymphocytic leukemia.^{16–27}

In addition to air pollutants, drilling and the use of heavy equipment during all stages of well development produces noise at levels that can affect health.^{11,28} This includes both audible A-weighted (measured in dBA) noise and low frequency sound pressure characterized as C-weighted (measured in dBC) noise.^{29,30} Approximately 37% of all complaints filed with the Colorado Oil and Gas Conservation Commission (COGCC) in 2015 were related to noise.³¹ Health effects associated with A-weighted noise greater than 50 dBA include increased stress, sleep disturbance, nausea, headaches, and cardiovascular disease.^{32–35} To date, there has been little research on possible health effects from C-

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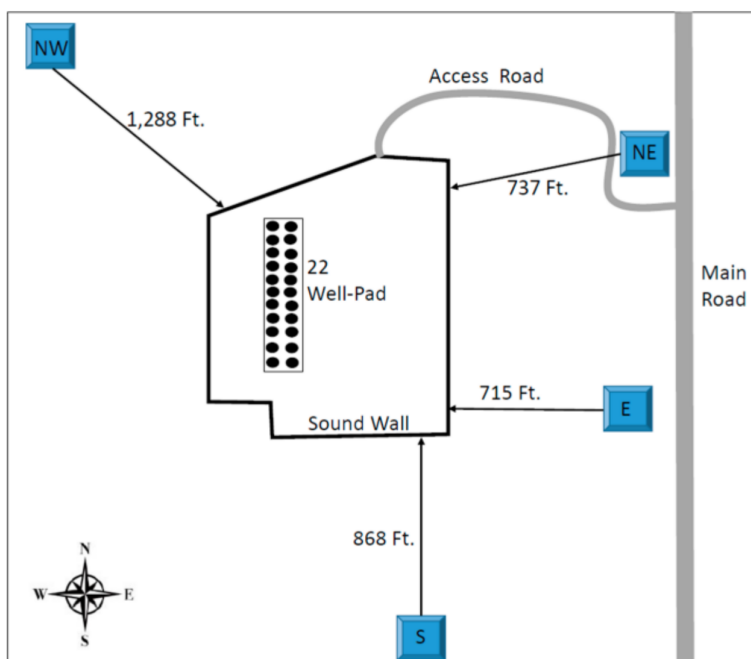


Figure 1. Map of the 22-well pad under construction with a sound wall. The Northwest (NW), Northeast (NE), East (E), and South (S) sampling sites collected black carbon, $PM_{2.5}$, A-weighted, and C-weighted noise during drilling operations. The NE and S locations collected these variables during hydraulic fracturing, flowback, and production. In addition, a weather station and camera were installed at the NE site to record wind speeds and trucks driving to the pad on the access road.

weighted noise, though guidance suggests that sustained exposure be limited to under 60 dBC.³⁶

While MWP offers efficiency of scale and fewer overall well pads, MWPs also increase the intensity and duration of exposures to UOGD-related air pollutants and noise for nearby residents due to the development of many wells in succession. As MWPs have increased in size and intensity, many of these sites resemble industrial facilities. In Colorado and other states, MWPs are typically not subject to the same zoning codes as other industrial facilities and it is not uncommon for MWPs to be in the middle of residential areas and near schools.^{4,5,37} In Colorado the current setback, i.e., the distance from which a new well can be sited from an existing home, is 152.4 m (500 ft) in most areas and 304.8 m (1000 ft) in urban mitigation areas and established well pads can be expanded without meeting the current setback requirements.³⁸ In the state of Colorado, there are at least 378 000 people within 1609 m (1 mi) of a well, and this population is growing at a faster rate than the overall population.³⁹ As the Denver-Julesburg Basin in northeastern Colorado continues to experience rapid growth in both oil and gas development and population, it is expected that more people will be living near MWPs.^{39–41}

Relatively few studies have concurrently measured air pollution and noise levels near MWPs, and even fewer characterize levels during specific phases of UOGD. To fill this knowledge gap, we collected continuous data documenting particulate matter less than $2.5 \mu\text{m}$ in diameter ($PM_{2.5}$), black carbon (BC), and A- and C-weighted noise levels as well as truck counts during each phase of the development of a MWP in a residential area of Weld County, Colorado.

MATERIALS AND METHODS

Site Information. We monitored $PM_{2.5}$ and BC, as well as A-weighted and C-weighted noise at four residences located between 217.9 m (715 ft) and 392.6 m (1288 ft) from the sound wall of a large MWP during drilling operations from January 27 - April 24, 2017 (Northeast, East, South, and Northwest monitoring sites). We continued to monitor these pollutants at the Northeast and South (224.6 m (737 ft) and 264.6 m (868 ft) from the sound wall, respectively) residences from July 24 to August 21, 2017, October 2 to November 20, 2017, and January 8 to March 2, 2018, which corresponded to periods of hydraulic fracturing, flowback, and production activities on the well pad, respectively. The development phases of drilling, hydraulic fracturing, and production were later verified using information from nearby residents and data from the COGCC database. This database does not provide dates for flowback, but this phase could be deduced given the timing and activity on the pad and was verified by nearby residents. The Northeast monitoring site was located along the well pad access road and the three other monitoring sites were away from roadways and thus less influenced by traffic. The MWP is permitted for 22 wells, 22 oil tanks, 22 separators, four vapor recovery units, two water tanks, three modular large volume tanks, and two lease automatic custody transfer units. All 22 wells were producing oil and natural gas when we finished monitoring in March 2018. For this MWP, the operator used electrically powered drilling rigs, constructed a 9.8 m (32 ft) high sound wall around the site, and used “green completion” techniques as well as other noise, traffic, and pollution mitigation measures.⁴² A sketch of the well pad site including the sound wall and pad access road and the four monitoring locations is shown in Figure 1.

Table 1. Description of Dates and Duration of Air and Noise Measurements Collected at a New Multi-Well Pad in Weld County, Colorado

phase	dates	pollutant	time resolution	number of measurements included from <i>Northeast</i> ^g site	number of measurements included from <i>South</i> ^h site	number of measurements i included from <i>Northwest</i> ⁱ site	number of measurements included from <i>East</i> ^j site	
drilling	January 27, 2017 to April 24, 2017	BC ^a	5 min	14 752	7939	16 712	7935	
		PM _{2.5} ^b	1 min	84 846	40 265	80 995	39 663	
	April 21–24, 2017	dBA ^c	1 min	57 594	25 851	57 433	22 323	
		dB ^d	1 min	57 586	25 854	57 426	25 791	
hydraulic fracturing	July 24, 2017 to August 21, 2017	heavy trucks ^e	1 h	75	0	0	0	
		non-heavy trucks ^f	1 h	75	0	0	0	
	August 7–14, 2017	BC ^a	1 min	0	0	0	0	
		PM _{2.5} ^b	1 min	40 058	39 893	0	0	
	October 2, 2017 to November 20, 2017	dBA ^c	1 min	39 959	39 983	0	0	
		dB ^d	1 min	39 972	39 995	0	0	
	flowback	October 6–13, 2017	heavy trucks ^e	1 h	167	0	0	0
			non-heavy trucks ^f	1 h	167	0	0	0
January 8, 2018 to March 2, 2018		BC ^a	1 min	65 546	69 731	0	0	
		PM _{2.5} ^b	1 min	69 507	67 393	0	0	
production	January 15–22, 2018	dBA ^c	1 min	64 721	70 254	0	0	
		dB ^d	1 min	70 283	64 765	0	0	
	March 2, 2018	heavy trucks ^e	1 h	169	0	0	0	
		non-heavy trucks ^f	1 h	169	0	0	0	
January 15–22, 2018	BC ^a	1 min	73 264	73 329	0	0		
	PM _{2.5} ^b	1 min	74 206	74 285	0	0		
January 15–22, 2018	dBA ^c	1 min	63 669	65 466	0	0		
	dB ^d	1 min	59 255	62 887	0	0		
January 15–22, 2018	heavy trucks ^e	1 h	167	0	0	0		
	non-heavy trucks ^f	1 h	167	0	0	0		

^aBlack Carbon (BC) was measured every 5 min during drilling and was changed to every 1 min for the other phases to match the time resolution of other pollutant measurements. ^bParticulate Matter less than 2.5 μm in diameter (PM_{2.5}). ^cA-weighted noise measured in decibels (dBA). ^dC-weighted noise measured in decibels (dB). ^eHeavy trucks (semitrailer). ^fNon-Heavy (light duty/pick-up) were counted and categorized by each hour. ^gThe *Northwest* site was a home located along the well pad access road where monitoring was conducted during drilling, hydraulic fracturing, flowback, and production. ^hThe *South* site refers to a home where monitoring was conducted during drilling, hydraulic fracturing, flowback, and production. ⁱThe *Northwest*, and *East* sites refer to one of two homes where monitoring was conducted during drilling only.

Table 2. Descriptive Statistics for Black Carbon and PM_{2.5} Concentrations Collected Across Development Phases of a New 22-Well Pad in Weld County, Colorado

averaging time	phase	location	BC (ng/m ³) ^a				PM _{2.5} (μg/m ³) ^b				
			N	mean	median	maximum	N	mean	median	maximum	
short-term ^c	drilling	Northeast ^d	14 752	539	336	35 022	84 846	3.4	2.6	106.5	
		South ^e	7939	468	292	46 326	40 265	2.4	1.6	1098.0	
		Northwest ^f	16 712	447	287	24 719	80 995	2.3	1.7	58.1	
		East ^f	7935	525	317	10 388	39 663	2.8	2.7	21.8	
	hydraulic fracturing	Northeast ^d					40 058	5.2	4.6	95.9	
		South ^e					39 893	5.2	4.7	46.5	
	flowback	Northeast ^d	65 546	1060	743	20 237	69 507	4.3	3.6	121.0	
		South ^e	69 731	851	588	49 169	67 393	4.0	2.3	96.1	
	production	Northeast ^d	73 264	894	597	17 674	74 206	3.8	2.8	38.9	
		South ^e	73 329	819	523	60 593	74 285	5.5	3.6	75.9	
	hourly	drilling	Northeast ^d	1241	536	346	5971	1418	3.4	2.6	30.6
			South ^e	669	465	313	9447	672	2.4	1.7	68.0
Northwest ^f			1411	446	296	7122	1384	2.2	1.6	24.7	
East ^f			669	521	334	3654	667	2.8	2.7	11.1	
hydraulic fracturing		Northeast ^d					670	5.2	4.6	18.8	
		South ^e					669	5.1	4.6	21.8	
flowback		Northeast ^d	1108	1052	783	5409	1170	4.3	3.6	22.0	
		South ^e	1177	846	627	9146	1129	4.0	2.2	18.5	
production		Northeast ^d	1237	894	596	5639	1240	3.8	2.8	34.5	
		South ^e	1237	818	491	5644	1241	5.5	3.6	31.1	
daily		drilling	Northeast ^d	55	545	486	2283	60	3.4	3.3	15.0
			South ^e	29	464	476	1453	29	2.3	2.0	7.2
	Northwest ^f		60	444	414	1453	60	2.2	1.8	9.1	
	East ^f		29	514	417	1637	29	2.8	2.6	6.4	
	hydraulic fracturing	Northeast ^d					29	5.3	4.8	9.6	
		South ^e					29	5.2	4.5	10.2	
	flowback	Northeast ^d	48	1062	1035	3023	50	4.2	3.9	11.6	
		South ^e	50	869	795	2505	50	4.1	2.5	14.0	
	production	Northeast ^d	54	902	682	3593	54	3.9	3.3	20.3	
		South ^e	54	827	619	3370	54	5.5	4.1	18.4	

^aBlack Carbon (BC). ^bParticulate Matter less than 2.5 μm in diameter (PM_{2.5}). ^cShort-term measurements were collected every 1 min except for BC during drilling which was collected every 5 min. ^dThe *Northeast* site was located along the well pad access road and refers to a home where monitoring was conducted during drilling, hydraulic fracturing, flowback, and production. ^eThe *South* site refers to a home where monitoring was conducted during drilling, hydraulic fracturing, flowback, and production. ^fThe *Northwest*, and *East* sites refer to one of two homes where monitoring was conducted during drilling only.

Monitoring. DustTrak II (TSI Incorporated, Shoreview, MN, U.S.A.) instruments were used to measure 1 min average PM_{2.5} concentration. The equipment was cleaned and calibrated according to the manufacturer's protocol prior to each of the four field monitoring campaigns that occurred over the course of the MWP development. The DustTrak was zeroed and recalibrated once a week, during which time the impaction plate was also cleaned and reoiled. Data was downloaded approximately once every 3 weeks. Average PM_{2.5} concentrations were recorded every minute in mg/m³ and converted to μg/m³. The limit of detection was 1 μg/m³. All measurement data were visually inspected to ensure reliability. All PM_{2.5} measurements were adjusted using a humidity correction factor⁴³ based on the relative humidity levels measured at our on-site weather station.

MicroAeth AES1 (AethLabs, San Francisco, CA, U.S.A.) aethalometers were used to measure 5 min average BC concentration during the drilling phase and changed to 1 min average BC concentration during flowback and production processes to match the time scale of other pollution measurements. The microAeth was set to draw an air sample at a flow rate of 100 mL/min through a 3 mm diameter portion

of filter media. The absorbance or attenuation of the sensing spot is measured relative to an adjacent reference portion of the filter. Measurements were converted to a mass concentration of BC and expressed in ng/m³ using the known optical absorbance per unit mass of BC material. In accordance with manufacturer recommended standard operating procedures, the device had its filter replaced twice-weekly and data downloaded once every 3 weeks. After evaluating the raw data, the instrument output was adjusted using an equation (eq 1) from Kirchstetter and Novakov⁴⁴ to adjust for accumulation of BC on the filter substrate over time:

$$BC_{adj} = 0.73 \times e^{-\Delta ATN/100} + 0.298 \quad (1)$$

We did not have access to a working aethalometer during the hydraulic fracturing phase, so for this period, we estimated BC from the PM_{2.5} data. This was done by calculating the mass fraction (MF) of BC to PM_{2.5} for each space/time collocated sample of the respective pollutants during the other three well development phases.⁴⁵ The distribution of the log-transformed mass fraction was approximately normally distributed and did not change much across development phases, so we used the

overall $\log(\text{MF})$ mean (eq 2) to derive estimated BC from measured $\text{PM}_{2.5}$ during hydraulic fracturing, BC_{HF} (eq 3).

$$\log(\text{MF}) = \frac{\sum_{i=1}^n \log\left(\frac{\text{BC}}{\text{PM}_{2.5}}\right)}{n} \quad (2)$$

$$\text{BC}_{\text{HF},i} = \exp(\log(\text{MF}) + \log \text{PM}_{2.5,\text{HF},i}) \quad (3)$$

Noise measurements were collected with Larson Davis (Depew, NY) Spark 703+ and Spark 706RC dosimeters each with a detachable 10.6 mm microphone/preamp with integrated 1 m cable (MPR001) and a windscren. Noise measurements were recorded as the 1 min equivalent continuous noise level (L_{eq}) as described in a previous manuscript that collected noise during drilling at this location.³⁰ Measurements made when wind speeds were greater than 16.1 km/h (10 mph) were omitted from our data analysis. A Davis Vantage Pro2 (Vernon Hills, IL, U.S.A.) weather station collected wind speed and temperature every 15 min at the *Northeast* monitoring site for the hydraulic fracturing, flowback, and production phases. During the drilling phase, a nearby weather station that recorded hourly information and reported to Weather Underground was used in its place.

In addition to the pollution monitoring equipment, a GoPro Hero 4 Silver (San Mateo, CA, U.S.A.) was set up to take and record an image every 30 s at the *Northeast* monitoring site. This location was adjacent to the access road used by any vehicle entering or leaving the well pad. Since this access road for the pad was the only entry point to the pad from the main road, any large vehicle traveling on it was part of the MWP development. We reviewed 4 days of images taken during drilling and 7 days of images for each of the other well development phases to obtain vehicle counts. Each time a vehicle was identified exiting the access road, the time-stamped image was saved for analysis. The images were categorized as heavy trucks (i.e., semitrailer), nonheavy trucks (i.e., light duty pickup), or another type of vehicle. An hourly count of the heavy trucks and nonheavy trucks was produced for the four or seven-day surveillance windows. A summary of dates and durations for all monitoring data can be found in Table 1.

Statistical Analysis. Descriptive statistics were computed for each air pollutant ($\text{PM}_{2.5}$ and BC) over three averaging times: short-term (1 min or 5 min sample), hourly, and daily by well development phase and sampling site. Different averaging times are used to characterize the temporal variability of these air pollutants during each phase of well development. Two-way ANOVA of the short-term measurements was used to compare concentrations across the monitoring sites and development phases.

Noise pollution statistics were computed for A-weighted and C-weighted noise across the factors of well development phase, weekday/weekend, and daytime (7:00am–7:00 pm) or nighttime (7:00 pm–7:00am) as defined by the COGCC. The 1 min L_{eq} was compared to the World Health Organization's guideline of 50 dBA for outdoor living areas⁴⁶ to calculate the percentage of total monitoring time that noise exceeded this level. As there has been little research to date on the health effects from C-weighted noise, we used the COGCC limit of 65 dBC (L_{eq} over 15 min) that necessitates a low frequency noise impact analysis⁴⁷ to calculate a similar exceedance percentage.

Finally, descriptive statistics for hourly truck counts were computed for both heavy and nonheavy trucks for each well development phase for daytime and nighttime hours. We did not compute statistics for weekend and weekday because we only had photo surveillance and truck counts for up to 1 week during each phase.

RESULTS AND DISCUSSION

Particulate Matter. Table 2 summarizes descriptive statistics for the air pollutants $\text{PM}_{2.5}$ and BC, stratified by averaging time, well development phase, and monitoring location. Hydraulic fracturing had the highest median $\text{PM}_{2.5}$ levels across sites (short-term medians of 4.6 and 4.7 $\mu\text{g}/\text{m}^3$ at the sites), which reflects the intensity of activity at the MWP during this phase. The mean short-term $\text{PM}_{2.5}$ concentration was highest during production at the *South* monitoring site (5.5 $\mu\text{g}/\text{m}^3$). Flaring during production was reported by residents and may have contributed to spikes in $\text{PM}_{2.5}$ levels that elevated the mean at that site, but we were not able to confirm the exact time of flaring to match it with our measurements. Average $\text{PM}_{2.5}$ was lowest during the drilling phase, with phase-specific means of 2.3–3.4 $\mu\text{g}/\text{m}^3$ at the monitoring sites. Mean $\text{PM}_{2.5}$ was typically higher at the *Northeast* site compared to the other sites except during production. This could be due to the combination of truck traffic and equipment on the pad during drilling, hydraulic fracturing, and flowback affecting measurements at this site. On the contrary, truck traffic during production should be minimal. Two-way ANOVA showed that $\text{PM}_{2.5}$ concentrations differed by the monitoring site ($p < 0.001$) and development phase ($p < 0.001$). The National Ambient Air Quality Standard (NAAQS) for the maximum allowable daily average of $\text{PM}_{2.5}$ is 35 $\mu\text{g}/\text{m}^3$. The daily average for $\text{PM}_{2.5}$ around this well pad was well below this level as is typical for $\text{PM}_{2.5}$ in northeastern Colorado.⁴⁸ Mean $\text{PM}_{2.5}$ levels from the closest monitor in the area, which is approximately 7.6 km (4.7 mi) to the east of the MWP and in an urbanized area along a major road, were 6.0, 9.6, 9.9, and 11.4 $\mu\text{g}/\text{m}^3$ during drilling, hydraulic fracturing, flowback, and production, respectively. Regional/seasonal variability likely contributes to the variability in our measurements and the differences in $\text{PM}_{2.5}$ between development phases are small in comparison to the overall variability.

Black Carbon. In addition to the measured values in Table 2, we estimated BC during hydraulic fracturing using our mass fraction model with mean estimates of 994 and 975 for the *Northeast* and *South* locations, respectively. The estimates of median BC were 881 and 883 for the *Northeast* and *South* locations, respectively. Descriptive statistics for measured and estimated BC data show an increase in levels for the hydraulic fracturing, flowback, and production phases compared to the drilling phase. As with $\text{PM}_{2.5}$, the median short-term estimated BC concentration was highest during hydraulic fracturing, which requires trucks to move the water, sand, and chemicals on site and uses diesel engines to power the process.¹³ Short-term BC median concentrations were again the lowest during drilling (287–336 ng/m^3) and reflect the use of electric drilling rigs. The mean short-term BC concentration was highest during flowback at the *Northeast* site (1060 ng/m^3). The greater difference between mean and median BC during flowback and production signals a skewed distribution of pollutants influenced by intermittent releases during flowback operations and flaring at times during production as opposed to the constant truck traffic and diesel equipment during

Table 3. Descriptive Statistics for Dosimeter Noise Measurements Collected Across Development Phases of a Multi-Well Pad in Weld County, Colorado

averaging time	phase	location	A-weighted ^a				C-weighted ^b			
			N	minimum	L_{eq} ^c	maximum	N	minimum	L_{eq} ^c	maximum
1 min	drilling	Northeast ^d	57 594	38.3	57.3	90.4	57 586	57.1	77.1	106.4
		South ^e	25 851	37.2	49.0	78.9	25 854	52.4	66.7	96.6
		Northwest ^f	57 433	35.9	49.1	74.5	57 426	54.5	70.8	96.4
		East ^f	22 323	38.4	52.2	75.2	25 791	56.2	75.3	98.5
	hydraulic fracturing	Northeast ^d	39 959	40.2	55.7	76.7	39 972	60.4	71.1	98.2
		South ^e	39 983	37.5	56.3	93.4	39 995	57.5	71.1	106.5
	flowback	Northeast ^d	64 721	39.2	58.2	91.9	70 283	57.5	78.6	107.6
		South ^e	70 254	36.6	61.6	92.5	64 765	55.5	82.2	106.2
	production	Northeast ^d	63 669	37.6	53.4	79.0	59 255	55.8	72.7	101.0
		South ^e	65 466	36.5	54.9	92.3	62 887	54.0	78.9	106.7

^aNoise measured on the A-weighted scale in decibels (dBA). ^bNoise measured on the C-weighted scale in decibels (dBC). ^cThe equivalent continuous noise level (L_{eq}) over all measurements collected at a given location during a particular phase. ^dThe Northeast site was located along the well pad access road. ^eThe South site refers to a home where monitoring was conducted during drilling, hydraulic fracturing, flowback, and production. ^fThe Northwest, and East sites refer to one of two homes where monitoring was conducted during drilling only.

Table 4. Percentage of Total Time That the 1 Min Average for A-Weighted Noise Exceeded 50 Decibels and C-weighted Noise Exceeded 65 Decibels at Homes Near a Multi-Well Pad under Development by Phase of Development, Time of Day, and Weekday/Weekend

phase	location	A-weighted ^a				C-weighted ^b			
		Monday–Friday		Saturday–Sunday		Monday–Friday		Saturday–Sunday	
		7:00 am–7:00 pm	7:00 pm–7:00 am	7:00 am–7:00 pm	7:00 pm–7:00 am	7:00 am–7:00 pm	7:00 pm–7:00 am	7:00 am–7:00 pm	7:00 pm–7:00 am
drilling	Northeast ^c	73.7	39.9	69.5	34.3	91.5	80.6	88.7	82.6
	South ^d	15.7	13.6	9.0	9.5	32.1	36.8	25.6	26.5
	Northwest ^e	16.6	10.9	11.9	4.8	87.3	77.5	71.8	79.1
	East ^e	32.9	29.1	18.8	15.1	93.3	92.0	86.9	85.4
hydraulic fracturing	Northeast ^c	93.9	80.6	84.6	77.8	98.1	92.9	91.0	90.2
	South ^d	50.9	64.0	39.9	59.3	64.7	64.7	53.6	59.4
flowback	Northeast ^c	87.3	53.6	82.5	55.7	82.2	54.5	76.8	56.0
	South ^d	35.0	45.7	42.5	47.9	57.0	54.5	63.8	52.4
production	Northeast ^c	79.2	38.8	60.8	29.8	69.5	39.4	52.9	42.3
	South ^d	24.7	8.7	17.7	11.0	37.3	19.6	37.3	22.0

^aNoise measured on the A-weighted scale in decibels (dBA). ^bNoise measured on the C-weighted scale in decibels (dBC). ^cThe Northeast site was located along the well pad access road. ^dThe South site refers to a home where monitoring was conducted during drilling, hydraulic fracturing, flowback, and production. ^eThe Northwest, and East sites refer to one of two homes where monitoring was conducted during drilling only.

hydraulic fracturing. The two-way ANOVA analysis indicated that BC concentrations differed by monitoring site ($p < 0.001$) and development phase ($p < 0.001$). The mean BC concentration was 3 to 25% higher at the Northeast monitoring location than the other monitoring locations. There is currently no health-based standard set for BC levels in ambient air.

Noise. Table 3 presents descriptive statistics for A- and C-weighted noise by well development phase and monitoring location. The L_{eq} for A-weighted noise exceeded the WHO’s community noise guidelines of 50 dBA during all phases and at all monitoring sites, except for drilling at the South and Northwest sites where the L_{eq} was 49.0 and 49.1 dBA, respectively, over the duration of the measurements. Flowback showed the highest A-weighted L_{eq} compared to the other phases at 61.6 dBA at the South site. The maximum 1 min measurement exceeded 90 dBA during each development phase. The A-weighted L_{eq} was higher at the South monitoring site compared to the Northeast monitoring site for all phases except for drilling.

The percentage of A-weighted L_{eq} noise measurements that exceeded 50 dBA stratified by weekday/weekend and daytime/nighttime are presented in Table 4. During daytime hours on weekdays, the A-weighted L_{eq} at the Northeast site exceeded 50 dBA at least 73% of the time for each well development phase. This represents a combination of noise from pad activity, truck traffic utilizing the pad access road, and local traffic driving on a nearby road. The percentage of noise exceedances were greatest during hydraulic fracturing and flowback, when a larger number of all truck types were using the access road. In comparison, the South, Northwest, and East sites exceeded 50 dBA a far lower percentage of the time, with hydraulic fracturing being the most frequent phase, with over half of the South measurements exceeding the 50-dBA threshold. Generally, the percentage of time that the A-weighted L_{eq} exceeded the threshold decreased from weekday to weekend and from day to night.

Across all phases and monitoring sites, the L_{eq} for C-weighted noise exceeded both the current 60 dBC recommendation to limit health effects³⁶ and the COGCC’s 65 dBC 15 min L_{eq} limit at 107 m (350 ft) that triggers a noise impact

Table 5. Descriptive Statistics for Hourly Heavy (e.g., Semi-Trailer) and Non-Heavy (e.g., Light Duty Pick-Up) Trucks Per Hour Identified by Photo Surveillance Across Development Phases of a New 22-Well Pad in Weld County, Colorado Categorized by Daytime (7:00 am–7:00 pm) and Nighttime (7:00 pm–7:00 am)

phase	days of surveillance	heavy trucks						non-heavy trucks					
		7:00 am–7:00 pm			7:00 pm–7:00 am			7:00 am–7:00 pm			7:00 pm–7:00 am		
		mean	median	max	mean	median	max	mean	median	max	mean	median	max
drilling	4	1.5	1.0	7.0	0.3	0.0	3.0	1.2	1.0	7.0	0.4	0.0	3.0
hydraulic fracturing	7	8.9	9.0	16.0	8.5	9.0	16.0	8.1	5.0	37.0	4.4	2.0	21.0
flowback	7	2.0	1.0	8.0	1.0	1.0	6.0	13.5	12.0	43.0	6.6	4.0	29.0
production	7	0.8	1.0	2.0	0.7	1.0	3.0	1.1	1.0	7.0	0.5	0.0	4.0

study and mitigation measures.⁴⁷ The C-weighted noise was highest during flowback at the *South* site, with an L_{eq} of 82.2 dBC. Drilling, which would often be associated with this type of vibrational noise, had higher C-weighted noise at the *Northeast* site (77.1 dBC) than the other sites (66.7–75.3 dBC). During the high impact phases of drilling, hydraulic fracturing, and flowback, C-weighted noise exceeded 65 dBC more than 50% of the time regardless of whether it was a weekday/weekend or a daytime/nighttime except for the *South* monitoring site during drilling. C-weighted noise exceeded 65 dBC more than 90% of the time during hydraulic fracturing at the *Northeast* site, which likely reflects the vibration from constant truck traffic. As expected, C-weighted noise generally had the fewest exceedances during the production phase, especially during evening hours. Measurements during production were still above 65 dBC approximately 20% of the time from 7:00 pm to 7:00 am at both monitoring locations.

Traffic. As summarized in Table 5 truck traffic was highly variable by development phase. Hydraulic fracturing, which requires heavy-trucks to move large amounts of water, sand, and chemicals to the site, had the highest number of these vehicles during the 1-week surveillance period. The number of heavy trucks during this phase was essentially the same during daytime (mean = 8.9/hour) and nighttime hours (8.5/hour), substantiating a consistent complaint of residents living near these operations.⁴² The nine heavy trucks per hour average amounts to one truck every six or 7 min, 24 h a day, in a residential area. This number does not include the nonheavy trucks, which also accessed the pad road during hydraulic fracturing. The two-way ANOVA analysis indicated that heavy truck counts differed during daytime/nighttime and phase of development ($p < 0.001$ for each factor). Multiple comparisons of means revealed that heavy truck counts during hydraulic fracturing were significantly higher than other phases. Daytime and nighttime heavy truck counts during hydraulic fracturing were not significantly different from each other.

Nonheavy trucks counts were highest during flowback, which averaged 13.5 trucks/h during the daytime with a maximum of 43 trucks/h. Hydraulic fracturing also had high nonheavy truck/h that averaged 8.1 trucks/h from 7:00 am to 7:00 pm and 4.4 truck/h from 7:00 pm to 7:00 am. Drilling and production had comparatively lower numbers of trucks/h. The two-way ANOVA analysis indicated that nonheavy truck traffic differed during daytime/nighttime and phase of development ($p < 0.001$ for each factor). Nonheavy truck/h counts were higher for flowback during daytime hours compared to other phases at any time of day ($p < 0.001$). Nonheavy truck counts for flowback and hydraulic fracturing were higher than during drilling or production.

Strengths. This case study focused on a single MWP and makes a unique contribution to the literature by adding to the limited knowledge about the concurrent air and noise pollution emitted from equipment and traffic associated with UOGD operations. This is the first study to simultaneously measure $PM_{2.5}$, BC, noise, and to explore the impacts of truck traffic during all phases of the development process. These data also provide finer temporal resolution than has been achieved in the past, which will help researchers further understand peak short-term exposure to these pollutants near these and similar facilities elsewhere.

The $PM_{2.5}$ and BC air pollution results provide additional information that can be incorporated into exposure models and other assessments that evaluate the impacts of these facilities on human health.^{49,50} Our results may be useful for assessing exposure in both retrospective and prospective studies and provide insights on the interventions that would be most effective in reducing emissions during specific UOGD phases. These results may also provide insight on short-term exposure peaks that may be related to some of the observed health effects that have critical exposure windows.^{51–53}

We also collected high temporal resolution A-weighted and C-weighted noise measurements across all UOGD phases. As required by the COGCC, the operator of this MWP conducted a background noise assessment before starting development. That assessment reported an A-weighted L_{eq} of 42.8 dBA and a C-weighted L_{eq} of 55.8 dBC. We report noise substantially above these levels across all phases and monitoring locations. A study about daytime noise in high-traffic areas of three major United States cities found a 10 min A-weighted L_{eq} between 65.1 and 69.2 dBA.⁵⁴ Our measured continuous noise levels are closer to those reported for suburban areas about 30–60 m from a main road.⁵⁵ However, one main difference is that most studies measuring traffic noise are taking readings during the day, whereas our L_{eq} includes both daytime and nighttime measurements. We could not find comparable studies regarding C-weighted noise. Since there is little publicly available data about noise at MWPs, our results provide a reference point for future studies. As with this site, operators in Colorado are usually required to construct sound walls around the pad. Therefore, our results reflect levels experienced by residents with this mitigation in place and provide additional evidence that sound walls may have limited success at reducing C-weighted noise.²⁹ Thus, we expect that C-weighted noise will become an important component for both mitigation strategies and future research on UOGD's impacts on nearby communities.

In addition to air and noise pollution measurements, we were able to analyze the potential impact of well pad truck traffic in a community by including two sites during each monitoring period, one at a residence adjacent to the pad

access road and the other at a residence that should be minimally influenced by the pad truck traffic. Through our analysis of images, we obtained hourly truck counts for 4–7 days of each development phase. The impacts of truck traffic are often overlooked when O&G sites are developed in residential areas. Trucks emit diesel exhaust, noise (during both driving and idling), and generate dust on what are typically gravel access roads. More broadly, there is evidence of additional local and regional impacts from increased accidents from oil and gas related vehicles that could be due to an increased number of miles driven and fatigue by truckers who often work long hours.^{56–58} Our results document that the hydraulic fracturing phase, which often operates 24 h a day for weeks at a time, leads to increased truck traffic day and night in this residential area, which likely contributes to sleep disturbance, annoyance, and increased stress for those living nearby.

Limitations. The MWP in this case study should be representative of the scale and current practices at large MWPs in northeastern Colorado.^{4–6} It might not reflect the impacts from MWPs in other states that have different regulations or other geologic formations. Several additional factors, including the number of wells, operator, subcontractors, types of equipment, and available infrastructure, such as nearby pipelines, can potentially affect the pollutants produced by a MWP.⁵⁰ Additionally, changes in drilling and production technology and state-level regulations will have an impact at these types of MWP sites in the future. Due to its location in a suburb along Colorado's northern front range, this MWP was deemed a large Urban Mitigation Area Facility and was subject to best management practices for pollution mitigation and impact reduction.⁵⁹ Thus, we expect our pollution measurements to be closer to a best-case scenario than a worst-case scenario for the industry in this region. While our data are likely not representative of all MWPs, they should be representative of the current technology being used for O&G development in residential areas. Since large MWPs being placed in neighborhoods are a particularly contentious issue^{4,5} that has public health relevance, this information should be useful for regulators, local governments, and researchers moving forward. As with other sources of pollution, malfunctioning or improperly maintained equipment can drastically increase emissions. It is unknown whether equipment was working properly on the MWP that we monitored, and we would likely need to monitor many MWPs to quantify the likelihood of "super-emitters" and the corresponding increase in air pollutants.⁶⁰ These measurements were collected on private land and we did not work with the oil and gas company that was developing the MWP, so it is unknown if they had any knowledge that we were monitoring the site or if any activities were altered due to the presence of our monitoring equipment.

Unfortunately, we were unable to directly measure BC during hydraulic fracturing as the aethalometers were unavailable when we became aware that this phase was occurring. As described in the methods, we estimated BC concentrations based on the available PM_{2.5} measurements. The difference between means of the measured and estimated short-term BC at the monitoring sites during the phases when we did have data was between 2 and 30%. Given the expected increase in the ratio of BC to PM during hydraulic fracturing due to constant use of diesel equipment to power operations and associated truck traffic, we expect our modeled BC

statistics to be underestimates of actual BC levels. Also, by using the mean of the logMF distribution we are only capturing the variability of PM_{2.5} and not the variability in the ratio of BC to PM_{2.5}. As a result, our estimates do not capture all the short-term spikes in BC concentration that one would expect, with the net effect of biasing our estimated BC levels low.

We did not conduct monitoring inside of homes and cannot estimate the actual exposures of individuals living near this MWP. Home characteristics would significantly impact how inside levels of pollutants would be correlated with our outside measures.⁶¹ Residents adjacent to this site filed 58 official complaints with the COGCC regarding issues of noise, air quality, lighting, flaring, and odor, with noise during the hydraulic fracturing period being of particular concern.⁶²

We only analyzed truck traffic images for 1 week (and 4 days for drilling) of each development phase, and it is possible that these time periods were not representative of each development phase. However, due to the time and money required to obtain the specialized workers and equipment for each development phase, it is reasonable to assume that once a phase commences, it continues at a full pace until completion. Thus, we do not expect truck traffic to differ drastically for times when we did not conduct surveillance. Utilizing software that uses motion detection to automatically capture images could make quantifying the traffic associated with a MWP more feasible on a routine basis.

Finally, we were only able to monitor four sites during drilling and two sites for the other well development phases. It is possible that other locations around the pad would have had slightly different results. The wind direction reported by our weather station showed variable winds throughout data collection. The least dominant wind direction was southwest, meaning that our Northeast monitor would most likely be more influenced by traffic on the well pad access road than activity on the pad. We did not attempt to describe how wind speed and direction impacted our air pollutant measurements. Our goal was not to model a surface of air pollutants as any type of modeled surface would have been difficult to create with only two monitoring locations. As shown in Figure 1, the well pad is a large site with potential sources at any given location on site at a particular time. Therefore, obtaining a direction more specific than "generally upwind" or "generally downwind" would be difficult. It is also possible that the sound wall would affect the way in which the wind dispersed pollutants. Given that winds in this region are constantly shifting,⁴⁸ the length of measurement time should mean that our samples over time are representative of pollutant levels near where residents are living.

Future Public Health Research. We did not measure specific compounds such as benzene or other VOCs that are likely relevant for assessing health outcomes.⁶³ It will be important that future studies consider obtaining VOC measurements, and the data we collected across all phases of an MWP life cycle. Benzene has been estimated to dominate the risk profile of living near an O&G well.⁶³ Knowing the distributions of VOCs and how they diffuse as the distance from the well pad increases will help inform the process of developing health-relevant exposure isopleths and/or better controls on these compounds at specific stages of the development process.

There have not been any health studies to date that have examined the effect on biomarkers or stress of living near a

MWP during initial pad construction, drilling, hydraulic fracturing, and flowback. We have documented air pollution, noise pollution, and truck traffic levels near a MWP. The cumulative health effects from multiple stressors for individuals living near these facilities is not known. Furthermore, excessive noise levels and increased truck traffic during the night, when people are home and trying to sleep, could have compounding effects on health and quality of life. Future public health research in all these areas is needed to assess the potential impacts of living near these MWPs that are increasing in size.

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Notes

The authors declare no competing financial interest.

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Birth Outcomes and Maternal Residential Proximity to Natural Gas Development in Rural Colorado

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BACKGROUND: Birth defects are a leading cause of neonatal mortality. Natural gas development (NGD) emits several potential teratogens, and U.S. production of natural gas is expanding.

OBJECTIVES: We examined associations between maternal residential proximity to NGD and birth outcomes in a retrospective cohort study of 124,842 births between 1996 and 2009 in rural Colorado.

METHODS: We calculated inverse distance weighted natural gas well counts within a 10-mile radius of maternal residence to estimate maternal exposure to NGD. Logistic regression, adjusted for maternal and infant covariates, was used to estimate associations with exposure tertiles for congenital heart defects (CHDs), neural tube defects (NTDs), oral clefts, preterm birth, and term low birth weight. The association with term birth weight was investigated using multiple linear regression.

RESULTS: Prevalence of CHDs increased with exposure tertile, with an odds ratio (OR) of 1.3 for the highest tertile (95% CI: 1.2, 1.5); NTD prevalence was associated with the highest tertile of exposure (OR = 2.0; 95% CI: 1.0, 3.9, based on 59 cases), compared with the absence of any gas wells within a 10-mile radius. Exposure was negatively associated with preterm birth and positively associated with fetal growth, although the magnitude of association was small. No association was found between exposure and oral clefts.

CONCLUSIONS: In this large cohort, we observed an association between density and proximity of natural gas wells within a 10-mile radius of maternal residence and prevalence of CHDs and possibly NTDs. Greater specificity in exposure estimates is needed to further explore these associations.

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Introduction

Approximately 3.3% of U.S. live-born children have a major birth defect (Centers for Disease Control and Prevention 2013; Parker et al. 2010); these defects account for 20% of infant deaths as well as 2.3% of premature death and disability (McKenna et al. 2005). Oral clefts, neural tube defects (NTDs), and congenital heart defects (CHD) are the most common classes of birth defects (Parker et al. 2010). These defects are thought to originate in the first trimester as a result of polygenic inherited disease or gene–environment interactions (Brent 2004). Suspected nongenetic risk factors for these birth defects include folate deficiency (Wald and Sneddon 1991), maternal smoking (Honein et al. 2006), alcohol abuse and solvent use (Romitti et al. 2007), and exposure to benzene (Lupo et al. 2010b; Wennborg et al. 2005), toluene (Bowen et al. 2009), polycyclic aromatic hydrocarbons (PAHs) (Ren et al. 2011), and petroleum-based solvents, including aromatic hydrocarbons (Chevrier et al. 1996). Associations between air pollution [volatile organic compounds (VOCs), particulate matter (PM), and nitrogen dioxide (NO₂)] and low birth weight and preterm birth have been reported (Ballester et al. 2010; Brauer et al. 2008; Davdand et al. 2013; Ghosh et al. 2012; Llop et al. 2010). Many of these air pollutants are

emitted during development and production of natural gas (referred to herein as NGD), and concerns have been raised that they may increase risk of adverse birth outcomes and other health effects (Colborn et al. 2011; McKenzie et al. 2012). Increased prevalence of low birth weight and small for gestational age and reduced APGAR scores were reported in infants born to mothers living near NGD in Pennsylvania (Hill 2013).

Technological advances in directional drilling and hydraulic fracturing have resulted in a global boom of drilling and production of natural gas reserves [U.S. Energy Information Administration (EIA) 2011a, 2011b; Vidas and Hugman 2008]. NGD is an industrial process resulting in potential worker and community exposure to multiple environmental stressors (Esswein et al. 2013; King 2012; Witter et al. 2013). Diesel-powered heavy equipment is used for worksite development as well as transporting large volumes of water, sand, and chemicals to sites and for waste removal (Witter et al. 2013). It is increasingly common for NGD to encroach on populated areas, potentially exposing more people to air and water emissions as well as to noise and community-level changes that may arise from industrialization [Colorado Oil and Gas Conservation Commission (COGCC) 2009]. Studies in Colorado, Texas, Wyoming, and Oklahoma

have demonstrated that NGD results in emission of VOCs, NO₂, sulfur dioxide (SO₂), PM, and PAHs from either the well itself or from associated drilling processes or related infrastructure (i.e., drilling muds, hydraulic fracturing fluids, tanks containing waste water and liquid hydrocarbons, diesel engines, compressor stations, dehydrators, and pipelines) (CDPHE 2007; Frazier 2009; Kembal-Cook et al. 2010; Olaguer 2012; Walther 2011; Zielinska et al. 2011). Some of these pollutants, such as toluene, xylenes, and benzene, are suspected teratogens (Lupo et al. 2010b; Shepard 1995) or mutagens (Agency for Toxic Substances and Disease Registry 2007) and are known to cross the placenta (Bukowski 2001), raising the possibility of fetal exposure to these and other pollutants resulting from NGD. Currently, there are few studies on the effects of air pollution or NGD on birth outcomes.

In this analysis, we explored the association between maternal exposure to NGD and birth outcomes, using a data set with individual-level birth data and geocoded natural gas well locations. We conducted a retrospective cohort study to investigate the association between density and proximity of natural gas wells within a 10-mile radius of maternal residences in rural Colorado and three classes of birth defects, preterm birth, and fetal growth.

Methods

Study population. We used information available in the publically accessible Colorado Oil and Gas Information System (COGIS) to

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build a geocoded data set with latitude, longitude, and year of development (1996–2009) for all gas wells in rural Colorado (COGIS 2011). Live birth data were obtained from the Colorado Vital Birth Statistics (CDPHE, Denver, CO). Geocoded maternal addresses at time of birth were linked to the well locations. Distance of each maternal residence from all existing (not abandoned) natural gas wells within a 10-mile radius was then computed using spherically adjusted straight line distances. We conducted our analysis on the final de-identified database containing maternal and birth outcome data described below and distance to all wells within the 10-mile radius. The Colorado Multiple Institutional Review Board reviewed and approved our study protocol. Informed consent was not required.

We restricted analysis to births occurring from 1996 through 2009 to focus our analysis on growth of unconventional NGD, characterized by use of hydraulic fracturing and/or directional drilling (King 2012), which expanded rapidly in Colorado beginning around 2000 (COGIS 2011). We also restricted our analysis to rural areas and towns with populations of < 50,000 (excluding the Denver metropolitan area, El Paso County, and the cities of Fort Collins, Boulder, Pueblo, Grand Junction, and Greeley) in 57 counties to reduce potential for exposure to other pollution sources, such as traffic, congestion, and industry. The final study area included locations with and without NGD. We conducted a retrospective study on the resulting cohort of 124,842 live births to explore associations between birth outcomes and exposure to NGD operations. We restricted eligibility to singleton births and excluded the small proportion (< 5%) of non-white births because there were too few to analyze separately.

Birth outcomes. Identified birth outcomes were *a*) oral cleft, including cleft lip with and without cleft palate as well as cleft palate [International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM) code 749.xx] (National Center for Health Statistics 2011); *b*) NTD, including anencephalus, spina bifida without anencephaly, and encephalocele (ICD-9-CM 740.xx, 741.xx, and 742.0); *c*) CHD, including transposition of great vessels, tetralogy of Fallot, ventricular septal defect, endocardial cushion defect, pulmonary valve atresia and stenosis, tricuspid valve atresia and stenosis, Ebstein's anomaly, aortic valve stenosis, hypoplastic left heart syndrome, patent ductus arteriosus, coarctation of aorta, and pulmonary artery anomalies (codes 745.xx, 746.xx, 747.xx, excluding 746.9, 747.5); *d*) preterm birth (< 37 weeks completed gestation); *e*) term low birth weight (≥ 37 weeks completed gestation and birth weight < 2,500 g); and *f*) term birth weight

as a continuous measure. Births with an oral cleft, NTD, or CHD were excluded from preterm birth and term low birth weight analysis. Preterm births were excluded from term birth weight analysis. Oral cleft, CHD, and NTD cases in the Colorado Responds to Children with Special Needs (CRCSN) birth registry, obtained from hospital records, the Newborn Genetics Screening Program, the Newborn Hearing Screening Program, laboratories, physicians, and genetic, developmental, and other specialty clinics (CRCSN 2011) were matched with Colorado live birth certificates. Cases are reflective of reporting as of 12 July 2012, were not necessarily confirmed by medical record review, and are subject to change as CRCSN ascertains diagnosis up to 3 years of child's age and/or supplements information by medical record review. We analyzed birth defects in three heterogeneous groups to increase statistical power. Data set information was not sufficient to distinguish between multiple and isolated birth anomalies or to identify chromosomal birth anomalies. In an exploratory analysis, we considered seven clinical diagnostic groupings of CHDs: *a*) conotruncal defects (tetralogy of Fallot and transposition of great vessels); *b*) endocardial cushion and mitrovalve defects (EMD; endocardial cushion defect and hypoplastic left heart syndrome); *c*) pulmonary artery and valve defects (PAV; pulmonary valve atresia and stenosis and pulmonary artery anomalies); *d*) tricuspid valve defects (TVD; tricuspid valve atresia and stenosis and Ebstein's anomaly); *e*) aortic artery and valve defects (aortic valve stenosis and coarctation of aorta); *f*) ventricular septal defects (VSD); and *g*) patent ductus arteriosus in births > 2,500 g (Gilboa et al. 2005).

Exposure assessment. Distribution of the wells within a 10-mile radius of maternal residence shows 50% and 90% of wells to be within 2.3 and 7.7 miles of maternal residence, respectively. We used an inverse distance weighted (IDW) approach, commonly used to estimate individual air pollutant exposures from multiple fixed locations (Brauer et al. 1998; Ghosh et al. 2012), to estimate maternal exposure. Our IDW well count accounts for the number of wells within the 10-mile radius of the maternal residence, as well as distance of each well from the maternal residence, giving greater weight to wells closest to the maternal residence. For example, an IDW well count of 125 wells/mile could be computed from 125 wells each located 1 mile from the maternal residence or 25 wells each located 0.2 miles from the maternal residence. We calculated the IDW well count of all existing natural gas wells in the birth year within a 10-mile radius of each maternal residence as a continuous exposure metric:

$$\text{IDW well count} = \sum_{i=1}^n \frac{1}{d_i^p} \quad [1]$$

where IDW well count is the IDW count of existing wells within a 10-mile radius of maternal residence in the birth year; d_i is the distance of the i th individual well from maternal residence; and n is the number of existing wells within a 10-mile radius of maternal residence in the birth year.

The IDW well count was calculated for each maternal residence with ≥ 1 gas wells within 10 miles. The final distribution then was divided into tertiles (low, medium, and high) for subsequent logistic and linear regression analysis. Each tertile was compared with the referent group (no natural gas wells within 10 miles, IDW well count = 0).

Statistical analysis. We used logistic regressions to study associations between each dichotomous outcome and IDW exposure group. We also considered term birth weight as a continuous outcome using multiple linear regression. First, we estimated the crude odds ratio (OR) associated with IDW exposure tertile for each binary outcome, followed by a Cochran–Armitage test to evaluate linear trends in binomial proportions with increasing IDW exposure (none, low, medium, and high). We further investigated associations by adjusting for potential confounders, as well as infant and maternal covariates selected based on both *a priori* knowledge and empirical consideration of their association with exposure and an outcome. Specifically, covariates in our analysis of all outcomes except outcomes with very few events (i.e., NTDs, conotruncal defects, EMDs, and TVDs) included maternal age, education (< 12, 12, 13–15, ≥ 16 years), tobacco use (smoker, nonsmoker), ethnicity (Hispanic, non-Hispanic white), and alcohol use (yes, no), as well as parity at time of pregnancy (0, 1, 2, > 2) and infant sex. Gestational age was also included in the analysis of term birth weight. Elevation of maternal residence also was considered in the analysis because most wells are < 7,000 feet, and elevation has been associated with both preterm birth and low birth weight (Niermeyer et al. 2009). For 272 births where elevation of maternal residence was missing, elevation was imputed using mean elevation for maternal ZIP code. For outcomes with very few events, only elevation was included in the multiple logistic modeling to avoid unstable estimates. The ORs and their 95% CIs were used to approximate relative risks for each outcome associated with IDW count exposure tertile (low, medium, and high) compared with no wells within 10 miles, which is reasonable because of the rarity of the outcomes. We considered the statistical significance of the association, as well as the trend, in evaluating results, at an alpha of 0.05. We evaluated the confounding potential of the 1998 introduction of folic acid fortification on the birth defect outcomes and found only a decrease in

NTD prevalence after 1998 (see Supplemental Material, Table S1).

In a sensitivity analyses, we explored reducing exposure to 2- and 5-mile buffers around the maternal residence, as well as restricting the cohort to births occurring between 2000 and 2009 to exclude births before the expansion of NGD. We report estimated associations with 95% CIs. All statistical analyses were conducted using SAS® software version 9.3 (SAS Institute Inc., Cary, NC).

Results

Births were approximately evenly divided between exposed and unexposed groups (0 wells in a 10-mile radius versus ≥ 1 well in a 10-mile radius) (Table 1). Estimated exposure, represented by IDW well counts, tended to be higher for births to mothers with residence addresses at lower elevations (< 6,000 feet), and among nonsmoking and Hispanic mothers (Table 1).

Both crude and adjusted estimates indicate a monotonic increase in the prevalence of CHDs with increasing exposure to NGD, as represented by IDW well counts (Table 2). Births to mothers in the most exposed tertile (> 125 wells/mile) had a 30% greater prevalence of CHDs (95% CI: 1.2, 1.5) than births to mothers with no wells within a 10-mile radius of their residence.

Prevalence of NTDs was positively associated with only the third exposure tertile, based on crude and estimated adjusted ORs for elevation (Table 2). Births in the highest tertile (> 125 wells/mile) were 2.0 (95% CI: 1.0, 3.9) times more likely to have a NTD than those with no wells within a 10-mile radius, based on 59 available cases. We observed no statistically significant associations between oral clefts and NGD, based on trend analysis across categorical IDW well count exposure (Table 2).

Both crude and adjusted estimates for preterm birth suggest a slight (< 10%) decreased risk of preterm birth with increasing exposure to NGD (Table 3). Crude term low birth weight measures suggested decreased risk of term low birth weight with increasing exposure to NGD. A weak non-linear trend remained after adjusting for elevation and other covariates. This association is consistent with the multiple linear regression results for continuous term birth weight, in which mean birth weights were 5–24 g greater in the higher IDW well count exposure tertiles than the referent group.

We observed a monotonic increase in the prevalence of NTDs with increasing exposure to NGD in our sensitivity analyses using 2- and 5-mile exposure radii as well as some attenuation in decreased risk for preterm birth and term low birth weight (see Supplemental Material, Tables S2–7). Restricting births

to 2000 through 2009, the period of most intense NGD in Colorado, attenuated the positive association between NTDs in the highest tertile and did not alter observed relationships for other birth outcomes (see Supplemental Material, Tables S2–S7).

Exploratory analysis of CHDs by clinical diagnostic groups indicates increased prevalence of PAV defects by 60% (95% CI: 1.1, 2.2), VSDs by 50% (95% CI: 1.1, 2.1), and TVDs by 400% (95% CI: 1.3, 13) in the most exposed tertile compared with those with no wells within a 10-mile radius (Table 4).

Discussion

We found positive associations between density and proximity of natural gas wells within a 10-mile radius of maternal residence and birth prevalence of CHDs and possibly NTDs. Prevalence of CHDs increased monotonically from the lowest to highest exposure tertile, although even in the highest tertile the magnitude of the association was modest. Prevalence of NTDs was elevated only in the highest tertile of exposure. We also observed small negative associations between density and proximity of natural gas wells within a 10-mile radius of maternal residence and

Table 1. Study population characteristics for unexposed and exposed subjects from rural Colorado 1996–2009.

Maternal or infant characteristic	Total	Referent group (0 wells within 10 miles)	Low (first tertile) ^a	Medium (second tertile) ^a	High (third tertile) ^a
Total n (%)	124,842	66,626 (53)	19,214 (15)	19,209 (15)	19,793 (16)
Median	27	27	26	27	27
25th percentile	22	22	21	22	23
75th percentile	32	32	30	31	31
Maternal ethnicity (%) ^b					
Non-Hispanic white	73	74	72	76	69
Sex (%)					
Male	51	51	51	51	51
Maternal smoking (%) ^c					
Smokers	11	11	14	13	8
Maternal alcohol (%) ^c					
No	99	98	99	99	99
Parity (%)					
0	33	33	31	32	32
1	23	23	24	24	25
2	19	19	20	19	20
>2	25	25	26	25	24
Residential elevation (feet)					
Median	5,000–5,999	6,000–6,999	< 5,000	5,000–5,999	< 5,000
25th percentile	< 5,000	5,000–5,999	< 5,000	< 5,000	< 5,000
75th percentile	7,000–7,999	7,000–7,999	5,000–5,999	6,000–6,999	5,000–5,999
Maternal education (%)					
< 12 years	21	20	26	19	22
12 years	30	30	33	29	28
13–15 years	23	22	25	25	24
≥ 16 years	26	28	18	26	27

^aFirst tertile, 1–3.62 wells/mile; second tertile, 3.63–125 wells/mile; third tertile, 126–1,400 wells/mile. ^bIncludes both Non-Hispanic and Hispanic white. ^cDuring pregnancy.

Table 2. Association between inverse distance weighted well count within 10-mile radius of maternal residence and CHDs, NTDs, and oral clefts.

Inverse distance weighted well count ^a	0 wells within 10 miles	Low (first tertile)	Medium (second tertile)	High (third tertile)	Cochran–Armitage trend test <i>p</i> -value ^b
Live births (n)	66,626	19,214	19,209	19,793	
CHDs					
Cases (n)	887	281	300	355	
Crude OR	1	1.1	1.2	1.3	< 0.0001
Adjusted OR (95% CI) ^c		1.1 (0.93, 1.3)	1.2 (1.0, 1.3)	1.3 (1.2, 1.5)	
NTDs					
Cases (n)	27	6	7	19	
Crude OR	1	0.77	0.90	2.4	0.01
Adjusted OR (95% CI) ^d		0.65 (0.25, 1.7)	0.80 (0.34, 1.9)	2.0 (1.0, 3.9)	
Oral clefts					
Cases (n)	139	31	41	40	
Crude OR	1	0.77	1	0.97	0.9
Adjusted OR (95% CI) ^e		0.65 (0.43, 0.98)	0.89 (0.61, 1.3)	0.82 (0.55, 1.2)	

^aFirst tertile, 1–3.62 wells/mile; second tertile, 3.63–125 wells/mile; third tertile, 126–1,400 wells/mile. ^bPerformed as two-tailed test on unadjusted logistic regression. ^cAdjusted for maternal age, ethnicity, smoking, alcohol use, education, and elevation of residence, as well as infant parity and sex. ^dAdjusted only for residence elevation because of low numbers.

preterm birth and term low birth weight, and a small positive association with mean birth weight. We found no indication of an association between density and proximity of natural gas wells within a 10-mile radius of maternal residence and oral cleft prevalence.

Nongenetic risk factors for CHDs and NTDs possibly attributable to NGD include maternal exposure to benzene (Lupo et al. 2010b; Wennborg et al. 2005), PAHs (Ren et al. 2011), solvents (Brender et al. 2002; Chevrier et al. 1996; Desrosiers et al. 2012; McMartin et al. 1998), and air pollutants (NO₂, SO₂, PM) (Vrijheid et al. 2011). NGD emits multiple air pollutants, including benzene and toluene, during the “well completion” phase (when gas and water flow back to the surface after hydraulic fracturing) as

well as from related infrastructure (CDPHE 2009a, 2009b; Garfield County Public Health Department 2009; Gilman et al. 2013; McKenzie et al. 2012; Pétron et al. 2012). Ambient benzene levels in areas with active NGD in Northeast Colorado ranged from 0.03 to 6 parts per billion by volume (ppbv) (CDPHE 2012; Gilman et al. 2013; Pétron et al. 2012). Furthermore, 24-hr average ambient air benzene levels near active well development sites in western Colorado ranged from 0.03 to 22 ppbv (McKenzie et al. 2012).

Two previous case–control studies have reported associations between maternal exposure to benzene and birth prevalence of NTDs and/or CHDs (Lupo et al. 2010b; Wennborg et al. 2005). The study by Lupo et al. (2010b) of 4,531 births in Texas found that mothers

living in census tracts with the highest ambient benzene levels (0.9–2.33 ppbv) were 2.3 times more likely to have offspring with spina bifida than mothers living in census tracts with the lowest ambient benzene levels (95% CI: 1.22, 4.33). An occupational study of Swedish laboratory employees found a significant association between exposure to occupational levels of benzene in the critical window between conception, organogenesis, and neural crest formation and neural crest malformations (Wennborg et al. 2005). Children born to 298 mothers exposed to benzene had 5.3 times greater prevalence of neural crest malformations than children born to mothers not exposed to benzene (95% CI: 1.4, 21.1). Other studies of maternal exposures to organic solvents, some of which contain benzene, have reported associations between maternal occupational exposure to organic solvents and major birth defects (Brender et al. 2002; Desrosiers et al. 2012; McMartin et al. 1998). Although exposure to benzene is a plausible explanation for the observed associations, further research is needed to examine whether these associations are replicated and whether benzene specifically explains these associations.

Air pollutants emitted from diesel engines used extensively in NGD also may be associated with CHDs and/or NTDs. Trucks with diesel engines are used to transport supplies, water, and waste to and from gas wells, with 40 to 280 truck trips per day per well pad during development (Witter et al. 2013). Generators equipped with diesel engines are used in both drilling wells and hydraulic fracturing. Air pollutants in diesel exhaust include NO₂, SO₂, PM, and PAHs. A meta-analysis of four studies suggested associations of maternal NO₂ and SO₂ exposures with coarctation of the aorta and tetralogy of Fallot, and of maternal PM₁₀ exposure with arterial septal defects (Vrijheid et al. 2011). Two case–control studies in China reported positive associations between PAH concentrations in maternal blood and the placenta and NTDs (Li et al. 2011; Naufal et al. 2010). Several CHDs were associated with traffic related carbon monoxide and ozone pollution in a case control study of births from 1987 to 1993 in Southern California (Ritz et al. 2002).

The small negative associations with term low birth weight and preterm birth in our study population were unexpected given that other studies have reported positive associations between these outcomes and urban air pollution (Ballester et al. 2010; Brauer et al. 2008; Dadvand et al. 2013; Ghosh et al. 2012; Llop et al. 2010) and proximity to natural gas wells (Hill 2013). It is possible that rural air quality near natural gas wells in Colorado is not as compromised as urban air quality in these studies, and exposure represented as IDW well count may not adequately

Table 3. Association between inverse distance weighted well count within 10-mile radius of maternal residence and preterm birth and term low birth weight.

Inverse distance weighted well count ^a	0 wells within 10 miles	Low (first tertile)	Medium (second tertile)	High (third tertile)	Cochran–Armitage trend test p-value ^b
Preterm birth					
Live births (n)	65,506	18,884	18,854	19,384	
Cases (n)	4,849	1,358	1,289	1,274	
Crude OR	1	0.97	0.92	0.88	< 0.0001
Adjusted OR (95% CI) ^c		0.96 (0.89, 1.0)	0.93 (0.87, 1.0)	0.91 (0.85, 0.98)	
Term low birth weight					
Full-term live births (n)	60,653	17,525	17,565	18,104	
Cases (n)	2,287	525	471	432	
Crude OR	1	0.79	0.70	0.62	< 0.0001
Adjusted OR (95% CI) ^c		1.0 (0.9, 1.1)	0.86 (0.77, 0.95)	0.9 (0.8, 1)	
Mean difference in birth weight (g) ^d	0	5 (–2.2, 13)	24 (17, 31)	22 (15, 29)	

^aFirst tertile, 1–3.62 wells/mile; second tertile, 3.63–125 wells/mile; third tertile, 126–1,400 wells/mile. ^bPerformed as two-tailed test on unadjusted logistic regression. ^cAdjusted for maternal age, ethnicity, smoking, alcohol use, education, and elevation of residence, as well as infant parity and sex. ^dAdjusted for maternal age, ethnicity, smoking, alcohol use, education, and elevation of residence, as well as infant parity, sex, and gestational age.

Table 4. Association between inverse distance weighted well count within 10-mile radius of maternal residence and CHD diagnostic groups.

Inverse distance weighted well count ^a	0 wells within 10 miles	Low (first tertile)	Medium (second tertile)	High (third tertile)
Conotruncal defects				
Cases (n)	40	14	13	15
Adjusted OR (95% CI) ^b	1	1.1 (0.57, 2.2)	1.1 (0.55, 2.0)	1.2 (0.6, 2.2)
Ventricular septal defects				
Cases (n)	210	68	59	84
Adjusted OR (95% CI) ^c	1	1.3 (0.96, 1.8)	1.1 (0.81, 1.5)	1.5 (1.1, 2.1)
Endocardial cushion and mitrovalve defects				
Cases (n)	39	14	12	12
Adjusted OR (95% CI) ^b		0.81 (0.42, 1.6)	0.80 (0.41, 1.5)	0.67 (0.33, 1.32)
Pulmonary artery and valve defects				
Cases (n)	137	52	62	66
Adjusted OR (95% CI) ^c	1	1.3 (0.89, 1.8)	1.5 (1.1, 2.1)	1.6 (1.1, 2.2)
Tricuspid valve defects				
Cases (n)	9	5	8	8
Adjusted OR (95% CI) ^b	1	2.6 (0.75, 9.1)	3.9 (1.3, 11)	4.2 (1.3, 13)
Aortic artery and valve defects				
Cases (n)	75	22	21	24
Adjusted OR (95% CI) ^c	1	1.1 (0.68, 1.9)	1.0 (0.62, 1.8)	1.2 (0.73, 2.1)
Patent ductus arteriosus				
Cases (n)	59	18	17	15
Adjusted OR (95% CI) ^c	1	1.0 (0.56, 1.8)	0.96 (0.55, 1.7)	0.83 (0.44, 1.5)

^aFirst tertile, 1–3.62 wells/mile; second tertile, 3.63–125 wells/mile; third tertile, 126–1,400 wells/mile. ^bAdjusted only for residence elevation of because of low numbers. ^cAdjusted for maternal age, ethnicity, smoking, alcohol use, education, and elevation of residence, as well as infant parity and sex.

represent air quality. In addition, the power of our large cohort increases the likelihood of false positive results for small associations close to the null. Although associations were consistent across measures of birth weight (i.e., reduced risk of term low birth weight and increase in mean birth weight), they attenuated toward the null in sensitivity analysis for 2- and 5-mile radii (see Supplemental Material, Tables S6–S7). If causal, stronger associations would be expected with more stringent exposure definitions. Our incomplete ability to adjust for socioeconomic status, health, nutrition, prenatal care, and pregnancy complications likely accounts for these unexpected findings.

This study has several limitations inherent in the nature of the available data. Not all birth defects were confirmed by medical record review. Also, birth defects are most likely undercounted, because stillbirths, terminated pregnancies, and later-life diagnoses (after 3 years of age) are not included. Birth weight and gestational age were obtained from birth certificates, which are generally accurate for birth weight and useful but less accurate for gestational age (DiGiuseppe et al. 2002). Data on covariates were obtained from birth certificates and were limited to basic demographic, education, and behavioral information available in the vital records. Distribution of covariates among exposure tertiles and the unexposed group was similar; nevertheless, our incomplete ability to adjust for socioeconomic status, health, nutrition, prenatal care, and pregnancy complications may have resulted in residual confounding. In addition, low event outcomes (e.g., NTDs) were adjusted only for elevation. The data set did not contain information on maternal folate consumption and genetic anomalies, both independent predictors of our outcomes, which may have confounded these results. We did observe a large decrease in the prevalence of NTDs after the introduction of folic acid in 1998, and small increases in the prevalence of CHDs and oral clefts, although none of the estimates are statistically significant (see Supplemental Material, Table S1). Further study is needed to determine whether unaccounted folate confounding is attenuating our results toward the null. There is no evidence indicating genetic anomalies would differ by IDW well count around maternal residence.

Because of the rarity of specific birth defects in the study population, birth defects were aggregated into three general groups. This limited our study in that associations with specific birth defects may have been obscured. An exploratory analysis of CHDs by clinical diagnostic groups indicates increased prevalence of specific diagnostic groups (i.e., PAV, VSD, and TVD) compared with aggregated CHDs (Table 4).

Another limitation of this study is the lack of temporal and spatial specificity of the exposure assessment. Because we did not have maternal residential history, we assumed that maternal address at time of delivery was the same as maternal address during the first trimester of pregnancy—the critical time period for formation of birth defects. Studies in Georgia and Texas estimate that 22–30% of mothers move residence during their pregnancy, and most mothers move within their locality (Lupo et al. 2010a; Miller et al. 2010), potentially introducing some exposure misclassification for the early pregnancy period of interest. However, these studies found little difference in mobility between cases and controls (Lupo et al. 2010a; Miller et al. 2010), and maternal mobility did not significantly influence the assessment of benzene exposure (Lupo et al. 2010a). We were able to determine only whether a well existed within the calendar year of birth (e.g., 2003) and did not have sufficient data to determine if a well existed within the first trimester of the pregnancy. Therefore, some nondifferential exposure misclassification is likely and the overall effect of this is unknown.

Similarly, we had consistent information only on existence of a well in the birth year. Lack of information on natural gas well activity levels, such as whether or not wells were producing or undergoing development, may have resulted in exposure misclassification. Actual exposure to natural gas–related pollutants likely varies by intensity of development activities. Lack of temporal and spatial specificity of the exposure assessment would most likely have tended to weaken associations (Ritz et al. 2007; Ritz and Wilhelm 2008). To address spatial and temporal variability, additional air pollution measurements and modeling will be needed to improve exposure estimates at specific locations. Last, information on the mother's activities away from her residence, such as work and recreation, as well as proximity of these activities to NGD was not available and may have led to further exposure misclassification and residual confounding.

Conclusion

This study suggests a positive association between greater density and proximity of natural gas wells within a 10-mile radius of maternal residence and greater prevalence of CHDs and possibly NTDs, but not oral clefts, preterm birth, or reduced fetal growth. Further studies incorporating information on specific activities and production levels near homes over the course of pregnancy would improve exposure assessments and provide more refined effect estimates. Recent data indicate that exposure to NGD activities is increasingly common. The COGCC estimates that 26% of the > 47,000 oil and

gas wells in Colorado are located within 150–1,000 feet of a home or other type of building intended for human occupancy (COGCC 2012). Taken together, our results and current trends in NGD underscore the importance of conducting more comprehensive and rigorous research on the potential health effects of NGD.

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Article

Health Symptoms and Proximity to Active Multi-Well Unconventional Oil and Gas Development Sites in the City and County of Broomfield, Colorado

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Abstract: City and County of Broomfield (CCOB) residents reported over 500 health concerns between January 2020 and December 2021. Our objective was to determine if CCOB residents living within 1 mile of multi-well unconventional oil and gas development (UOGD) sites reported more frequent health symptoms than residents living > 2 miles away. We invited 3993 randomly selected households to participate in a health survey. We applied linear regression to test associations between distance to UOGD and summed Likert scores for health symptom categories. After covariate adjustment, respondents living within 1 mile of one of CCOB's UOGD sites tended to report higher frequencies of upper respiratory, lower respiratory, gastrointestinal and acute symptoms than respondents living more than 2 miles from the sites, with the largest differences for upper respiratory and acute symptoms. For upper respiratory and acute symptoms, scores differed by 0.81 (95% CI: 0.06, 2.58) and 0.75 (95% CI: 0.004, 1.99), respectively. Scores for adults most concerned about air pollution, noise and odors trended higher within 1 mile for all symptom categories, while scores among adults least concerned trended lower. Scores trended higher for lower respiratory, gastrointestinal and acute symptoms in children living within 2 miles of UOGD, after covariate adjustment. We did not observe any difference in the frequency of symptoms reported in unadjusted results. Additional study is necessary to understand relationships between proximity to UOGD and health symptoms.

Keywords: epidemiology; unconventional oil and gas development; health symptoms; air pollution; hydraulic fracturing; acute exposure symptoms



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1. Introduction

1.1. Unconventional Oil and Gas Development

The United States (US) is now the world's top producer of both oil and natural gas [1], largely because of advances in extraction technology over the past 20 years [2,3]. These technological advances allow operators to co-locate many wells on one site (multi-well sites) and reduce the number of well pads in an area, as well as pipeline routes, and production facilities [4]. However, there is a growing concern regarding the increase in intensity, frequency and duration of air pollutant and noise emissions related to multi-well unconventional oil and gas development (hereinafter referred to as UOGD) sites [5,6].

Colorado is among the top five oil-producing states, with the majority of UOGD sites operating within the Denver–Julesburg basin (DJB) in northeast Colorado, including the urban corridor along the Northern Front Range [7]. Concurrent to UOGD growth, the Northern Front Range has experienced intensive population growth over the past 20 years [8]. Co-current intensive population and UOGD growth in the DJB led to a 14% increase in the size of the DJB population living within 1 mile of an UOGD site

between 2000 and 2012 [9]. The rate of population growth continues to increase across Colorado's Front Range, but especially within the City and County of Broomfield (CCOB). The CCOB is expected to experience a population increase of 24% by 2030 (from 2020 population counts) [10], double the projected population increase of 12% for the entire state [8]. Approximately 10.4% of CCOB's 74,112 residents currently live within 1 mile of 6 multi-well UOGD sites; another 15.1% live between 1 and 2 miles from the sites [11].

1.2. Oil and Gas History in the City and County of Broomfield

The CCOB is one of two consolidated municipal and county governments in the state of Colorado [12], created out of parts of four neighboring counties in 2001. These adjacent counties are as politically and economically diverse as Boulder County, which has historically had a progressive environmental and conservation ethos [13], and Weld County, whose economy relies heavily on resource and mineral extraction [14]. This diversity provides a unique nexus and test case for the risks, challenges and opportunities relating to UOGD in proximity to urban environments.

In 2018, a Denver-based UOGD operator received permits [15] from the Colorado Oil and Gas Conservation Commission (COGCC) to drill 84 unconventional oil and gas wells across six UOGD sites in the rapidly urbanizing area of north/central Broomfield. Prior to COGCC approval and amidst much public outcry from high-income neighborhoods opposing the construction of the UOGD sites, city officials negotiated the final locations of the pads along with an agreement that enumerated a series of measures (referred to as best management practices, or BMPs) intended to reduce impacts to health, safety and the environment [16].

The final, negotiated well pad locations were constructed on CCOB-owned public lands and are surrounded by single-family residential areas, some of which are 1000 ft. from the nearest pad (see UOGD locations in Figure 1). After the approval of the locations for the six UOGD sites, strong opposition from nearby residents remained, and concerns were raised about cumulative exposures to toxic air emissions from living near multiple sites, as well as exposure to additional traffic, dust, noise and lighting. One year after the six multi-well pad project was approved, Colorado Senate Bill 181 (SB-181), which paved the way for the COGCC to adopt new oil and gas locations setback distances at a minimum of 2000 ft. from occupied residential structures, was passed by the state legislature. This landmark bill was supported, in part, by a risk assessment that demonstrated a potential for health impacts to occur up to 2000 ft. from UOGD as a result of possible exposure to air toxics [17,18].

1.3. Air and Noise Pollution

Multiple studies have demonstrated potential impacts to human health from air pollutants emitted from Colorado's UOGD well sites [5,6,18,19]. The CCOB has a robust air quality monitoring network with 14 sensors surrounding the six multi-well UOGD sites [20]. Previous studies indicate that the use of BMPs, such as closed loop flowback systems, can reduce the frequency of increased ambient air volatile organic compounds (VOCs) concentrations [21].

While BMPs, such as the closed loop flowback systems used in Broomfield, lower air pollutant emissions from UOGD well sites, reducing VOCs during pre-production activities is dependent upon available technological mitigations. Broomfield's monitoring system has demonstrated that, regardless of strict BMPs, there are still numerous increases in the frequency, magnitude and duration of VOC emissions during pre-production operations, especially during well bore drilling (likely attributed to drill cuttings containing hydrocarbons) and coiled tubing/mill out [22].

Noise from UOGD occurs in nearly all phases of well development and into production [6,23]. Noise can disturb nearby residents and disproportionately impact vulnerable populations, including the elderly and chronically ill [24]. Recent studies indicate that

BMPs, such as sound walls, are not effective in mitigating noise exposures for nearby residents [6,25].

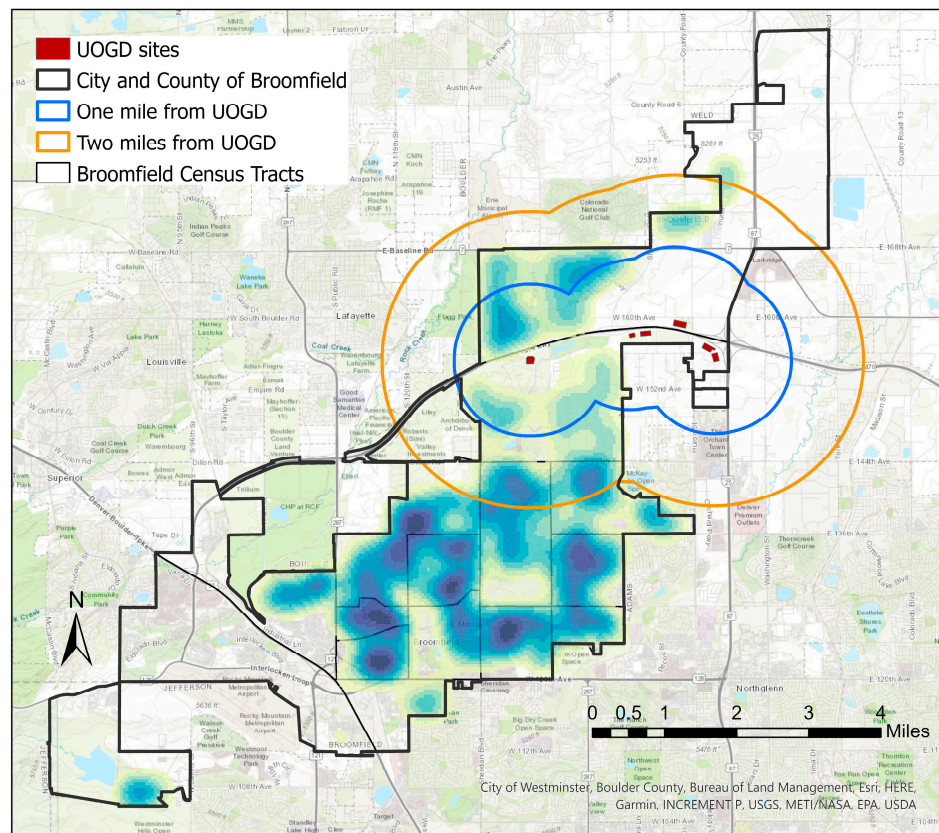


Figure 1. Kernel Density map indicating location densities of 3993 households randomly selected to participate in the health survey. Darker colors indicate a greater number of surveys were sent to that location.

1.4. Human Health Impacts and Proximity to UOGD

Several months after the commencement of construction and drilling at several of the UOGD sites, residents began to complain to city officials of health symptoms they believed were caused by air toxics and noise related to UOGD [26]. The CCOB's Department of Public Health and Environment formalized a way for residents to submit health complaints online and within a 2-year period (2020–2021), during which time several well pads were being constructed, residents reported over 500 health concerns. The majority of concerns were related to air pollution, noise and odor associated with six multi-well UOGD sites [26]. Health concern reports increased during pre-production and included reports of headaches, eye and throat irritation, and nosebleeds. Over all phases of UOGD, residents most commonly reported difficulty sleeping and anxiety or stress and often stated noise disturbances from nearby oil and gas operations as the cause [27]. The Human Health Risk Assessment [17,18], which gave support for the passage of Colorado Senate Bill 181 (SB-181), was the basis for CCOB's health collection efforts, as the risk assessment recommended efforts focusing on population-specific, local data collection.

The body of epidemiological literature indicates that UOGD affects the health of nearby residents. A current review found that, in 25 of 29 studies, there was at least one statistically significant association between UOGD exposure and adverse health outcomes (hospitalizations, adverse birth outcomes, cancer and asthma exacerbations) [28]. More recently published studies report associations between intensity of oil and gas activity and

indicators and exacerbations of cardiovascular disease [29–31], and further evidence of associations with adverse birth outcomes [32–34]. Additionally, residents living within 1 km of an UOGD site self-report more skin conditions and upper respiratory symptoms than those living farther away [35].

Several studies document sociopsychological impacts in residents living near UOGD sites due to anxieties related to the potential release of toxins and carcinogens [36]. Commonly reported symptoms from those living near UOGD included psychosocial stress associated with community change [23], worry [37,38] and adverse mental [39] and physical health effects [40]. As UOGD outpaces the scientific community's ability to understand potential health effects, studies of self-reported outcomes are a vital way to understand health impacts in order to influence public policy [40]. After the onset of pre-production UOGD activities and the notably large number of symptoms reported to CCOB's Department of Public Health and Environment, it became clear that a more robust study was needed to better assess self-reported health symptoms and distance to UOGD. Our objective is to determine whether CCOB residents living near the CCOB's multi-well oil and gas sites, which are considered to have some of the most rigorous BMPs in the State of Colorado, report more health symptoms than CCOB residents not living near the sites. At the time this study was conducted, no other studies have aimed to associate symptoms at various proximities to UOGD in a jurisdiction that requires such extensive BMPs.

2. Materials and Methods

We conducted a cross-sectional study of 3993 randomly selected CCOB households to collect data on self-reported health symptoms between October and December 2021.

2.1. Study Area and Population

The CCOB is located in Colorado's Front Range with a total land area of 33 square miles and a population of approximately 74,000 [11]. In 2021, CCOB was rated as the fifth healthiest county in the United States, according to research conducted by University of Missouri Extension Center for Applied Research and Engagement Systems (CARES) [41]. Seventy-six percent of the population identifies as white alone [11]; 59% have obtained a Bachelor's degree or higher; and the median household income is \$107,638, nearly one-third higher than the state of Colorado's median household income [42]. Prior to the start of this research, 84 UOGD wells were permitted for development in Northern CCOB (Figure 1) located across six sites. During the time health surveys were being collected, 30 wells were in the production phase, with another 21 wells in the pre-production phase (drilling, hydraulic fracturing and/or the coiled tubing/mill out), and 33 wells had no activity.

2.2. Survey Instrument

We designed our survey and questions based on symptoms collected in prior oil and gas survey research [35,43] as well as symptoms collected by the State of Colorado's Department of Public Health and Environment's Oil and Gas Health Information and Response line, and the CCOB's Health Concern line. An important objective of this research is to understand symptoms and proximity to UOGD sites, and building off symptoms defined in the previous literature helps to characterize how the population in CCOB may report similar or different symptoms related to living near or away from UOGD. Surveys contained Likert scale questions, commonly used in epidemiological survey research [35,43], and provided a way to quantify responses. We asked about the frequency of 20 separate symptoms experienced in the past 14 days. Choices included never, once, 2–5 times, 5–13 times or everyday (0–4 Likert scale). The survey also contained questions on occurrence of each symptom (yes, no) within the past two and five years: before major UOGD projects began, preexisting chronic health conditions, demographics, household size, smoking (tobacco and marijuana) status and exercise habits, as well as the degree of concern for nine environmental issues (e.g., noise, odor, air, etc.) by using

a 0–4 Likert scale—not at all concerned, slightly, somewhat, moderately or extremely concerned (see Supplemental Material, “Survey”). Survey data were collected using ESRI’s ArcGIS Survey123 platform.

2.3. Household Selection and Recruitment

Households were randomly selected using ArcGIS Desktop version 10.8.1. Random selection helped reduce participant bias and ensure households were targeted at locations throughout CCOB. There are approximately 21,000 residential parcels in CCOB [11], and 19% received a postcard in the mail with a survey link. Approximately one-fourth of the total number of parcels are located in CCOB’s two northernmost census tracts; these tracts contain all UOGD activity in CCOB. Since the survey mentioned that this research was related to UOGD activity, we expected a greater response rate from those living in the census tracts near UOGD than from those living in the tracts farther away. To ensure an adequate sample size was collected, we weighted the distribution of randomly selected households for population density while also oversampling in the southernmost census tracts (which are located further from UOGD) (Figure 1). To accomplish this, a fishnet grid was created for the two northernmost census tracts and again for the 13 southernmost census tracts. The centroid of each grid was attached to the nearest residential parcel for household selection. Initially, about 1800 households were selected throughout CCOB to receive surveys in the mail. However, due to a low response rate within the first month of data collection, this process was repeated again and approximately 2200 additional households were selected to receive postcards with a link to the survey. Households were also sent two to three reminder postcards to encourage participation. Overall, we sent postcards with a link to the survey via QR code to 524 households within 1 mile of UOGD, 693 households within 1–2 miles of UOGD and 2776 households located >2 miles from UOGD activity.

Postcards were translated into English and Spanish and stated the intent of the research, the length of time expected to complete the health survey (20–30 min) and instructions for accessing the survey via QR code or webpage (see Supplemental Material, “Postcard”). Survey questions were available in English and Spanish.

We asked that only one adult complete the survey per household. To reduce selection bias, instructions asked that the adult selected was the one whose birthday was closest to the date they received the survey in the mail and that the adult lives in the household full time. We encouraged additional survey questions for children to be completed per household by an adult for a child under the age of 18 living in their household, if applicable, and asked that the same selection method be applied for the child. The Institutional Review Board for the University of Colorado (COMIRB) reviewed and approved this research (COMIRB# 21-3719).

2.4. Residence Proximity to Nearest Multi-Well Oil and Gas Site

We used ArcGIS to calculate the distance between each respondent’s residence and each UOGD site in CCOB. We then classified residences according to their distance from the nearest UOGD site into distance bands of less than 1 mile, 1–2 miles or >2 miles. We based the 1- and 2-mile cut points on residential locations for CCOB residents filing health complaints attributed to UOGD between 2019 and 2021 [26]. Complainants lived predominantly in CCOB’s two northernmost census tracts where homes are within 2 miles of the multi-well oil and gas sites, with most complainants living within 1 mile of a multi-well oil and gas site.

2.5. Outcomes

We grouped health symptoms from the household survey based on physiological organ system [35] and mental health. We assigned: coughs, nasal congestion, runny nose, throat irritation and bloody noses to upper respiratory; shortness of breath and lung irritation to lower respiratory; dizziness, difficulty concentrating, headaches, numbness

and tingling, ringing ears and hearing loss, and muscle aches and weakness to neurological; nausea and vomiting to gastrointestinal; and anxiety and stress, difficulty sleeping, difficulty concentrating, and lack of energy and fatigue to mental health.

We also performed a principal component analysis on all symptoms. The first three components capture 58% of the variability, with Eigenvalues > 1 . The first component captured 33% of the variability, with Eigenvalues > 0.1 for all symptoms. The second component captured 7.2% of the variance, with Eigenvalues > 0.1 for primarily mental health symptoms (anxiety/stress, difficulty concentrating, lack of energy/fatigue, difficulty sleeping). The third component captured another 6.6% of the variance, with Eigenvalues > 0.1 for several acute symptoms (nausea, vomiting, nosebleeds, lung irritation, shortness of breath, cough and throat irritation). Based on these PCA results, we assigned all symptoms to an outcome group named total symptoms and symptoms with Eigenvalues > 0.1 in the third component to an outcome group named acute response. We had already created a mental health outcome group with the symptoms loading to the second component.

2.6. Statistical Analysis

The mean Likert score for each self-reported outcome and the total number of symptoms reported as occurring at least once (Likert score > 0) in the past 14 days for each respondent were calculated according to the distance of the respondent's residence (<1 , $1-2$ or >2 miles) from the nearest multi-well UOGD site. Because many symptoms surveyed may also be associated with COVID and of higher COVID infection rates in Colorado's Hispanic/Latino, Native Hawaiian/Pacific Islander, American Indian/Alaska Native and African American communities in 2021 [44], we assigned responses from the race/ethnicity choices into two groups: (1) White, Asian, Asian/White or Asian/White/Native Hawaiian/other Pacific Islander and (2) Hispanic/Latino, Hispanic/Latino/White, American Indian/Alaska Native, Native Hawaiian/other Pacific Islander or Black/White, or other. No survey respondents identified as only Black. We classified reported occupation as management or professional; service, sales, or office; natural resources, construction, maintenance, production, transportation, or material moving; and not working [45].

Because the distribution of the summed Likert scores for adults was log normal, all summed scores were log transformed to approximate a normal distribution. Summed Likert scores for children approximated a normal distribution. We applied the method of least squares linear regression to test the association between residence distance from the closest UOGD site (distance band) and the mean overall number of symptoms and mean summed Likert scores for all symptoms as well as the mean summed Likert scores for each of six groups of health symptoms (upper respiratory, lower respiratory, gastrointestinal, neurological, acute response and mental health, see supplemental material, Table S1) for unadjusted and adjusted models. We ran separate models for adult respondents and children (<18 years) because children did not provide their own responses and there were fewer covariates available for children. Based on a priori knowledge of their association with both exposure and outcomes, we adjusted both the adult and child models for age (ordinal), gender identification (male and female or other), smoked or smoker ever present in household (yes/no), number of chronic health conditions reported (continuous) and number of children under 18 years of age living in household (continuous). The adult model was also adjusted for days per week of exercise (continuous), alcoholic drinks consumed each week (ordinal), hours per day spent at residence (ordinal), level of education (ordinal), race/ethnicity (dichotomous), occupation (categorical) and years at current residence ($<$, ≥ 2 years). An evaluation of correlation between co-variables indicated little correlation between covariates. We evaluated for effect modification by performing stratified analysis for gender, smoker ever present in household, years at current residence, age ($<$, ≥ 55 years), number of chronic conditions (0 , >0) and hours per day spent at residence ($<$, ≥ 13 h). Additionally, we evaluated for mediation as well as effect modification by the three most frequently reported environmental concerns (air pollution, noise and odors) in CCOB's oil and gas complaint database [26] by using multiple linear regression with (1) the mediator

(sum of Likert scores for air pollution, noise and odor concerns) as the dependent variable and setback distance as the main predictor; (2) the sum of Likert scores for a group of health symptoms as the dependent variable and the mediator as the main predictor; and (3) the sum of Likert scores for a group of health symptoms as the dependent variable and setback distance as the main predictor [46]. We considered mediation to be present if all three regressions returned statistically significant results for the main predictor [47]. To evaluate for effect modification, we stratified by the median summed Likert score ($<$, ≥ 4) for air pollution, noise and odor concerns, as well as stratifying by the median summed Likert score ($<$, ≥ 8) for the remaining seven environmental concerns in the survey (light, dust, wildlife, traffic, water, oil spill, waste). Given the exploratory nature of this study, no adjustments were made for multiple comparisons, and significance was established at the two-sided 0.05 level. We conducted all statistical analysis using SAS 9.3 (SAS Institute, Cary, NC, USA).

3. Results

Four hundred twenty-seven adults responded to our survey, and 59 adults provided responses for a child living in their household. Response rates for the three distance bands ranged from 10–11.6%, and the overall response rate was 10.7% (Table 1).

3.1. Demographics

Demographic results are presented in Table 1. According to the U.S. Census [11], CCOB does not have extensive racial diversity, with 76% of respondents identifying as white alone, which is reflected in our survey respondents. In general, a higher proportion of respondents living within 1 mile and 1–2 miles (than from those living more than 2 miles away) from one of CCOB's UOGD sites identified as male, never smoked or lived with someone that smoked, consumed more alcoholic beverages, were aged 55 years or older, spent less time at home each day and lived less than 2 years in their current home. Level of concern with oil and gas stressors (air pollution, noise and odors) did not differ by distance band.

3.2. Self-Reported Health Symptoms

We observed no differences in unadjusted analysis of self-reported health symptoms by setback distance (Table 2). A full list of symptoms can be viewed in Supplemental Material (Table S1).

After covariate adjustment, the total number of symptoms reported at least once in the past 14 days and summed Likert scores for all symptoms trended higher as distance to UOGD decreased (Table 3). Respondents living within 1 mile of one of CCOB's UOGD sites tended to report higher frequencies of upper respiratory, lower respiratory, gastrointestinal and acute symptoms than respondents living 1–2 miles and more than 2 miles from the sites, with the largest differences for upper respiratory and acute symptoms. Mean summed Likert scores differed by 0.81 (95% CI: 0.06, 2.58) and 0.75 (95% CI: 0.004, 1.99) for upper respiratory and acute symptoms, respectively. We observed null results for mental health and neurological symptoms in our adjusted model.

Level of concern for the top three environmental complaints (noise, odor and air) in CCOB's oil and gas complaint database did not mediate the relationships between reported symptoms and distance band (see Supplemental Material, Tables S2 and S3); however, air pollution, noise and odor concerns did modify the relationship (Table 3). Among respondents reporting greater concern for air pollution, odor and noise (sum Likert scores within the top 50th percentile, ≥ 4), those living within 1 mile of CCOB's UOGD sites reported 2.88 more health symptoms in the past 14 days (95% CI: 1.14, 4.63) than those living > 2 miles from the sites. Among these respondents, we also observed a 7.26 mean difference in the sum of Likert scores for the sum of all symptoms (95% CI: 3.16, 11.35) and statistically higher means for all symptom categories between those living < 1 mile and > 2 miles from the UOGD sites (Table 4). Among respondents reporting less concern for air,

odor and noise (Sum Likert scores less than the 50th percentile, <4), those living within 1 mile of CCOB's UOGD sites reported fewer health symptoms in the past 14 days and lower frequencies of all symptom categories than those living >2 miles. Stratified analysis by the median summed Likert score (<, ≥8) for the six remaining environmental concerns indicate effect modification to a lesser extent (see Supplemental Material Table S4).

Table 1. Demographics of adult survey respondents and household distance from well site.

Parameter	Within 1 Mile	1–2 Miles	>2 Miles	Total
Number of survey respondents (response rate [%])	61 (11.6)	69 (10.0)	297 (10.7)	427 (10.7)
	Age in Years (%)			
18–44	18	5.9	23.9	21.8
45–54	8.2	29	20.2	19.9
55–64	14.8	29	20.5	21.1
65–74	41	14.5	26.9	26.9
≥75	18	11.6	8.5	10.3
White alone (%) ¹	89.9	90.2	90.9	90.6
Female (%)	44.3	44.9	59.3	54.8
Never smoked or lived with someone who smoked (%)	88.5	89.9	82.5	84.5
Average Days of Exercise per Week	3.9	4.7	3.5	3.8
	Average number of alcoholic drinks per week (%)			
None	31.1	44.9	40.7	40.1
1–2	27.9	17.4	23.6	23.2
3–5	19.7	20.3	9.5	19.7
6–10	13.1	14.5	11.1	11.9
>10	8.2	2.9	5.1	5.2
	Average Hours Spent in Home Per Day (%)			
Less than 8	6.6	5.8	1.4	2.8
8–12	19.7	14.5	12.1	13.6
13–15	16.4	24.6	20.9	20.8
16–20	47.5	21.7	31	31.9
≥21	9.8	33.3	34.7	30.9
<2 years in household	19.7	5.8	7.7	9.1
	Occupation (%)			
Management, professional and related occupations	29.5	42.0	52.5	47.5
Service, sales, office, natural resources, construction, maintenance, production, transportation and material moving occupations ²	11.5	8.7	9.1	9.4
Not working (retired, homemaker, student, unemployed)	59.0	49.3	38.4	43.1
Mean Likert Score for Concerns about air, noise and water	4.9	4.8	4.6	4.7

¹ Percentage of respondents that identified as white. Approximately 10% of respondents identified as either Asian alone (2.6%), Hispanic/Latino alone (2.1%), American Indian/Alaska Native, Native Hawaiian/other Pacific Islander, Asian/White, Hispanic/Latino/White, Black/White or other. No survey respondents identified as Black or African American alone. ² No respondents reported that they worked in the oil and gas industry.

Table 2. Unadjusted model for difference in means for survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021.

Outcome	Unadjusted Model Main Analysis (N = 427)	
	Difference between >2 Mile and 1–2 Mile Means (LCL, UCL)	Difference between >2 Mile and <1 Mile Means (LCL, UCL)
Total Number of Symptoms (N)	−0.31 (−1.57, 0.96)	−0.44 (−1.77, 0.89)
Total summed Likert Score	−0.92 (−3.14, 1.67)	−1.01 (−3.34, 1.71)
¹ Upper Respiratory (summed Likert Score)	−0.40 (−1.06, 0.41)	0.15 (−0.62, 1.09)
² Lower Respiratory (summed Likert Score)	0.03 (−0.16, 0.25)	0.04 (−0.16, 0.28)
³ Mental Health (summed Likert Score)	−0.06 (−0.82, 0.88)	−0.88 (1.55, 0.04)
⁴ Neurological (summed Likert Score)	−0.34 (−1.10, 0.57)	−0.39, (−1.18, 0.56)
⁵ Gastrointestinal (summed Likert Score)	−0.003 (−0.13, 0.14)	0.020 (−0.12, 0.18)
⁶ Acute (summed Likert Score)	−0.13 (−0.70, 0.53)	0.17 (−0.46, 0.90)

¹ Upper Respiratory = cough + nasal congestion + runny nose + throat irritation + nosebleeds. ² Lower Respiratory = short breath + lung irritation. ³ Mental Health = anxiety stress + diff sleeping + difficulty concentrating + lack energy fatigue. ⁴ Neurological = dizziness + difficulty concentrating + headaches + numbness tingling + ringing ears hearing loss + muscle aches weakness pain. ⁵ Gastrointestinal = nausea + vomiting. ⁶ Acute = nausea + vomiting + Nosebleeds + lung irritation + short breath +cough + throat irritation. LCL = lower 95% confidence level, UCL = upper 95% confidence level.

While we did not observe modification by gender identification, we did observe greater mean differences in summed Likert scores for upper respiratory (1.54, 95%CI: 0.16, 2.97) and acute symptoms (1.30, 95%CI: 0.13, 2.47) in respondents identifying as male. Likewise, while we did not observe modification by number of chronic conditions, we did observe lower mean differences in summed Likert scores for upper respiratory (0.75, 95%CI: −0.83, 2.33) and greater differences for acute symptoms (1.20 95%CI: −0.16, 2.58) in respondents reporting more than one chronic condition (see Supplemental Material, Table S5). In sensitivity analyses for respondents that identified as white, never smoked or lived with someone that smoked, lived in their current home for 2 or more years, were at home more than 12 h per day and were aged 55 years or older, we observed results similar to results for all respondents (see Supplemental Material, Table S6).

3.3. Results for Children

Fifty-nine respondents reported health symptoms for one child in their household. Because of the small population of children, we compared children living < 2 miles to children living > 2 miles from Broomfield’s UOGD sites. Parents living < 2 miles from a Broomfield UOGD site reported more symptoms and higher frequencies of all symptoms, except neurological symptoms, in their children than those living more than 2 miles from the sites, after covariate adjustment (Table 4). The mean total number of symptoms differed by 2.29 (95% CI: 0.05, 4.53), and mean summed Likert scores differed by 0.83 (95% CI: 0.12, 1.54), 0.81 (95% CI: 0.3, 1.31) and 2.38 (95% CI: 0.36, 4.41) for lower respiratory, GI and acute symptoms, respectively, between children residing <2 and >2 miles from Broomfield’s UOGD sites. We observed null results for mental health and neurological symptoms in our adjusted model for children.

Table 3. Difference in means for survey respondents living more than 2 miles, 1–2 miles, and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021 ¹.

Outcome	Main Analysis (N = 427)		Sum Likert Score for Odors, Noise and Air in Top 50th Percentile (≥4, N = 239)		Sum Likert Score for Odors, Noise and Air in below the 50th Percentile (<4, N = 188)	
	Difference between >2 Mile and 1–2 Mile Means (LCL, UCL)	Difference between >2 Mile and <1 Mile Means (LCL, UCL)	Difference between >2 Mile and 1–2 Mile Means (LCL, UCL)	Difference between >2 Mile and <1 Mile Means (LCL, UCL)	Difference between >2 Mile and 1–2 mile Means (LCL, UCL)	Difference between >2 Mile and <1 Mile Means (LCL, UCL)
Total Number of Symptoms (N)	0.31 (−0.94, 1.55)	0.70 (−0.62, 2.02)	−0.05 (−1.59, 1.49)	2.88 (1.14, 4.63)	0.25 (−1.60, 2.05)	−1.51 (−3.26, 0.23)
Total summed Likert Score	0.56 (−1.64, 4.53)	1.57 (−1.04, 6.20)	−0.37 (−2.92, 5.32)	8.53 (2.39, 20.17)	0.61 (−1.99, 6.44)	−3.09 (−4.23, 0.33)
² Upper Respiratory (summed Likert Score)	−0.15 (−0.63, 0.97)	0.81 (0.06, 2.58)	−0.34 (−0.93, 1.64)	3.16 (0.82, 8.60)	−0.18 (−0.66, 1.34)	−0.58 (−0.87, 0.54)
³ Lower Respiratory (summed Likert Score)	0.09 (−0.11, 0.47)	0.18 (−0.06, 0.63)	0.15 (−0.14, 0.87)	0.51 (0.03, 1.62)	−0.11 (−0.27, 0.26)	−0.13 (−0.28, 0.22)
⁴ Mental Health (summed Likert Score)	0.88 (−0.31, 3.43)	0.24 (−0.75, 2.53)	0.18 (−0.96, 3.45)	2.62 (0.21, 8.45)	1.21 (−0.40, 6.10)	−1.33 (−2.44, 0.42)
⁵ Neurological (summed Likert Score)	0.13 (−0.50, 1.42)	0.05 (−0.59, 1.38)	−0.03 (−0.74, 1.86)	1.42 (0.001, 4.68)	0.07 (−0.72, 2.27)	−1.01 (−1.29, 0.25))
⁶ Gastrointestinal (summed Likert Score)	0.03 (−0.09, 0.23)	0.09 (−0.05, 0.32)	0.01 (−0.17, 0.26)	0.30 (0.01, 0.84)	−0.03 (−0.14, 0.19)	−0.005 (−0.12, 0.21)
⁷ Acute (summed Likert Score)	0.09 (−0.44, 1.03)	0.75 (0.004, 1.99)	−0.027 (−0.79, 1.64)	2.76 (0.89, 6.24)	−0.07 (−0.55, 0.94)	−0.47 (−0.81, 0.30)

¹ Adjusted for age, sex, race, smoking, alcohol consumption, time spent in home, number of children <18 years in home, exercise, number of chronic health conditions, time of residence at current home, education level and occupation. ² Upper Respiratory = cough + nasal congestion + runny nose + throat irritation + nosebleeds. ³ Lower Respiratory = short breath + lung irritation. ⁴ Mental Health = anxiety stress + diff sleeping + difficulty concentrating + lack energy fatigue. ⁵ Neurological = dizziness + difficulty concentrating + headaches + numbness tingling + ringing ears hearing loss + muscle aches weakness pain. ⁶ Gastrointestinal = nausea + vomiting. ⁷ Acute = nausea + vomiting + nosebleeds + lung irritation + short breath + cough + throat irritation. LCL = lower 95% confidence level, UCL = upper 95% confidence level. **Bold Italics** indicate statistically significant results at a *p*-value < 0.05.

Table 4. Difference in means for 59 children living more than 2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021 ¹.

Outcome	Difference between >2 Mile and <1 Mile Means (LCL, UCL)
Total Number of Symptoms (N)	2.29 (0.05, 4.53)
Total summed Likert Score	3.99 (−1.65, 9.64)
² Upper Respiratory (summed Likert Score)	1.63 (−0.63, 3.89)
³ Lower Respiratory (summed Likert Score)	0.83 (0.12, 1.54)
⁴ Mental Health (summed Likert Score)	0.06 (−1.81, 1.93)
⁵ Neurological (summed Likert Score)	−0.36 (−1.87, 1.14)
⁶ Gastrointestinal (summed Likert Score)	0.81 (0.3, 1.31)
⁷ Acute (summed Likert Score)	2.38 (0.36, 4.41)

¹ Adjusted for age, sex, smoking, number of children <18 years in home, number of chronic conditions. ² Upper Respiratory = cough + nasal congestion + runny nose + throat irritation + nosebleeds. ³ Lower Respiratory = short breath + lung irritation. ⁴ Mental Health = anxiety stress + diff sleeping + difficulty concentrating + lack energy fatigue. ⁵ Neurological = dizziness + difficulty concentrating + headaches + numbness tingling + ringing ears hearing loss + muscle aches weakness pain. ⁶ Gastrointestinal = nausea + vomiting. ⁷ Acute = nausea + vomiting + nosebleeds + lung irritation + short breath + cough + throat irritation. LCL = lower 95% confidence level, UCL = upper 95% confidence level. **Bold Italics** indicate statistically significant results at a *p*-value < 0.05.

4. Discussion

This large cross-sectional health survey of randomly selected households, to the best of our knowledge, is the first study to date on the association between self-reported health symptoms and active UOGD sites utilizing well-defined BMPs. In adjusted models, survey respondents living within 1 mile of a multi-well UOGD site in CCOB reported greater frequencies of upper respiratory and acute response symptoms in the past 14 days than respondents living more than 2 miles from the sites. Respondents living within 2 miles of a UOGD site also reported that their children experienced greater frequencies of lower respiratory, GI and acute response symptoms in the past 14 days as well as a greater number of total symptoms, in adjusted models. We observed null results for mental health and neurological symptoms in our adjusted models. Among respondents most concerned with odors, noise and air pollution, those living within 1 mile reported greater frequencies for all types of symptoms; while among respondents least concerned with odors, noise and air pollution, those living within 1 mile reported less frequencies for all symptom types than those living more than 2 miles from the sites.

Our results are similar to previously published studies that found associations between proximity to unconventional natural gas development in Pennsylvania’s Marcellus Shale and upper respiratory symptoms [35,40,48]. However, our study is the first to report greater frequencies of self-reported nosebleeds, nausea, vomiting and shortness of breath symptoms near UOGD sites. One potential explanation is that the previous studies evaluated exposure proximity to unconventional natural gas well sites and included single well sites, while we evaluated proximity to large multi-well unconventional oil and natural gas sites in our study. Larger multi-well sites that include oil extraction may increase cumulative impacts from exposure to air pollutants, such as volatile organic compounds (VOCs), which are commonly emitted from UOGD sources and can cause a variety of acute health reactions including, but not limited to nose and throat irritation, dizziness and nausea [49].

The CCOB’s air quality monitoring system has documented numerous VOC release events from multi-well UOGD sites that were attributed to drilling and hydraulic fracturing activities during the survey period. From November–December 2021, plumes of BTEX emissions (benzene, toluene, ethylbenzene, xylenes) were frequently observed at a monitoring station within a CCOB neighborhood and were consistent with transport from UOGD sites in pre-production phases, located 1.5 miles away. On December 4, 2021, several large

plumes were captured throughout the day near a UOGD site, showing elevated VOCs, including benzene levels that reached a 1-hour average estimated at 224 parts per billion (ppb) [22], exceeding the Agency for Toxic Substances and Disease Registry's (ATSDR) federal, short-term Minimum Risk Level of 9 ppb [50]. One hour benzene averages are calculated by analyzing a one minute benzene canister sample and then applying conversion factors to each minute of the total VOC (TVOC) indicator reading for a one-hour duration [51]. This event was one of the highest total TVOC readings ever recorded in CCOB. Laboratory results of air samples confirm the plume was significantly influenced by oil and gas activity, and wind direction suggests the plume was sourced from nearby UOGD operations during the start of coiled tubing/mill out. Overall, air quality events captured by CCOB's monitoring network lasted, on average, for 3.5 h and TVOC's concentrations reached 23,000 ppb. Further research, which could estimate levels of pollutants for those living at various distances, could help identify potential exposure scenarios that might be linked to health outcomes.

Results from this research have important implications for future policy efforts that aim to reduce resident exposure to emissions from UOGD sites. This research calls into question the adequacy of Colorado's current 2000 ft. setback [52] as CCOB's air quality monitoring program has evidence of oil and gas plumes traveling over one mile and into neighborhoods. Residents in Broomfield are uniquely situated near six UOGD sites with dozens of wells, which may result in cumulative emissions exposure. Even with the most stringent BMPs in place, emissions during pre-production activities contained elevated levels of BTEX and other air toxics that may have contributed to some of the symptoms reported in our health survey. This research builds off the current body of epidemiological oil and gas literature by highlighting that cumulative emissions exposure may result from living in proximity to multiple UOGD sites. Research such as this can help inform state policymakers about BMPs and setback distances that aim to protect public health.

Interestingly, we found that a respondent's level of concern with the top three complaints (air pollution, noise and odors) in CCOB's oil and gas complaint database significantly modified the relationship between frequency of symptoms and setback distance. This could be due to perception bias, where those most concerned about environmental stressors are more likely to notice and/or report symptoms and those with less concerns are less likely to report symptoms or a psychosomatic effect where the anxiety and concern with pollution is causing some of these symptoms. It could also be due to recall or awareness bias in which individuals with health symptoms are more likely to remember perceived environmental exposures or notice environmental exposures. However, our mediation analysis indicates that level of environmental concerns did not differ by setback distance (see Supplemental Material, Table S2), which indicates these biases may not explain the differences in symptoms by setback distance. It also may be possible that affiliation bias (a respondent's affiliation concerning UOGD) affected our results through either over- or under-reporting symptoms. Our cross-sectional design limits our ability to further evaluate the temporality of the bias.

Our study benefited from random selection of households with response rates evenly distributed by setback distances from CCOB's UOGD sites and more than enough adult respondents to detect differences in frequencies of symptoms by setback distance. We were also able to adjust for many covariates that could be associated with the symptoms. We used well-established methods to evaluate the proximity of households to UOGD by using ArcGIS software 10.8.1 and geocoding the household locations for those that completed a survey.

Inherent biases in self-reporting (as previously discussed) may have affected our results. Additionally, selection bias within a household could have occurred if respondents purposely selected an individual within the household with greater (or fewer) symptoms, rather than choosing one adult (and one child, if applicable) whose birth date is closest to the date they received the survey in the mail. Participation bias may have occurred if those

in favor of and/or not in favor of UOGD in CCOB or those experiencing symptoms were more or less likely to respond to the survey.

With only 59 children and fewer covariates for children, our results for children lack precision and may be biased towards the null. While we did adjust our analysis for many potential confounders, it is possible that an unexplained confounder or residual confounding is present with an unknown effect on our results. Proximity to major roadways, the COVID pandemic and source of drinking water may have affected our results. However, respondents living within 1 mile and greater than 2 miles were equally likely to be living near a major roadway (Figure 1); thus, proximity to a major roadway was not likely a major confounder. Because our survey was conducted when COVID incidence in CCOB was relatively low and COVID incidence was not associated with proximity to UOGD in CCOB, the COVID pandemic was not likely a major confounder. We also note that our stratified analysis by age and race, both known to be associated with COVID incidence, indicate that neither age or race confounded the results (see Supplemental Material, Table S6). Because CCOB lies within the Denver metro region and most residential properties are connected to municipal water sourced from outside of Broomfield [53], source of drinking was not likely a major confounder.

We did not include other populations living near the six UOGD sites in CCOB, and our results may not represent resident symptoms outside of CCOB. Some residents in adjacent Adams County were among the closest individuals living to pre-production development. While including counties with residents living in close proximity to CCOB's UOGD would have improved precision, it is not possible to know how it would affect our results. Including all residents within proximity to UOGD regardless of jurisdictional boundaries would improve the representativeness and generalizability of future studies.

5. Conclusions

Our results indicate that people living within 1 mile of multi-well unconventional oil and natural gas sites more frequently report upper respiratory and acute (e.g., nosebleeds, nausea, shortness of breath) symptoms than people living more than 2 miles from the sites. Because our cross-sectional design does not provide temporal information, it is not possible to determine if proximity to UOGD caused any of the reported symptoms. A possible explanation for the increase in symptoms reported near oil and gas sites could include cumulative and additive impacts from exposure to emissions from multiple UOGD sites. However, other explanations are possible. Additional study using more precise estimates of exposure and objective measures of health outcomes, as well as qualitative designs with focus groups would be useful to better understand the relationship between proximity to UOGD and the health symptoms reported in this study.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/ijerph20032634/s1>, Figure S1: Survey; Figure S2: Postcard; Table S1: Frequency of health symptoms (unadjusted) for adults within the past 14 days and distance from unconventional oil and gas development; Table S2: Mediation analysis for adult survey respondents living more than 2 miles, 1–2 miles, and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Association between distance band and summed Likert score for oil and gas environmental concerns (air pollution, noise and odors); Table S3: Mediation analysis for adult survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Association between Likert scores for reported health symptoms and summed Likert score for oil and gas environmental concerns (air pollution, noise and odors); Table S4: Difference in means for adult survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Sensitivity Analysis for respondents at home more than 12 h a day and stratified analysis Likert score for environmental concerns other than oil and gas in the upper and lower 50th percentile; Table S5: Difference in means for adult survey respondents living more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Stratified by gender and chronic conditions; Table S6: Difference in means for adult survey respondents living

more than 2 miles, 1–2 miles and <1 mile from a multi-well oil and gas site in Broomfield Colorado, October–December 2021: Sensitivity Analysis for respondents identifying as white, never smoked or lived with a smoker, 55 years and older and lived in their home for 2 or more years.

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Human health risk assessment of air emissions from development of unconventional natural gas resources ^{☆☆☆}

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ABSTRACT

Background: Technological advances (e.g. directional drilling, hydraulic fracturing), have led to increases in unconventional natural gas development (NGD), raising questions about health impacts.

Objectives: We estimated health risks for exposures to air emissions from a NGD project in Garfield County, Colorado with the objective of supporting risk prevention recommendations in a health impact assessment (HIA).

Methods: We used EPA guidance to estimate chronic and subchronic non-cancer hazard indices and cancer risks from exposure to hydrocarbons for two populations: (1) residents living $> \frac{1}{2}$ mile from wells and (2) residents living $\leq \frac{1}{2}$ mile from wells.

Results: Residents living $\leq \frac{1}{2}$ mile from wells are at greater risk for health effects from NGD than are residents living $> \frac{1}{2}$ mile from wells. Subchronic exposures to air pollutants during well completion activities present the greatest potential for health effects. The subchronic non-cancer hazard index (HI) of 5 for residents $\leq \frac{1}{2}$ mile from wells was driven primarily by exposure to trimethylbenzenes, xylenes, and aliphatic hydrocarbons. Chronic HIs were 1 and 0.4 for residents $\leq \frac{1}{2}$ mile from wells and $> \frac{1}{2}$ mile from wells, respectively. Cumulative cancer risks were 10 in a million and 6 in a million for residents living $\leq \frac{1}{2}$ mile and $> \frac{1}{2}$ mile from wells, respectively, with benzene as the major contributor to the risk.

Conclusions: Risk assessment can be used in HIAs to direct health risk prevention strategies. Risk management approaches should focus on reducing exposures to emissions during well completions. These preliminary results indicate that health effects resulting from air emissions during unconventional NGD warrant further study. Prospective studies should focus on health effects associated with air pollution.

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1. Introduction

The United States (US) holds large reserves of unconventional natural gas resources in coalbeds, shale, and tight sands. Technological advances, such as directional drilling and hydraulic fracturing, have led to a rapid increase in the development of these resources. For example, shale gas production had an average annual growth rate of 48% over the 2006 to 2010 period and is projected to grow almost fourfold from 2009 to 2035 (US EIA, 2011). The number of

unconventional natural gas wells in the US rose from 18,485 in 2004 to 25,145 in 2007 and is expected to continue increasing through at least 2020 (Vidas and Hugman, 2008). With this expansion, it is becoming increasingly common for unconventional natural gas development (NGD) to occur near where people live, work, and play. People living near these development sites are raising public health concerns, as rapid NGD exposes more people to various potential stressors (COGCC, 2009a).

The process of unconventional NGD is typically divided into two phases: well development and production (US EPA, 2010a; US DOE, 2009). Well development involves pad preparation, well drilling, and well completion. The well completion process has three primary stages: 1) completion transitions (concrete well plugs are installed in wells to separate fracturing stages and then drilled out to release gas for production); 2) hydraulic fracturing (“fracking”: the high pressure injection of water, chemicals, and proppants into the drilled well to release the natural gas); and 3) flowback, the return of fracking and geologic fluids, liquid hydrocarbons (“condensate”) and natural gas to the surface (US EPA, 2010a; US DOE, 2009). Once development is

Abbreviations: BTEX, benzene, toluene, ethylbenzene, and xylenes; COGCC, Colorado Oil and Gas Conservation Commission; HAP, hazardous air pollutant; HI, hazard index; HIA, health impact assessment; HQ, hazard quotient; NATA, National Air Toxics Assessment; NGD, natural gas development.

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complete, the “salable” gas is collected, processed, and distributed. While methane is the primary constituent of natural gas, it contains many other chemicals, including alkanes, benzene, and other aromatic hydrocarbons (TERC, 2009).

As shown by ambient air studies in Colorado, Texas, and Wyoming, the NGD process results in direct and fugitive air emissions of a complex mixture of pollutants from the natural gas resource itself as well as diesel engines, tanks containing produced water, and on site materials used in production, such as drilling muds and fracking fluids (CDPHE, 2009; Frazier, 2009; Walther, 2011; Zielinska et al., 2011). The specific contribution of each of these potential NGD sources has yet to be ascertained and pollutants such as petroleum hydrocarbons are likely to be emitted from several of these NGD sources. This complex mixture of chemicals and resultant secondary air pollutants, such as ozone, can be transported to nearby residences and population centers (Walther, 2011; GCPH, 2010).

Multiple studies on inhalation exposure to petroleum hydrocarbons in occupational settings as well as residences near refineries, oil spills and petrol stations indicate an increased risk of eye irritation and headaches, asthma symptoms, acute childhood leukemia, acute myelogenous leukemia, and multiple myeloma (Glass et al., 2003; Kirkeleit et al., 2008; Brosselein et al., 2009; Kim et al., 2009; White et al., 2009). Many of the petroleum hydrocarbons observed in these studies are present in and around NGD sites (TERC, 2009). Some, such as benzene, ethylbenzene, toluene, and xylene (BTEX) have robust exposure and toxicity knowledge bases, while toxicity information for others, such as heptane, octane, and diethylbenzene, is more limited. Assessments in Colorado have concluded that ambient benzene levels demonstrate an increased potential risk of developing cancer as well as chronic and acute non-cancer health effects in areas of Garfield County Colorado where NGD is the only major industry other than agriculture (CDPHE, 2007; Coons and Walker, 2008; CDPHE, 2010). Health effects associated with benzene include acute and chronic nonlymphocytic leukemia, acute myeloid leukemia, chronic lymphocytic leukemia, anemia, and other blood disorders and immunological effects. (ATSDR, 2007a, IRIS, 2011). In addition, maternal exposure to ambient levels of benzene recently has been associated with an increase in birth prevalence of neural tube defects (Lupo et al., 2011). Health effects of xylene exposure include eye, nose, and throat irritation, difficulty in breathing, impaired lung function, and nervous system impairment (ATSDR, 2007b). In addition, inhalation of xylenes, benzene, and alkanes can adversely affect the nervous system (Carpenter et al., 1978; Nilsen et al., 1988; Galvin and Marashi, 1999; ATSDR, 2007a; ATSDR, 2007b).

Previous assessments are limited in that they were not able to distinguish between risks from ambient air pollution and specific NGD stages, such as well completions or risks between residents living near wells and residents living further from wells. We were able to isolate risks to residents living near wells during the flowback stage of well completions by using air quality data collected at the perimeter of the wells while flowback was occurring.

Battlement Mesa (population ~5000) located in rural Garfield County, Colorado is one community experiencing the rapid expansion of NGD in an unconventional tight sand resource. A NGD operator has proposed developing 200 gas wells on 9 well pads located as close as 500 ft from residences. Colorado Oil and Gas Commission (COGCC) rules allow natural gas wells to be placed as close as 150 ft from residences (COGCC, 2009b). Because of community concerns, as described elsewhere, we conducted a health impact assessment (HIA) to assess how the project may impact public health (Witter et al., 2011), working with a range of stakeholders to identify the potential public health risks and benefits.

In this article, we illustrate how a risk assessment was used to support elements of the HIA process and inform risk prevention recommendations by estimating chronic and subchronic non-

cancer hazard indices (HIs) and lifetime excess cancer risks due to NGD air emissions.

2. Methods

We used standard United States Environmental Protection Agency (EPA) methodology to estimate non-cancer HIs and excess lifetime cancer risks for exposures to hydrocarbons (US EPA, 1989; US EPA, 2004) using residential exposure scenarios developed for the NGD project. We used air toxics data collected in Garfield County from January 2008 to November 2010 as part of a special study of short term exposures as well as on-going ambient air monitoring program data to estimate subchronic and chronic exposures and health risks (Frazier, 2009; GCPH, 2009; GCPH, 2010; GCPH, 2011; Antero, 2010).

2.1. Sample collection and analysis

All samples were collected and analyzed according to published EPA methods. Analyses were conducted by EPA certified laboratories. The Garfield County Department of Public Health (GCPH) and Olsson Associates, Inc. (Olsson) collected ambient air samples into evacuated SUMMA® passivated stainless-steel canisters over 24-hour intervals. The GCPH collected the samples from a fixed monitoring station and along the perimeters of four well pads and shipped samples to Eastern Research Group for analysis of 78 hydrocarbons using EPA's compendium method TO-12, Method for the Determination of Non-Methane Organic Compounds in Ambient Air Using Cryogenic Pre-concentration and Direct Flame Ionization Detection (US EPA, 1999). Olsson collected samples along the perimeter of one well pad and shipped samples to Atmospheric Analysis and Consulting, Inc. for analysis of 56 hydrocarbons (a subset of the 78 hydrocarbons determined by Eastern Research Group) using method TO-12. Per method TO-12, a fixed volume of sample was cryogenically concentrated and then desorbed onto a gas chromatography column equipped with a flame ionization detector. Chemicals were identified by retention time and reported in a concentration of parts per billion carbon (ppbC). The ppbC values were converted to micrograms per cubic meter ($\mu\text{g}/\text{m}^3$) at 01.325 kPa and 298.15 K.

Two different sets of samples were collected from rural (population < 50,000) areas in western Garfield County over varying time periods. The main economy, aside from the NGD industry, of western Garfield County is agricultural. There is no other major industry.

2.1.1. NGD area samples

The GCPH collected ambient air samples every six days between January 2008 and November 2010 (163 samples) from a fixed monitoring station located in the midst of rural home sites and ranches and NGD, during both well development and production. The site is located on top of a small hill and 4 miles upwind of other potential emission sources, such as a major highway (Interstate-70) and the town of Silt, CO (GCPH, 2009; GCPH, 2010; GCPH, 2011).

2.1.2. Well completion samples

The GCPH collected 16 ambient air samples at each cardinal direction along 4 well pad perimeters (130 to 500 ft from the well pad center) in rural Garfield County during well completion activities. The samples were collected on the perimeter of 4 well pads being developed by 4 different natural gas operators in summer 2008 (Frazier, 2009). The GCPH worked closely with the NGD operators to ensure these air samples were collected during the period while at least one well was on uncontrolled (emissions not controlled) flowback into collection tanks vented directly to the air. The number of wells on each pad and other activities occurring on the pad were not documented. Samples were collected over 24 to 27-hour intervals, and samples included emissions from both uncontrolled flowback and

diesel engines (i.e., from trucks and generators supporting completion activities). In addition, the GCPH collected a background sample 0.33 to 1 mile from each well pad (Frazier, 2009). The highest hydrocarbon levels corresponded to samples collected directly downwind of the tanks (Frazier, 2009; Antero, 2010). The lowest hydrocarbon levels corresponded either to background samples or samples collected upwind of the flowback tanks (Frazier, 2009; Antero, 2010).

Antero Resources Inc., a natural gas operator, contracted Olsson to collect eight 24-hour integrated ambient air samples at each cardinal direction at 350 and 500 ft from the well pad center during well completion activities conducted on one of their well pads in summer 2010 (Antero, 2010). Of the 12 wells on this pad, 8 were producing salable natural gas; 1 had been drilled but not completed; 2 were being hydraulically fractured during daytime hours, with ensuing uncontrolled flowback during nighttime hours; and 1 was on uncontrolled flowback during nighttime hours.

All five well pads are located in areas with active gas production, approximately 1 mile from Interstate-70.

2.2. Data assessment

We evaluated outliers and compared distributions of chemical concentrations from NGD area and well completion samples using Q-Q plots and the Mann–Whitney *U* test, respectively, in EPA's ProUCL version 4.00.05 software (US EPA, 2010b). The Mann–Whitney *U* test was used because the measurement data were not normally distributed. Distributions were considered as significantly different at an alpha of 0.05. Per EPA guidance, we assigned the exposure concentration as either the 95% upper confidence limit (UCL) of the mean concentration for compounds found in 10 or more samples or the maximum detected concentration for compounds found in more than 1 but fewer than 10 samples. This latter category included three compounds: 1,3-butadiene, 2,2,4-trimethylpentane, and styrene in the well completion samples. EPA's ProUCL software was used to select appropriate methods based on sample distributions and detection frequency for computing 95% UCLs of the mean concentration (US EPA, 2010b).

2.3. Exposure assessment

Risks were estimated for two populations: (1) residents >½ mile from wells; and (2) residents ≤½ mile from wells. We defined

residents ≤½ mile from wells as living near wells, based on residents reporting odor complaints attributed to gas wells in the summer of 2010 (COGCC, 2011).

Exposure scenarios were developed for chronic non-cancer HIs and cancer risks. For both populations, we assumed a 30-year project duration based on an estimated 5-year well development period for all well pads, followed by 20 to 30 years of production. We assumed a resident lives, works, and otherwise remains within the town 24 h/day, 350 days/year and that lifetime of a resident is 70 years, based on standard EPA reasonable maximum exposure (RME) defaults (US EPA, 1989).

2.3.1. Residents >½ mile from well pads

As illustrated in Fig. 1, data from the NGD area samples were used to estimate chronic and subchronic risks for residents >½ mile from well development and production throughout the project. The exposure concentrations for this population were the 95% UCL on the mean concentration and median concentration from the 163 NGD samples.

2.3.2. Residents ≤½ mile from well pads

To evaluate subchronic non-cancer HIs from well completion emissions, we estimated that a resident lives ≤½ mile from two well pads resulting a 20-month exposure duration based on 2 weeks per well for completion and 20 wells per pad, assuming some overlap in between activities. The subchronic exposure concentrations for this population were the 95% UCL on the mean concentration and the median concentration from the 24 well completion samples. To evaluate chronic risks to residents ≤½ mile from wells throughout the NGD project, we calculated a time-weighted exposure concentration (C_{S+c}) to account for exposure to emissions from well completions for 20-months followed by 340 months of exposure to emissions from the NGD area using the following formula:

$$C_{S+c} = (C_c \times ED_c/ED) + (C_S \times ED_S/ED)$$

where:

C_c Chronic exposure point concentration ($\mu\text{g}/\text{m}^3$) based on the 95% UCL of the mean concentration or median concentration from the 163 NGD area samples

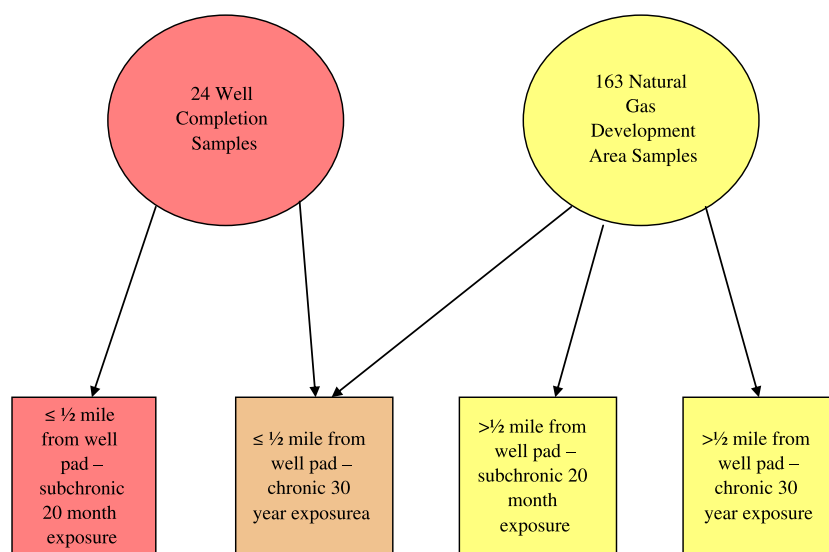


Fig. 1. Relationship between completion samples and natural gas development area samples and residents living ≤½ mile and >½ mile from wells. *Time weighted average based on 20-month contribution from well completion samples and 340-month contribution from natural gas development samples.

ED _c	Chronic exposure duration
C ₅	Subchronic exposure point concentration (µg/m ³) based on the 95% UCL of the mean concentration or median concentration from the 24 well completion samples
ED ₅	Subchronic exposure duration
ED	Total exposure duration

estimate the cumulative cancer risk. Risks are expressed as excess cancers per 1 million population based on exposure over 30 years.

Toxicity values (i.e., RfCs or IURs) or a surrogate toxicity value were available for 45 out of 78 hydrocarbons measured. We performed a quantitative risk assessment for these hydrocarbons. The remaining 33 hydrocarbons were considered qualitatively in the risk assessment.

2.4. Toxicity assessment and risk characterization

For non-carcinogens, we expressed inhalation toxicity measurements as a reference concentration (RfC in units of µg/m³ air). We used chronic RfCs to evaluate long-term exposures of 30 years and subchronic RfCs to evaluate subchronic exposures of 20-months. If a subchronic RfC was not available, we used the chronic RfC. We obtained RfCs from (in order of preference) EPA's Integrated Risk Information System (IRIS) (US EPA, 2011), California Environmental Protection Agency (CalEPA) (CalEPA, 2003), EPA's Provisional Peer-Reviewed Toxicity Values (ORNL, 2009), and Health Effects Assessment Summary Tables (US EPA, 1997). We used surrogate RfCs according to EPA guidance for C₅ to C₁₈ aliphatic and C₆ to C₁₈ aromatic hydrocarbons which did not have a chemical-specific toxicity value (US EPA, 2009a). We derived semi-quantitative hazards, in terms of the hazard quotient (HQ), defined as the ratio between an estimated exposure concentration and RfC. We summed HQs for individual compounds to estimate the total cumulative HI. We then separated HQs specific to neurological, respiratory, hematological, and developmental effects and calculated a cumulative HI for each of these specific effects.

For carcinogens, we expressed inhalation toxicity measurements as inhalation unit risk (IUR) in units of risk per µg/m³. We used IURs from EPA's IRIS (US EPA, 2011) when available or the CalEPA (CalEPA, 2003). The lifetime cancer risk for each compound was derived by multiplying estimated exposure concentration by the IUR. We summed cancer risks for individual compounds to

3. Results

3.1. Data assessment

Evaluation of potential outliers revealed no sampling, analytical, or other anomalies were associated with the outliers. In addition, removal of potential outliers from the NGD area samples did not change the final HIs and cancer risks. Potential outliers in the well completion samples were associated with samples collected downwind from flowback tanks and are representative of emissions during flowback. Therefore, no data was removed from either data set.

Descriptive statistics for concentrations of the hydrocarbons used in the quantitative risk assessment are presented in Table 1. A list of the hydrocarbons detected in the samples that were considered qualitatively in the risk assessment because toxicity values were not available is presented in Table 2. Descriptive statistics for all hydrocarbons are available in Supplemental Table 1. Two thirds more hydrocarbons were detected at a frequency of 100% in the well completion samples (38 hydrocarbons) than in the NGD area samples (23 hydrocarbons). Generally, the highest alkane and aromatic hydrocarbon median concentrations were observed in the well completion samples, while the highest median concentrations of several alkenes were observed in the NGD area samples. Median concentrations of benzene, ethylbenzene, toluene, and m-xylene/p-xylene were 2.7, 4.5, 4.3, and 9 times higher in the well completion samples than in the NGD area samples, respectively. Wilcoxon–Mann–Whitney test results indicate that

Table 1
Descriptive statistics for hydrocarbon concentrations with toxicity values in 24-hour integrated samples collected in NGD area and samples collected during well completions.

Hydrocarbon (µg/m ³)	NGD area sample results ^a						Well completion sample results ^b							
	No.	% >MDL	Med	SD	95% UCL ^c	Min	Max	No.	% >MDL	Med	SD	95% UCL ^c	Min	Max
1,2,3-Trimethylbenzene	163	39	0.11	0.095	0.099	0.022	0.85	24	83	0.84	2.3	3.2	0.055	12
1,2,4-Trimethylbenzene	163	96	0.18	0.34	0.31	0.063	3.1	24	100	1.7	17	21	0.44	83
1,3,5-Trimethylbenzene	163	83	0.12	0.13	0.175	0.024	1.2	24	100	1.3	16	19.5	0.33	78
1,3-Butadiene	163	7	0.11	0.020	0.0465	0.025	0.15	16	56	0.11	0.021	NC	0.068	0.17
Benzene	163	100	0.95	1.3	1.7	0.096	14	24	100	2.6	14	20	0.94	69
Cyclohexane	163	100	2.1	8.3	6.2	0.11	105	24	100	5.3	43	58	2.21	200
Ethylbenzene	163	95	0.17	0.73	0.415	0.056	8.1	24	100	0.77	47	54	0.25	230
Isopropylbenzene	163	38	0.15	0.053	0.074	0.020	0.33	24	67	0.33	1.0	1.0	0.0	4.8
Methylcyclohexane	163	100	3.7	4.0	6.3	0.15	24	24	100	14	149	190	3.1	720
m-Xylene/p-Xylene	163	100	0.87	1.2	1.3	0.16	9.9	24	100	7.8	194	240	2.0	880
n-Hexane	163	100	4.0	4.2	6.7	0.13	25	24	100	7.7	57	80	1.7	255
n-Nonane	163	99	0.44	0.49	0.66	0.064	3.1	24	100	3.6	61	76	1.2	300
n-Pentane	163	100	9.1	9.8	14	0.23	62	24	100	11	156	210	3.9	550
n-Propylbenzene	163	66	0.10	0.068	0.10	0.032	0.71	24	88	0.64	2.4	3.3	0.098	12
o-Xylene	163	97	0.22	0.33	0.33	0.064	3.6	24	100	1.2	40	48.5	0.38	190
Propylene	163	100	0.34	0.23	0.40	0.11	2.5	24	100	0.41	0.34	0.60	0.16	1.9
Styrene	163	15	0.15	0.26	0.13	0.017	3.4	24	21	0.13	1.2	NC	0.23	5.9
Toluene	163	100	1.8	6.2	4.8	0.11	79	24	100	7.8	67	92	2.7	320
Aliphatic hydrocarbons C ₅ –C ₈ ^d	163	NC	29	NA	44	1.7	220	24	NC	56	NA	780	24	2700
Aliphatic hydrocarbons C ₉ –C ₁₈ ^e	163	NC	1.3	NA	14	0.18	400	24	NC	7.9	NA	100	1.4	390
Aromatic hydrocarbons C ₉ –C ₁₈ ^f	163	NC	0.57	NA	0.695	0.17	5.6	24	NC	3.7	NA	27	0.71	120

Abbreviations: Max, maximum detected concentration; Med, median; Min, minimum detected concentration; NGD, natural gas development; NC, not calculated; No., number of samples; SD, standard deviation; % > MDL, percent greater than method detection limit; µg/m³ micrograms per cubic meter; 95% UCL 95% upper confidence limit on the mean.

^a Samples collected at one site every 6 six days between 2008 and 2010.

^b Samples collected at four separate sites in summer 2008 and one site in summer 2010.

^c Calculated using EPA's ProUCL version 4.00.05 software (US EPA, 2010b).

^d Sum of 2,2,2-trimethylpentane, 2,2,4-trimethylpentane, 2,2-dimethylbutane, 2,3,4-trimethylpentane, 2,3-dimethylbutane, 2,3-dimethylpentane, 2,4-dimethylpentane, 2-methylheptane, 2-methylhexane, 2-methylpentane, 3-methylheptane, 3-methylhexane, 3-methylpentane, cyclopentane, isopentane, methylcyclopentane, n-heptane, n-octane.

^e Sum of n-decane, n-dodecane, n-tridecane, n-undecane.

^f Sum of m-diethylbenzene, m-ethyltoluene, o-ethyltoluene, p-diethylbenzene, p-ethyltoluene.

Table 2

Detection frequencies of hydrocarbons without toxicity values detected in NGD area or well completion samples.

Hydrocarbon	NGD area sample ^a detection frequency (%)	Well completion sample ^{a,b} detection frequency (%)
1-Dodecene	36	81
1-Heptene	94	100
1-Hexene	63	79
1-Nonene	52	94
1-Octene	29	75
1-Pentene	98	79
1-Tridecene	7	38
1-Undecene	28	81
2-Ethyl-1-butene	1	0
2-Methyl-1-butene	29	44
2-Methyl-1-pentene	1	6
2-Methyl-2-butene	36	69
3-Methyl-1-butene	6	6
4-Methyl-1-pentene	16	69
Acetylene	100	92
a-Pinene	63	100
b-Pinene	10	44
cis-2-Butene	58	75
cis-2-Hexene	13	81
cis-2-Pentene	38	54
Cyclopentene	44	94
Ethane	100	100
Ethylene	100	100
Isobutane	100	100
Isobutene/1-Butene	73	44
Isoprene	71	96
n-Butane	98	100
Propane	100	100
Propyne	1	0
trans-2-Butene	80	75
trans-2-Hexene	1	6
trans-2-Pentene	55	83

Abbreviations: NGD, natural gas development.

^a Samples collected at one site every 6 six days between 2008 and 2010.

^b Samples collected at four separate sites in summer 2008 and one site in summer 2010.

concentrations of hydrocarbons from well completion samples were significantly higher than concentrations from NGD area samples ($p < 0.05$) with the exception of 1,2,3-trimethylbenzene, n-pentane, 1,3-butadiene, isopropylbenzene, n-propylbenzene, propylene, and styrene (Supplemental Table 2).

3.2. Non-cancer hazard indices

Table 3 presents chronic and subchronic RfCs used in calculating non-cancer HIs, as well critical effects and other effects. Chronic non-cancer HQ and HI estimates based on ambient air concentrations are presented in Table 4. The total chronic HIs based on the 95% UCL of the mean concentration were 0.4 for residents $> \frac{1}{2}$ mile from wells and 1 for residents $\leq \frac{1}{2}$ mile from wells. Most of the chronic non-cancer hazard is attributed to neurological effects with neurological HIs of 0.3 for residents $> \frac{1}{2}$ mile from wells and 0.9 for residents $\leq \frac{1}{2}$ mile from wells.

Total subchronic non-cancer HQs and HI estimates are presented in Table 5. The total subchronic HIs based on the 95% UCL of the mean concentration were 0.2 for residents $> \frac{1}{2}$ mile from wells and 5 for residents $\leq \frac{1}{2}$ mile from wells. The subchronic non-cancer hazard for residents $> \frac{1}{2}$ mile from wells is attributed mostly to respiratory effects (HI=0.2), while the subchronic hazard for residents $\leq \frac{1}{2}$ mile from wells is attributed to neurological (HI=4), respiratory (HI=2), hematologic (HI=3), and developmental (HI=1) effects.

For residents $> \frac{1}{2}$ mile from wells, aliphatic hydrocarbons (51%), trimethylbenzenes (22%), and benzene (14%) are primary contributors to the chronic non-cancer HI. For residents $\leq \frac{1}{2}$ mile from wells,

trimethylbenzenes (45%), aliphatic hydrocarbons (32%), and xylenes (17%) are primary contributors to the chronic non-cancer HI, and trimethylbenzenes (46%), aliphatic hydrocarbons (21%) and xylenes (15%) also are primary contributors to the subchronic HI.

3.3. Cancer risks

Cancer risk estimates calculated based on measured ambient air concentrations are presented in Table 6. The cumulative cancer risks based on the 95% UCL of the mean concentration were 6 in a million for residents $> \frac{1}{2}$ from wells and 10 in a million for residents $\leq \frac{1}{2}$ mile from wells. Benzene (84%) and 1,3-butadiene (9%) were the primary contributors to cumulative cancer risk for residents $> \frac{1}{2}$ mile from wells. Benzene (67%) and ethylbenzene (27%) were the primary contributors to cumulative cancer risk for residents $\leq \frac{1}{2}$ mile from wells.

4. Discussion

Our results show that the non-cancer HI from air emissions due to natural gas development is greater for residents living closer to wells. Our greatest HI corresponds to the relatively short-term (i.e., sub-chronic), but high emission, well completion period. This HI is driven principally by exposure to trimethylbenzenes, aliphatic hydrocarbons, and xylenes, all of which have neurological and/or respiratory effects. We also calculated higher cancer risks for residents living nearer to wells as compared to residents residing further from wells. Benzene is the major contributor to lifetime excess cancer risk for both scenarios. It also is notable that these increased risk metrics are seen in an air shed that has elevated ambient levels of several measured air toxics, such as benzene (CDPHE, 2009; GCPH, 2010).

4.1. Representation of exposures from NGD

It is likely that NGD is the major source of the hydrocarbons observed in the NGD area samples used in this risk assessment. The NGD area monitoring site is located in the midst of multi-acre rural home sites and ranches. Natural gas is the only industry in the area other than agriculture. Furthermore, the site is at least 4 miles upwind from any other major emission source, including Interstate 70 and the town of Silt, Colorado. Interestingly, levels of benzene, m,p-xylene, and 1,3,5-trimethylbenzene measured at this rural monitoring site in 2009 were higher than levels measured at 27 out of 37 EPA air toxics monitoring sites where SNMOCs were measured, including urban sites such as Elizabeth, NJ, Dearborn, MI, and Tulsa, OK (GCPH, 2010; US EPA, 2009b). In addition, the 2007 Garfield County emission inventory attributes the bulk of benzene, xylene, toluene, and ethylbenzene emissions in the county to NGD, with NGD point and non-point sources contributing five times more benzene than any other emission source, including on-road vehicles, wildfires, and wood burning. The emission inventory also indicates that NGD sources (e.g. condensate tanks, drill rigs, venting during completions, fugitive emissions from wells and pipes, and compressor engines) contributed ten times more VOC emissions than any source, other than biogenic sources (e.g. plants, animals, marshes, and the earth) (CDPHE, 2009).

Emissions from flowback operations, which may include emissions from various sources on the pads such as wells and diesel engines, are likely the major source of the hydrocarbons observed in the well completion samples. These samples were collected very near (130 to 500 ft from the center) well pads during uncontrolled flowback into tanks venting directly to the air. As for the NGD area samples, no sources other than those associated with NGD were in the vicinity of the sampling locations.

Subchronic health effects, such as headaches and throat and eye irritation reported by residents during well completion activities

Table 3
Chronic and subchronic reference concentrations, critical effects, and major effects for hydrocarbons in quantitative risk assessment.

Hydrocarbon	Chronic		Subchronic		Critical effect/ target organ	Other effects
	RfC (µg/m ³)	Source	RfC (µg/m ³)	Source		
1,2,3-Trimethylbenzene	5.00E+00	PPTRV	5.00E+01	PPTRV	Neurological	Respiratory, hematological
1,3,5-Trimethylbenzene	6.00E+00	PPTRV	1.00E+01	PPTRV	Neurological	Hematological
Isopropylbenzene	4.00E+02	IRIS	9.00E+01	HEAST	Renal	Neurological, respiratory
n-Hexane	7.00E+02	IRIS	2.00E+03	PPTRV	Neurological	–
n-Nonane	2.00E+02	PPTRV	2.00E+03	PPTRV	Neurological	Respiratory
n-Pentane	1.00E+03	PPTRV	1.00E+04	PPTRV	Neurological	–
Styrene	1.00E+03	IRIS	3.00E+03	HEAST	Neurological	–
Toluene	5.00E+03	IRIS	5.00E+03	PPTRV	Neurological	Developmental, respiratory
Xylenes, total	1.00E+02	IRIS	4.00E+02	PPTRV	Neurological	Developmental, respiratory
n-propylbenzene	1.00E+03	PPTRV	1.00E+03	Chronic RfC PPTRV	Developmental	Neurological
1,2,4-Trimethylbenzene	7.00E+00	PPTRV	7.00E+01	PPTRV	Decrease in blood clotting time	Neurological, respiratory
1,3-Butadiene	2.00E+00	IRIS	2.00E+00	Chronic RfC IRIS	Reproductive	Neurological, respiratory
Propylene	3.00E+03	CalEPA	1.00E+03	Chronic RfC CalEPA	Respiratory	–
Benzene	3.00E+01	ATSDR	8.00E+01	PPTRV	Decreased lymphocyte count	Neurological, developmental, reproductive
Ethylbenzene	1.00E+03	ATSDR	9.00E+03	PPTRV	Auditory	Neurological, respiratory, renal
Cyclohexane	6.00E+03	IRIS	1.80E+04	PPTRV	Developmental	Neurological
Methylcyclohexane	3.00E+03	HEAST	3.00E+03	HEAST	Renal	–
Aliphatic hydrocarbons C ₅ –C ₈ ^a	6E+02	PPTRV	2.7E+04	PPTRV	Neurological	–
Aliphatic hydrocarbons C ₉ –C ₁₈	1E+02	PPTRV	1E+02	PPTRV	Respiratory	–
Aromatic hydrocarbons C ₉ –C ₁₈ ^b	1E+02	PPTRV	1E+03	PPTRV	Decreased maternal body weight	Respiratory

Abbreviations: 95%UCL, 95% upper confidence limit; CalEPA, California Environmental Protection Agency; HEAST, EPA Health Effects Assessment Summary Tables 1997; HQ, hazard quotient; IRIS, Integrated Risk Information System; Max, maximum; PPTRV, EPA Provisional Peer-Reviewed Toxicity Value; RfC, reference concentration; µg/m³, micrograms per cubic meter. Data from CalEPA 2011; IRIS (US EPA, 2011); ORNL 2011.

^a Based on PPTRV for commercial hexane.

^b Based on PPTRV for high flash naphtha.

occurring in Garfield County, are consistent with known health effects of many of the hydrocarbons evaluated in this analysis (COGCC, 2011; Witter et al., 2011). Inhalation of trimethylbenzenes

and xylenes can irritate the respiratory system and mucous membranes with effects ranging from eye, nose, and throat irritation to difficulty in breathing and impaired lung function (ATSDR, 2007a;

Table 4
Chronic hazard quotients and hazard indices for residents living >½ mile from wells and residents living ≤½ mile from wells.

Hydrocarbon	>½ mile		≤½ mile	
	Chronic HQ based on median concentration	Chronic HQ based on 95% UCL of mean concentration	Chronic HQ based on median concentration	Chronic HQ based on 95% UCL of mean concentration
1,2,3-Trimethylbenzene	2.09E–02	1.90E–02	2.87E–02	5.21E–02
1,2,4-Trimethylbenzene	2.51E–02	4.22E–02	3.64E–02	2.01E–01
1,3,5-Trimethylbenzene	1.96E–02	2.80E–02	3.00E–02	1.99E–01
1,3-Butadiene	5.05E–02	2.23E–02	5.05E–02	2.25E–02
Benzene	3.03E–02	5.40E–02	3.32E–02	8.70E–02
Cyclohexane	3.40E–04	9.98E–04	3.67E–04	1.46E–03
Ethylbenzene	1.63E–04	3.98E–04	1.95E–04	3.23E–03
Isopropylbenzene	3.68E–04	1.78E–04	3.90E–04	3.05E–04
Methylcyclohexane	1.18E–03	2.00E–03	1.36E–03	5.32E–03
n-Hexane	5.49E–03	9.23E–03	5.76E–03	1.47E–02
n-Nonane	2.11E–03	3.14E–03	2.95E–03	2.31E–02
n-Pentane	8.71E–03	1.32E–02	8.79E–03	2.39E–02
n-propylbenzene	9.95E–05	9.59E–05	1.28E–04	2.64E–04
Propylene	1.09E–04	1.27E–04	1.10E–04	1.30E–04
Styrene	1.43E–04	1.25E–04	1.42E–04	4.32E–04
Toluene	3.40E–04	9.28E–04	4.06E–04	1.86E–03
Xylenes, total	1.16E–02	1.57E–02	1.54E–02	1.71E–01
Aliphatic hydrocarbons C ₅ –C ₈	4.63E–02	7.02E–02	4.87E–02	1.36E–01
Aliphatic hydrocarbons C ₉ –C ₁₈	1.22E–02	1.35E–01	1.58E–02	1.83E–01
Aromatic hydrocarbons C ₉ –C ₁₈	5.44E–03	6.67E–03	7.12E–03	2.04E–02
Total Hazard Index	2E–01	4E–01	3E–01	1E+00
Neurological Effects Hazard Index ^a	2E–01	3E–01	3E–01	9E–01
Respiratory Effects Hazard Index ^b	1E–01	2E–02	2E–02	7E–01
Hematological Effects Hazard Index ^c	1E–01	1E–01	1E–01	5E–01
Developmental Effects Hazard Index ^d	4E–02	7E–02	5E–02	3E–01

Abbreviations: 95%UCL, 95% upper confidence limit; HQ, hazard quotient.

^a Sum of HQs for hydrocarbons with neurological effects: 1,2,3-Trimethylbenzene, 1,2,4-Trimethylbenzene, 1,3,5-Trimethylbenzene, 1,3-butadiene, benzene, cyclohexane, ethylbenzene, isopropylbenzene, n-hexane, n-nonane, n-pentane, n-propylbenzene, styrene, toluene, xylenes, aliphatic C₅–C₈ hydrocarbons.

^b Sum of HQs for hydrocarbons with respiratory effects: 1,2,3-Trimethylbenzene, 1,2,4-Trimethylbenzene, 1,3-butadiene, ethylbenzene, isopropylbenzene, n-nonane, propylene, toluene, xylenes, aliphatic C₉–C₁₈ hydrocarbons, aromatic C₉–C₁₈ hydrocarbons.

^c Sum of HQs for hydrocarbons with hematological effects: 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, benzene.

^d Sum of HQs for hydrocarbons with developmental effects: benzene, cyclohexane, toluene, and xylenes.

Table 5
Subchronic hazard quotients and hazard indices residents living >½ mile from wells and residents living ≤½ mile from wells.

Hydrocarbon (µg/m ³)	>½ mile		≤½ mile	
	Subchronic HQ based on median concentration	Subchronic HQ based on 95% UCL of mean concentration	Subchronic HQ based on median concentration	Subchronic HQ based on 95% UCL of mean concentration
1,2,3-Trimethylbenzene	2.09E-03	1.90E-03	1.67E-02	6.40E-02
1,2,4-Trimethylbenzene	2.51E-03	4.22E-03	2.38E-02	3.02E-01
1,3,5-Trimethylbenzene	1.18E-02	1.68E-02	1.29E-01	1.95E+00
1,3-Butadiene	5.04E-02	2.23E-02	5.25E-02	8.30E-02
Benzene	1.14E-02	2.02E-02	3.25E-02	2.55E-01
Cyclohexane	1.13E-04	3.33E-04	2.93E-04	3.24E-03
Ethylbenzene	1.81E-05	4.42E-05	8.56E-05	5.96E-03
Isopropylbenzene	1.63E-03	7.92E-04	3.62E-03	1.14E-02
Methylcyclohexane	1.18E-03	2.01E-03	4.67E-03	6.47E-02
n-Hexane	1.92E-03	3.23E-03	3.86E-03	3.98E-02
n-Nonane	2.11E-04	3.14E-04	1.80E-03	3.78E-02
n-Pentane	8.71E-04	1.32E-03	1.05E-03	2.13E-02
n-propylbenzene	9.95E-05	9.57E-05	6.36E-04	3.26E-03
Propylene	1.43E-04	3.80E-04	4.12E-04	6.02E-04
Styrene	5.68E-04	4.16E-05	4.00E-06	1.97E-03
Toluene	4.18E-05	9.28E-04	2.46E-04	1.84E-02
Xylenes, total	2.91E-03	3.93E-03	2.05E-02	7.21E-01
Aliphatic hydrocarbons C ₅ -C ₈	1.07E-03	1.63E-03	2.07E-03	2.89E-02
Aliphatic hydrocarbons C ₉ -C ₁₈	1.3E-02	1.41E-01	7.9E-02	1.03E-00
Aromatic hydrocarbons C ₉ -C ₁₈	6.00E-04	6.95E-04	3.7E-03	2.64E-02
Total Hazard Index	1E-01	2E-01	4E-01	5E+00
Neurological Effects Hazard Index ^a	9E-02	8E-02	3E-01	4E+00
Respiratory Effects Hazard Index ^b	7E-02	2E-01	2E-01	2E+00
Hematological Effects Hazard Index ^c	3E-02	4E-02	2E-01	3E+00
Developmental Effects Hazard Index ^d	1E-02	3E-02	5E-02	1E+00

Abbreviations: 95%UCL, 95% upper confidence limit; HQ, hazard quotient.

^a Sum of HQs for hydrocarbons with neurological effects: 1,2,3-Trimethylbenzene, 1,2,4-Trimethylbenzene, 1,3,5-Trimethylbenzene, 1,3-butadiene, benzene, cyclohexane, ethylbenzene, isopropylbenzene, n-hexane, n-nonane, n-pentane, n-propylbenzene, styrene, toluene, xylenes, aliphatic C₅-C₈ hydrocarbons.

^b Sum of HQs for hydrocarbons with respiratory effects: 1,2,3-Trimethylbenzene, 1,2,4-Trimethylbenzene, 1,3-butadiene, ethylbenzene, isopropylbenzene, n-nonane, propylene, toluene, xylenes, aliphatic C₉-C₁₈ hydrocarbons, aromatic C₉-C₁₈ hydrocarbons.

^c Sum of HQs for hydrocarbons with hematological effects: 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, benzene.

^d Sum of HQs for hydrocarbons with developmental effects: benzene, cyclohexane, toluene, and xylenes.

ATSDR, 2007b; US EPA, 1994). Inhalation of trimethylbenzenes, xylenes, benzene, and alkanes can adversely affect the nervous system with effects ranging from dizziness, headaches, fatigue at lower exposures to numbness in the limbs, incoordination, tremors, temporary limb paralysis, and unconsciousness at higher exposures (Carpenter et al., 1978; Nilsen et al., 1988; US EPA, 1994; Galvin and Marashi, 1999; ATSDR, 2007a; ATSDR, 2007b).

4.2. Risk assessment as a tool for health impact assessment

HIA is a policy tool used internationally that is being increasingly used in the United States to assess multiple complex hazards and exposures in communities. Comparison of risks between residents based on proximity to wells illustrates how the risk assessment process can be used to support the HIA process. An important component of the HIA process is to identify where and when public health is most likely to be impacted and to recommend mitigations to reduce or eliminate the potential

impact (Collins and Koplán, 2009). This risk assessment indicates that public health most likely would be impacted by well completion activities, particularly for residents living nearest the wells. Based on this information, suggested risk prevention strategies in the HIA are directed at minimizing exposures for those living closest to the well pads, especially during well completion activities when emissions are the highest. The HIA includes recommendations to (1) control and monitor emissions during completion transitions and flowback; (2) capture and reduce emissions through use of low or no emission flowback tanks; and (3) establish and maintain communications regarding well pad activities with the community (Witter et al., 2011).

4.3. Comparisons to other risk estimates

This risk assessment is one of the first studies in the peer-reviewed literature to provide a scientific perspective to the potential health risks associated with development of unconventional natural

Table 6
Excess cancer risks for residents living >½ mile from wells and residents living ≤½ mile from wells.

Hydrocarbon	WOE		Unit Risk (µg/m ³)	Source	>½ mile		≤½ mile	
	IRIS	IARC			Cancer risk based on median concentration	Cancer risk based on 95% UCL of mean concentration	Cancer risk based on median concentration	Cancer risk based on 95% UCL of mean concentration
1,3-Butadiene	B2	1	3.00E-05	IRIS	1.30E-06	5.73E-07	1.30E-06	6.54E-07
Benzene	A	1	7.80E-06	IRIS	3.03E-06	5.40E-06	3.33E-06	8.74E-06
Ethylbenzene	NC	2B	2.50E-06	CalEPA	1.75E-07	4.26E-07	2.09E-07	3.48E-06
Styrene	NC	2B	5.00E-07	CEP	3.10E-08	2.70E-08	3.00E-08	9.30E-08
Cumulative cancer risk					5E-06	6E-06	5E-06	1E-05

Abbreviations: 95%UCL, 95% upper confidence limit; CalEPA, California Environmental Protection Agency; CEP, (Caldwell et al., 1998); IARC, International Agency for Research on Cancer; IRIS, Integrated Risk Information System; Max, maximum; NC, not calculated; WOE, weight of evidence; µg/m³, micrograms per cubic meter. Data from CalEPA 2011; IRIS (US EPA, 2011).

gas resources. Our results for chronic non-cancer HIs and cancer risks for residents > than ½ mile from wells are similar to those reported for NGD areas in the relatively few previous risk assessments in the non-peer reviewed literature that have addressed this issue (CDPHE, 2010; Coons and Walker, 2008; CDPHE, 2007; Walther, 2011). Our risk assessment differs from these previous risk assessments in that it is the first to separately examine residential populations nearer versus further from wells and to report health impact of emissions resulting from well completions. It also adds information on exposure to air emissions from development of these resources. These data show that it is important to include air pollution in the national dialogue on unconventional NGD that, to date, has largely focused on water exposures to hydraulic fracturing chemicals.

4.4. Limitations

As with all risk assessments, scientific limitations may lead to an over- or underestimation of the actual risks. Factors that may lead to overestimation of risk include use of: 1) 95% UCL on the mean exposure concentrations; 2) maximum detected values for 1,3-butadiene, 2,2,4-trimethylpentane, and styrene because of a low number of detectable measurements; 3) default RME exposure assumptions, such as an exposure time of 24 h per day and exposure frequency of 350 days per year; and 4) upper bound cancer risk and non-cancer toxicity values for some of our major risk drivers. The benzene IUR, for example, is based on the high end of a range of maximum likelihood values and includes uncertainty factors to account for limitations in the epidemiological studies for the dose–response and exposure data (US EPA, 2011). Similarly, the xylene chronic RFC is adjusted by a factor of 300 to account for uncertainties in extrapolating from animal studies, variability of sensitivity in humans, and extrapolating from subchronic studies (US EPA, 2011). Our use of chronic RFCs values when subchronic RFCs were not available may also have overestimated 1,3-butadiene, n-propylbenzene, and propylene subchronic HQs. None of these three chemicals, however, were primary contributors to the subchronic HI, so their overall effect on the HI is relatively small.

Several factors may have led to an underestimation of risk in our study results. We were not able to completely characterize exposures because several criteria or hazardous air pollutants directly associated with the NGD process via emissions from wells or equipment used to develop wells, including formaldehyde, acetaldehyde, crotonaldehyde, naphthalene, particulate matter, and polycyclic aromatic hydrocarbons, were not measured. No toxicity values appropriate for quantitative risk assessment were available for assessing the risk to several alkenes and low molecular weight alkanes (particularly <C₅ aliphatic hydrocarbons). While at low concentrations the toxicity of alkanes and alkenes is generally considered to be minimal (Sandmeyer, 1981), the maximum concentrations of several low molecular weight alkanes measured in the well completion samples exceeded the 200–1000 µg/m³ range of the RFCs for the three alkanes with toxicity values: n-hexane, n-pentane, and n-nonane (US EPA, 2011; ORNL, 2009). We did not consider health effects from acute (i.e., less than 1 h) exposures to peak hydrocarbon emissions because there were no appropriate measurements. Previous risk assessments have estimated an acute HQ of 6 from benzene in grab samples collected when residents noticed odors they attributed to NGD (CDPHE, 2007). We did not include ozone or other potentially relevant exposure pathways such as ingestion of water and inhalation of dust in this risk assessment because of a lack of available data. Elevated concentrations of ozone precursors (specifically, VOCs and nitrogen oxides) have been observed in Garfield County's NGD area and the 8-h average ozone concentration has periodically approached the 75 ppb National Ambient Air Quality Standard (NAAQS) (CDPHE, 2009; GCPH, 2010).

This risk assessment also was limited by the spatial and temporal scope of available monitoring data. For the estimated chronic exposure, we used 3 years of monitoring data to estimate exposures over a 30 year exposure period and a relatively small database of 24 samples collected at varying distances up to 500 ft from a well head (which also were used to estimate shorter-term non-cancer hazard index). Our estimated 20-month subchronic exposure was limited to samples collected in the summer, which may have not captured temporal variation in well completion emissions. Our ½ mile cut point for defining the two different exposed populations in our exposure scenarios was based on complaint reports from residents living within ½ mile of existing NGD, which were the only data available. The actual distance at which residents may experience greater exposures from air emissions may be less than or greater than a ½ mile, depending on dispersion and local topography and meteorology. This lack of spatially and temporally appropriate data increases the uncertainty associated with the results.

Lastly, this risk assessment was limited in that appropriate data were not available for apportionment to specific sources within NGD (e.g. diesel emissions, the natural gas resource itself, emissions from tanks, etc.). This increases the uncertainty in the potential effectiveness of risk mitigation options.

These limitations and uncertainties in our risk assessment highlight the preliminary nature of our results. However, there is more certainty in the comparison of the risks between the populations and in the comparison of subchronic to chronic exposures because the limitations and uncertainties similarly affected the risk estimates.

4.5. Next steps

Further studies are warranted, in order to reduce the uncertainties in the health effects of exposures to NGD air emissions, to better direct efforts to prevent exposures, and thus address the limitations of this risk assessment. Next steps should include the modeling of short- and longer-term exposures as well as collection of area, residential, and personal exposure data, particularly for peak short-term emissions. Furthermore, studies should examine the toxicity of hydrocarbons, such as alkanes, including health effects of mixtures of HAPs and other air pollutants associated with NGD. Emissions from specific emission sources should be characterized and include development of dispersion profiles of HAPs. This emissions data, when coupled with information on local meteorological conditions and topography, can help provide guidance on minimum distances needed to protect occupant health in nearby homes, schools, and businesses. Studies that incorporate all relevant pathways and exposure scenarios, including occupational exposures, are needed to better understand the impacts of NGD of unconventional resources, such as tight sands and shale, on public health. Prospective medical monitoring and surveillance for potential air pollution-related health effects is needed for populations living in areas near the development of unconventional natural gas resources.

5. Conclusions

Risk assessment can be used as a tool in HIAs to identify where and when public health is most likely to be impacted and to inform risk prevention strategies directed towards efficient reduction of negative health impacts. These preliminary results indicate that health effects resulting from air emissions during development of unconventional natural gas resources are most likely to occur in residents living nearest to the well pads and warrant further study. Risk prevention efforts should be directed towards reducing air emission exposures for persons living and working near wells during well completions.

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RESEARCH ARTICLE

Childhood hematologic cancer and residential proximity to oil and gas development

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Abstract

Background

Oil and gas development emits known hematological carcinogens, such as benzene, and increasingly occurs in residential areas. We explored whether residential proximity to oil and gas development was associated with risk for hematologic cancers using a registry-based case-control study design.

Methods

Participants were 0–24 years old, living in rural Colorado, and diagnosed with cancer between 2001–2013. For each child in our study, we calculated inverse distance weighted (IDW) oil and gas well counts within a 16.1-kilometer radius of residence at cancer diagnosis for each year in a 10 year latency period to estimate density of oil and gas development. Logistic regression, adjusted for age, race, gender, income, and elevation was used to estimate associations across IDW well count tertiles for 87 acute lymphocytic leukemia (ALL) cases and 50 non-Hodgkin lymphoma (NHL) cases, compared to 528 controls with non-hematologic cancers.

Findings

Overall, ALL cases 0–24 years old were more likely to live in the highest IDW well count tertiles compared to controls, but findings differed substantially by age. For ages 5–24, ALL cases were 4.3 times as likely to live in the highest tertile, compared to controls (95% CI: 1.1 to 16), with a monotonic increase in risk across tertiles (trend p-value = 0.035). Further adjustment for year of diagnosis increased the association. No association was found between ALL for children aged 0–4 years or NHL and IDW well counts. While our study benefited from the ability to select cases and controls from the same population, use of cancer-controls, the limited number of ALL and NHL cases, and aggregation of ages into five year ranges, may have biased our associations toward the null. In addition, absence of

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Data Availability Statement: Data on the oil and gas well locations used in the Childhood and Oil and Gas development are available in Supplemental Material [S1 Table](#). Data on the distances of the wells from the participants, as well as cancer outcome and co-variables are available from the Colorado Department of Public Health and Environment Health Statistics and Evaluation Branch (cdphe.healthstatistics@state.co.us; 303-692-2160) to researchers who meet their criteria for access to confidential data.

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information on O&G well activities, meteorology, and topography likely reduced temporal and spatial specificity in IDW well counts.

Conclusion

Because oil and gas development has potential to expose a large population to known hematologic carcinogens, further study is clearly needed to substantiate both our positive and negative findings. Future studies should incorporate information on oil and gas development activities and production levels, as well as levels of specific pollutants of interest (e.g. benzene) near homes, schools, and day care centers; provide age-specific residential histories; compare cases to controls without cancer; and address other potential confounders, and environmental stressors.

Introduction

Among U.S. children ages 0–14, acute lymphocytic leukemia (ALL) is the most commonly diagnosed cancer, and non-Hodgkin lymphoma (NHL) is the most common lymphoma [1]. While ALL and NHL mortality rates in U.S. children are declining due to improved treatment, ALL and NHL incidence rates have increased by about 1% and 0.6% per year, respectively, between 2000 and 2010 [2, 3].

A number of factors, including genetic predisposition and susceptibility, as well as environmental factors, come together in the development of childhood cancers through a two step process, the first of which likely occurs in utero [4]. Environmental factors that may be associated with ALL include in-utero and postnatal exposures to vehicle exhaust fumes [5, 6], polycyclic aromatic hydrocarbons [7,8], and chemicals including benzene and other hydrocarbons [8–11]. Environmental factors that may be associated with NHL include benzene exposures [12].

U.S. oil and gas development has grown rapidly over the past 15 years. This industrial activity, which includes drilling, hydraulic fracturing, and production, has the potential to emit chemicals that may be associated with childhood ALL and/or NHL, including benzene and other hydrocarbons, polycyclic aromatic hydrocarbons, and diesel exhaust, into the air and water [13–18]. The use of hydraulic fracturing and horizontal drilling has facilitated extraction of petroleum reserves from shale and other tight formations, resulting in an extensive de-centralized dispersion of oil and gas wells and associated facilities across populated areas [19]. This has the potential to expose a large population to oil and gas development related pollutants. It is estimated that over 15.3 million Americans now live within 1.6 kilometers of an oil and gas well drilled since the year 2000 [19]. In Colorado's most intensive areas of oil and gas development, there may be hundreds of oil and gas wells within 1.6 kilometers of a home. The existing literature indicates that populations living in areas with oil and gas development may be at an increased risk for health effects, including cancers such as ALL and NHL, resulting from these exposures [20].

Previous ecological studies on the link between childhood cancer and oil and gas development are inconclusive because they aggregated cancer outcomes and exposures and did not consider latency periods and differentiate between types of leukemias [21, 22]. This analysis addresses these limitations by comparing individual-level residence of incident cancer cases to geocoded oil and gas well locations over a 10-year latency period using a registry based case-control approach to explore if children living near oil and gas development may be at higher

risk for childhood ALL and NHL compared to children diagnosed with non-hematologic malignancies and to inform the design of more comprehensive studies.

Methods

Study population

Childhood incidence cancer data for children diagnosed with cancer between 2001 and 2013 were obtained from the Colorado Central Cancer Registry (CCCR) [23] held at the Colorado Department of Public Health and Environment (CDPHE). Our study population consisted of 975 children in the registry diagnosed with cancer at ages 0–24 years, and residing in rural Colorado at the time of diagnosis. Subjects aged 15–24 years were included in the study to account for a possible 10 year latency period between childhood exposures before the age of 15 and onset of cancer [24–27]. We restricted analysis to cancers occurring from 2001–2013 to focus our analysis on growth of hydraulic fracturing and/or directional drilling, which expanded rapidly in Colorado beginning around the year 2000 [28]. This rapid expansion resulted in a twofold increase in active oil and gas wells in Colorado between 2000 and 2013; by 2013, Colorado had more than 51,000 oil and gas wells. We restricted the study area to rural areas and towns with populations of <50,000 in 57 counties to reduce potential for exposure to other pollution sources, such as traffic, and other industrial sources. Geocoded precise addresses were not available for 232 children (including 17 and 15 children diagnosed with ALL and NHL, respectively), so those children were excluded from the study (e.g., addresses not listed, specified as rural routes, or only as post office boxes). Using the final study group of 743 children, we conducted two separate registry-based case control studies to explore associations between childhood hematologic cancers and density of oil and gas development operations around the child's residence. Cases were children with ALL or NHL. Because we only had access to records in the CCCR for this exploratory study, controls were all children registered in the CCCR with a non-hematologic cancer, as has been done in previous registry based studies [29–32].

Exposure to oil and gas wells

We used information available in the publically accessible Colorado Oil and Gas Information System (COGIS) [33] to build a geocoded dataset with latitude and longitude coordinates of oil and gas wells in rural Colorado, and determined whether or not each well was active for each year between 1991 and 2013, as defined by the Colorado Oil and Gas Conservation Commission (COGCC) [28] (see [S1 Table](#)). The COGCC considers oil and gas wells to be active between the spud-in and abandon dates. "Spud-in" is the operation of drilling the first part of a new well; "abandon" is the permanent plugging of a well [28]. No spud-date is recorded for 28% of oil and gas wells in the COGIS. If a spud-in date was not available for a well, we used the earliest date available from other oil and gas activities which follow the spud-in (e.g., completion, first production, and treatment dates) to designate the beginning of the active well period. We provided this dataset of geocoded well locations to CDPHE staff.

To protect the identity of the children in the study, CDPHE staff linked the well locations in the dataset we provided to each child's address in the registry. Geocoded residential addresses at time of cancer diagnosis were linked to active well locations in the year of diagnosis, as well as active well locations in each of the 10 years preceding the cancer diagnosis. Distance of each residence from all active oil and gas wells within a 16.1-kilometer radius was then computed using spherically-adjusted straight line distances, to account for the Earth's curvature. Ages were truncated into five year ranges (0–4, 5–9, 10–14, 15–19, and 20–24 years) to further protect identity. The CDPHE staff then provided the analyst (LMM) with a de-identified dataset,

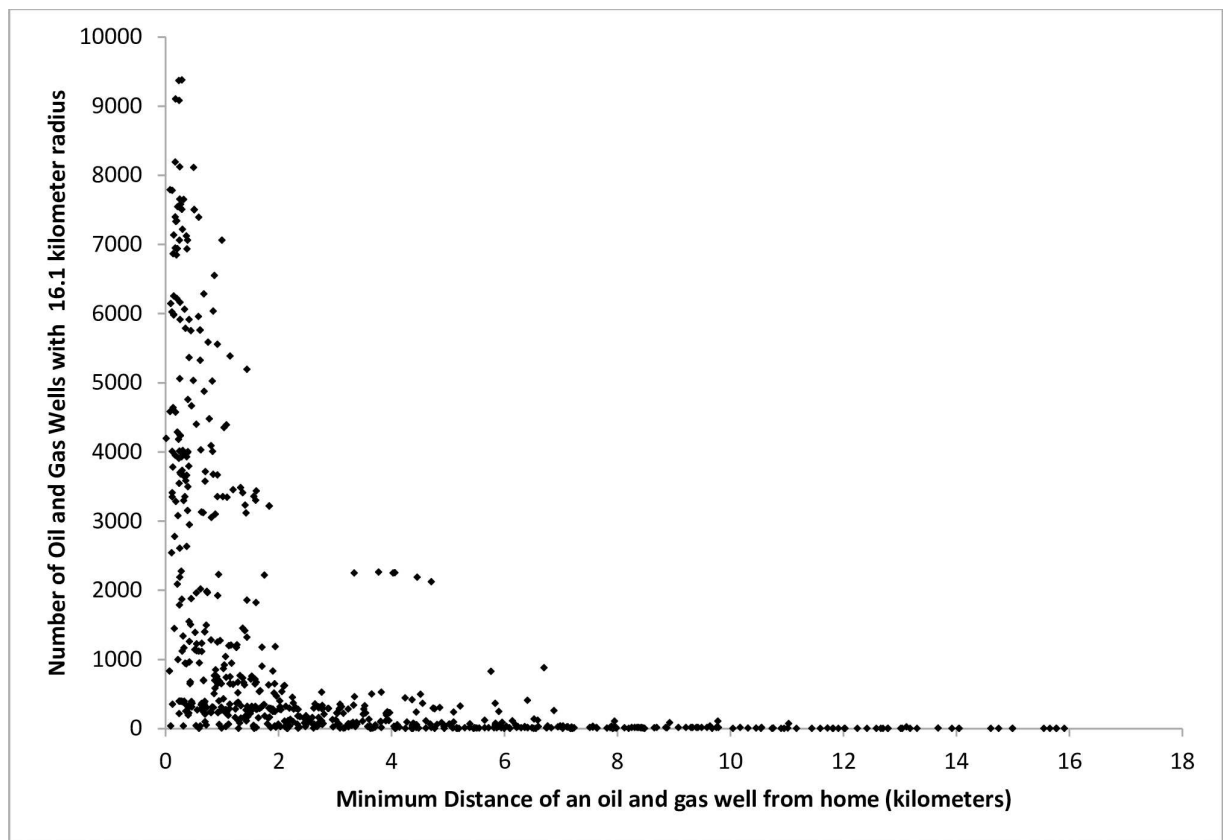


Fig 1. Number of oil and gas wells in 16.1-kilometer radius from a child's home versus the minimum distance of an oil and gas well from the child's home for children with at least one oil and gas well within the 16.1-kilometer radius.

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containing subject diagnosis, age group, gender, race/ethnicity, income quintile at zip code level, residential elevation, maternal smoking history (from linkages with birth certificates), and distance to each active oil and gas well within a 16.1-kilometer radius.

Because the number of wells is not associated with distance of the nearest well in the 16.1-kilometer radius around a child's home (Fig 1), we used an inverse distance weighted (IDW) approach to estimate the density of oil and gas wells surrounding a child's home. The IDW approach is commonly used to estimate individual air pollutant exposures from multiple fixed locations [34–36]. Annual IDW well counts account for the number of active wells within the 16.1-kilometer radius [36, 37] of the residence in a specific year as well as distance of each well from the residence, giving greater weight to wells closest to the residence. For example, an IDW well count of 78.1 wells per kilometer could be computed from 125 wells each located 1.6 kilometers from the maternal residence or 25 wells each located 0.32 kilometers from the child's residence.

Based on the latency period between exposure to benzene and diagnosis of leukemia of 1 to 10 years [24–27], we computed weighted average IDW well counts (referred to herein as IDW well count) over a 10 year period to capture IDW wells counts during the antenatal period and childhood. Because we had age ranges rather than specific ages, we averaged the annual IDW well count over a temporal range that would capture the latency period for five age categories as follows. For children aged 0–4 years, annual IDW well counts for 1–5 years prior to diagnosis

were averaged over 5 years. For children aged 5–9, 10–14 and 15–19 years, annual IDW well counts for 1–10 years prior to diagnosis were averaged over 10 years. For young adults 20–24 years, annual IDW well counts 6–10 years prior to diagnosis were averaged over 5 years to account for childhood exposures (i.e., occurring prior to age fifteen). If no wells existed within 16.1-kilometers of a child's home during the latency period for each age range, the weighted average IDW well count was 0. The final distribution of the non-zero IDW well counts was then divided into tertiles (low, medium, and high) for subsequent logistic regression. Each tertile was compared to the referent group of an IDW well count of zero.

Analysis

Childhood cancer outcomes considered for analysis were ALL (first primary tumor, includes Burkitt leukemia) (87 cases), and NHL nodal and extra-nodal (includes Burkitt and lymphoblastic lymphomas regardless of bone marrow involvement) (50 cases). The number of cases for other types of leukemia (<15 cases for each type including acute myeloid leukemia, and 26 cases combined) was too small to analyze individually. Cases diagnosed with other leukemia types ($n = 26$) and those with Hodgkin lymphoma ($n = 52$) were excluded from the control group. Case-control analyses were conducted separately for ALL and NHL. A total of 528 controls for each of these cancer outcomes included all children reported in the CCCR with non-hematologic cancers, (Table 1).

Statistical analysis

We used logistic regression to study associations between case-control status and IDW well count tertiles. First, we estimated the crude odds ratio (OR) associated with IDW well counts tertiles. We further investigated associations by adjusting for potential confounders, as well as child covariates, based on *a priori* knowledge of their association with both exposure and outcome. We conducted tests to evaluate linear trends in binominal proportions with increasing IDW well count by treating the categorical IDW well count variable as ordinal [38]. Specifically, covariates in our analysis were age category (0–4, 5–9, 10–14, 15–19, and 20–24 years) [1,4], race/ethnicity (white Hispanic, white non-Hispanic, non-white) [1], and gender [1]. Because the age range 0–4 years and ≥ 5 years may represent two distinct disease etiologies for ALL [4], we analyzed separately for children ages 0–4 years and ≥ 5 years. We adjusted for elevation of residence (< 2743 meters, ≥ 2743 meters because residential solar ultraviolet radiation exposure, which increases with elevation [39], may be associated with ALL [40]. We also adjusted for socio-economic status by distributing zip-code level median income into quintiles (0–20, 21–40, 41–60, 61–80, and 81–100 percentiles) [5]. In a second model, we further adjusted for year of cancer diagnosis (2001–2002, 2003–2004, 2005–2006, 2007–2008, 2009–2010, 2011–2013). We did not adjust for maternal smoking during pregnancy in the primary analyses because information on maternal smoking was missing for 59% of the study population. We report estimations for each outcome associated with the IDW well count tertile (low, medium, and high) compared to no wells within 16.1-kilometers with 95% confidence intervals (CI). We considered both the statistical significance of the association for each IDW well count category as well as the trend across categories in evaluating results, using a 2-sided alpha of 0.05.

In secondary analyses, we explored reducing IDW well counts to an 8-kilometer buffer around the maternal residence, as well as analyzing the subset of subjects with information on maternal smoking and adjusting for maternal smoking during pregnancy. All statistical analyses were conducted using SAS® software version 9.3 (Cary, NC). To further protect the identity of study participants we truncated counts of less than 5 to “<5” in result tables. The

Table 1. Cancer sites for children in rural Colorado 2001 to 2013¹.

Cancer Site ²	Frequency
Blood and lymph system	
-acute lymphocytic leukemia	104
-Hodgkin lymphoma	65
-non-Hodgkin lymphoma	65
-acute myeloid leukemia	18
-myeloma, other lymphocytic leukemia, chronic myeloid leukemia, other myeloid/monocytic leukemia, other acute leukemia, aleukemic,subleukemic and NOS	<5 of each
Nervous System (brain, cranial and other)	169
Endocrine System	136
Male genitals	
-testes	75
-penis	<5
Skin	
-Melanomas	76
-Other skin cancers	<5
Soft Tissue (including heart)	46
Bones and joints	42
Female genitals	
-Ovary	16
-Cervix Uteri	14
-Vagina, vulva, other	< 5 of each
Urinary System	
-kidney and renal pelvis	30
-bladder	< 5
Eye and orbit	15
Digestive System	
-liver	6
-esophagus, stomach, small intestine, appendix, colon and rectum, pancreas, retroperitoneum,cecum	< 5 each
Respiratory	
- lung and bronchus	7
-trachea, mediastinum and other respiratory; nose, nasal cavity, and middle ear; larynx	< 5 of each
Breast	8
Oral Cavity and Pharynx (tongue, salivary glands, gum, nasopharynx)	<5 of each

¹Includes children without geocoded addresses.

²17 cancers were classified as miscellaneous and less than 5 were classified as invalid.

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Colorado Multiple Institutional Review Board reviewed and approved our specific protocol for this study as exempt from human subjects research (COMIRB Protocol 14–1978). We (the researchers) only had access to de-identified data from the Colorado Cancer Registry which had been previously collected for reasons other than research and the data we analyzed anonymously.

Results

Geocoded addresses were missing for 24% of our study population, with a higher proportion missing for white Hispanics and young adults aged 19–24 years, as well as controls (Table 2).

Table 2. Study population characteristics for children residing in rural Colorado and diagnosed with cancer between 2001 and 2013 by case control status.

	NotGeocoded ^a	Geocoded	Geocoded ALL Cases	Geocoded NHL Cases	Geocoded Controls ^b
Number of children (n)	232	743	87	50	528
Race/Ethnicity (% of children)					
White—Non-Hispanic	76	76	77	78	77
White—Hispanic	21	15	12	<10	17
Non-white	2.8	7.8	12	16	5.7
Missing	6	0.67	0	0	0.95
Gender (% of total)					
Male	52	52	60	68	50
Elevation of residence (% of children)					
< 1524 meters	NA	31	37	32	31
1524–1828 meters	NA	27	25	28	25
1829–2133 meters	NA	19	20	24	19
2134–2437 meters	NA	14	8.0	12	16
2438–2742 meters	NA	5.4	<6	<10	6.1
2743meters or higher	NA	3.9	6.9	<10	3.4
Age range (% of children)					
0–4 years	16	20	45	10	18
5–9 years	11	9.7	26	18	6.4
10–14 years	12	12	14	18	12
15–19 years ^c	15	23	11	22	24
20–24 years ^d	46	35	<6	32	39
Zip code median income quintiles (% of children)					
0–20	7.0	9.2	9.2	<10	9.2
21–40	21	25	21	18	26
41–60	22	14	14	26	14
61–80	25	27	25	32	28
81–100	24	24	31	20	24
Year of Diagnosis (% of children)					
2001–2002	22	13	10	<10	13
2003–2004	16	16	18	22	15
2005–2006	16	14	15	14	13
2007–2008	12	16	20	12	16
2009–2010	13	18	14	24	19
2011–2013	20	23	23	18	23

^aGeocoded addresses were not 0061available (e.g., addresses not listed, or specified as rural routes or post office boxes) for 16% of ALL cases, 23% of NHL cases and 28% of controls.

^bDiagnosed with non-hematologic cancer (See Table 1).

^cChildren from 15 to 19 years were included in the study to account for a latency period of 10 years between exposure and onset of cancer.

^dChildren from 20–24 years were included in the study to account for a latency period of 10 years between exposure and onset of cancer.

NA = not available.

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The ALL cases were more likely than controls to be < 10 years of age, male, a non-white race, to live at an elevation > 2743 meters, and in the highest zip code median income quintile (Table 2). The NHL cases were more likely than controls to be 5–14 years of age, male, a non-

Table 3. Study population characteristics for children residing in rural Colorado with a geocoded address and diagnosed with cancer between 2001 and 2013 by exposure group.

	No Wells within 16.1 Kilometers	Exposure Tertiles		
		Low ^a	Medium ^a	High ^a
Number of children (n)	199	180	179	185
Race/Ethnicity (% of children)				
White—Non-Hispanic	75	78	79	74
White—Hispanic	17	14	13	17
Non-white	8.0	6.7	7.8	8.6
Missing	0	1.1	< 1	1.1
Gender (% of children)				
Male	55	45	55	56
Elevation of residence (% of children)				
< 1524 meters	10	35	37	45
1524–1828 meters	16	19	33	39
1829–2133 meters	11	31	26	11
2134–2437 meters	32	13	3.9	4.9
2438–2742 meters	18	2.2	0.56	0
2743meters or higher	15	0	0	0
Age range (% of children)				
0–4 years	14	21	18	26
5–9 years	9.1	6.1	12	11
10–14 years	11	11	16	13
15–19 years ^b	26	24	21	19
20–24 years ^c	41	37	32	30
Zip code median income quintiles (% of children)				
0–20	17	10	7.2	0
21–40	33	28	35	5.4
41–60	9.1	11	28	8.1
61–80	19	29	17	44
81–100	20	22	12	43
Year of Diagnosis (% of children)				
2001–2002	11	17	12	12
2003–2004	13	18	17	17
2005–2006	17	8.9	17	13
2007–2008	18	18	14	15
2009–2010	16	21	19	16
2011–2013	26	18	21	26

^a Low = first tertile, < 4.96 wells per 1.6 kilometers, medium = second tertile, 4.96 to 33.6 wells per 1.6 kilometers high = third tertile, more than 33.6 wells per 1.6 kilometers.

^bChildren from 15 to 19 years were included in the study to account for a latency period of 10 years between exposure and onset of cancer.

^cChildren from 20 to 24 years were included in the study to account for a latency period of 10 years between exposure and onset of cancer.

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white race, and to live in the middle zip code median income quintiles (Table 2). In the final study population of 743 children with cancer, 73% resided in a home within one of the IDW well count tertiles (≥ 1 active oil and gas well in a 16.1-kilometer radius) (Table 3). The IDW well counts were higher for children living at lower elevations (< 2134 meters), among children aged 0–4 years, and for children in the high zip code median income quintiles (Table 3).

Table 4. Association between annual inverse distance weighted well count within 16.1-kilometer radius of residence at diagnosis averaged over exposure period and acute lymphocytic leukemia (ALL).

Inverse Distance Weighted Well Count ^a	0 Wells within 16.1 Kilometers	Low ^a	Medium ^a	High ^a	P-value trend tests ^b
Total Study Population (0 to 24 years)					
Cases (N)	15 (9.2%)	21 (14%)	26 (18%)	25 (16%)	
Controls (N)	147	132	119	130	
Crude OR	1.0	1.6 (0.77, 3.1)	2.1 (1.1, 4.2)	1.9 (0.95, 3.7)	
Model 1 Adjusted OR (95% CI) ^c	1.0	2.3 (0.94, 5.5)	2.6 (1.1, 6.3)	1.9 (0.78, 4.8)	0.22
Model 2 Adjusted OR (95% CI) ^d	1.0	2.5 (1.0, 6.1)	2.8 (1.2, 6.8)	2.0 (0.80, 5.0)	0.21
5 to 24 Years					
Cases (N)	8 (5.9%)	9 (7.7%)	15 (13%)	16 (14%)	
Controls (N)	128	108	99	96	
Crude OR	1.0	1.3 (0.50, 3.6)	2.4 (0.99, 5.9)	2.7 (1.1, 6.5)	
Model 1 Adjusted OR (95% CI) ^c	1.0	2.9 (0.80, 11)	3.4 (0.99, 12)	4.3 (1.1, 16)	0.035
Model 2 Adjusted OR (95% CI) ^d	1.0	3.2 (0.84, 13)	3.6 (1.0, 13)	4.6 (1.2, 18)	0.032
0 to 4 Years					
Cases (N)	7 (26%)	12 (33%)	11 (35%)	9 (21%)	
Controls (N)	19	24	20	34	
Crude OR	1.0	1.4 (0.45, 4.1)	1.5 (0.48, 4.7)	0.72 (0.23, 2.2)	
Model 1 Adjusted OR (95% CI) ^e	1.0	1.7 (0.44, 6.5)	2.3 (0.57, 9.4)	0.73 (0.18, 3.0)	0.50
Model 2 Adjusted OR (95% CI) ^f	1.0	1.5 (0.38, 5.9)	2.3 (0.58, 9.4)	0.51 (0.12, 2.2)	0.31

^a All age groups: low = first tertile, < 4.9 wells per 1.6 kilometers, medium = second tertile, 4.9 to 33.6 wells per 1.6 kilometers, high = third tertile, more than 33.6 wells per 1.6 kilometers.

^b Trend tests performed by treating categorical inverse-distance well count as an ordinal.

^c Adjusted for age, race, gender, socioeconomic status, and elevation.

^d Adjusted for age, race, gender, socioeconomic status, elevation, and year of diagnosis.

^e Adjusted for race, gender, socioeconomic status, and elevation.

^f Adjusted for race, gender, socioeconomic status, elevation, and year of diagnosis.

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Both crude and adjusted estimates indicate an increase in odds of living near oil and gas development at the time of cancer diagnosis, as represented by IDW well counts, in children diagnosed with ALL (Table 4; see S2 and S3 Tables for the full logistic models). Overall, children aged 0–24 years diagnosed with ALL were more than 2 times as likely as controls to live in areas with active oil and gas wells within 16.1-kilometers of their residence during the latency period (p for trend = 0.22) after adjusting for age, race, gender, income, and elevation in model 1. Children aged 5–24 years diagnosed with ALL were 4.3 (95% CI: 1.1 to 16) times as likely as controls to live in the highest IDW well count tertile, and a monotonic increase across the IDW well count tertiles was observed (p for trend = 0.035) (Table 4). Further adjustment for year of diagnosis in model 2 resulted in slightly larger associations. We observed no statistically significant association between ALL and proximity to oil and gas development in our analysis of ALL for children ages 0–4 years in either model.

In secondary analyses using an 8-kilometer radius, results for cases of ALL ages 5–24 years and ages 0–4 years were similar to the primary analysis (S4 Table). In secondary analyses on the subset of children for whom information on maternal smoking was available, we observed similar associations to our primary analysis, with little evidence for confounding by maternal smoking history (S5 Table).

We observed no statistically significant associations between density of oil and gas development and NHL in either model, based on trend analysis across categorical IDW well counts

Table 5. Association between annual inverse distance weighted well count within 16.1 kilometer radius of residence at diagnosis averaged over the exposure period and non-Hodgkins lymphoma (NHL).

Inverse Distance Weighted Well Count	0 Wells within 16.1 Kilometers	Low ^a	Medium ^a	High ^a	P-value for trend tests ^b
Cases (N)	13 (8.1%)	13 (9.0%)	11 (8.5%)	13 (9.0%)	
Controls (N)	147	132	119	130	
Crude OR	1.0	1.1 (0.50, 2.5)	1.0 (0.45, 2.4)	1.1 (0.51, 2.5)	
Model 1 Adjusted OR (95% CI) ^c	1.0	1.2 (0.51, 2.9)	0.71 (0.28, 1.8)	1.0 (0.41, 2.6)	0.89
Model 2 Adjusted OR (95% CI) ^d	1.0	1.2 (0.49, 2.8)	0.63 (0.25, 1.6)	0.99 (0.39, 2.5)	0.61

^a low = first tertile, < 4.9 wells per 1.6 kilometers, medium = second tertile, 4.9 to 33.6 wells per 1.6 kilometers, high = third tertile, more than 33.6 wells per 1.6 kilometers.

^bTrend tests performed by treating categorical inverse-distance well count as an ordinal.

^cAdjusted for age, race, gender, socioeconomic status and elevation.

^dAdjusted for age, race, gender, socioeconomic status, elevation, and year of diagnosis.

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(Table 5) (see S6 and S7 Tables for the full logistic models). The observed outcomes for NHL from the analyses using an 8-kilometer radius or in the subsets of subjects with information on maternal smoking did not change the inferences drawn from the primary analysis (see S8 and S9 Tables).

Discussion

In this registry-based case-control study, we found that children aged 5–24 years diagnosed with ALL were 3–4 times as likely to live in areas with active oil and gas wells as were children diagnosed with non-hematologic cancers, and the association between ALL and residential density of oil and gas wells increased monotonically from the lowest to highest IDW well count categories after adjusting for age, race, gender, socioeconomic status, and elevation. Further adjustment for year of cancer diagnosis resulted in a slightly larger association in children aged 5–24 years. We did not observe an association between ALL and density of active oil and gas wells in children aged 0–4 years. We found no indication of an association between NHL and density of active oil and gas wells.

In model 2, we categorized year of cancer diagnosis into six categories each containing two to three diagnosis years (Table 2). We note that if diagnosis year is not aggregated into six categories, the association in children aged 5–24 years attenuates to 3.6 (CI: 0.93, 14) and the p-value for the trend is 0.056 (S10 Table). Aggregating diagnosis year results in 13 categories, several of which have <5 observations. In a small data set such as the data set for the 5–24 year age group, minor changes to subsets of the data with < 5 observations can easily lead to p-values switching from 0.03 to 0.06 or vice-versa. We selected the model with diagnosis year categorized into six categories because it is the more robust model.

Our analysis addressed the limitations of previous studies. The case-control design allowed us to evaluate individual outcomes and IDW well counts; and we considered a 1–10 year latency period and one specific type of childhood leukemia, rather than grouping all leukemias, in our analysis. An ecological study on childhood cancer incidence associated with hydraulic fracturing sites in Pennsylvania found no differences between childhood leukemia incidence before and after hydraulic fracturing began in several Pennsylvania counties [21]. That study aggregated all leukemia cases at the county level, and did not fully consider a latency period [41]. An ecological study in Texas aggregated cases at the zip-code level, finding higher childhood ALL incidence rates than expected in two zip codes with oil and gas development, but that difference was not statistically significant with only 11 cases [22].

It is thought that less than 5% of leukemia is attributed to only inherited genetic predisposition [4]; that genetic susceptibility and environmental factors combine in the development of ALL [4]; and that the etiology of infant ALL (<1 year) may differ from that of childhood ALL [42, 43]. Most infant ALL may develop through a one step process, the initiation of preleukemic clone involving MLL gene rearrangement at 11q23 in utero [4, 42–44]. Childhood ALL is thought to develop through a two step process [4, 43, 44], in which the first step also occurs in utero, with initiation of a preleukemic clone most often involving other gene rearrangements (e.g., TEL_AML rearrangements) [4, 42, 45]. The role played by chance versus other factors in the generation of in-utero preleukemic clones in both infant and childhood ALL is unclear [4]. The second step for childhood ALL, which possibly involves an interaction between genetic susceptibility and environmental factors post-utero, converts the preleukemic clone to leukemia [4, 42, 46]. This two step process may partially explain why we observed stronger associations between ALL and density of oil and gas development when we evaluated children ages 5 to 24 years than among those ages 0–4 years, which includes infant ALL.

One possible environmental risk factor for childhood ALL that is associated with oil and gas development is exposure to benzene and other petroleum hydrocarbons. Ambient air benzene levels in Colorado areas with active oil and gas development ranged from 0.03–22 parts per billion by volume (ppbv). Median benzene concentrations ranged from 0.212–0.757 ppbv which are greater than the Environmental Protection Agency's (EPA) risk based screening level (RBSL) of 0.102 ppbv for benzene in residential air [18, 20, 47–50]. Benzene concentrations in groundwater samples collected at oil and gas development sites in northeastern Colorado associated with surface spills range from less than 1–12,000 parts per billion (ppb), with a median of 1.5 ppb [16], which is greater than EPA's RBSL of 0.45 ppb for benzene in tap water [50]. It is important to note that EPA's RBSLs for benzene are based on cancer concerns.

Benzene is a well established cause of acute myeloid leukemia in adults [51]. Studies of benzene exposures and acute leukemias in children are limited and less conclusive. An ecological study in Texas reported that census tracts with the highest benzene levels (1.6 ppbv) had elevated rates of childhood ALL [11]. A case-control study in France reported that children aged 0–14 years living in a home adjoining to a gas station or repair garage were at increased odds of ALL [10]. Another case-control study in California reported elevated odds of ALL in children aged 0–5 years exposed to ambient levels of benzene and xylenes in the their third trimester of pregnancy [8]. However, a recent study in France found no association between benzene emissions from heavy traffic and ALL [52].

Our study benefited from the ability to select cases and controls from the same population. Because all our data were obtained from the CCCR, neither recall bias nor measurement bias affected our results. The possibility of random errors does exist in the CCCR, but in our judgment these are unlikely to affect our findings.

Geocoded addresses were missing for 27% of our study population, with a higher proportion of missing addresses for white Hispanics and young adults aged 19–24 years, as well as controls. These groups are more likely to include migrant workers, college students, and undocumented residents, so our results may not be representative of these groups.

Because ALL and NHL are rare diseases, there were only a small number of ALL and NHL cases in rural Colorado between 2001 and 2013. This limited number of cases affected the stability of our associations, as evidenced by wide confidence intervals, particularly for ALL in the 5–24 year and 0–4 year subsets and in the NHL analyses. Our controls were children diagnosed with a non-hematologic cancer, which may share some risk factors with NHL and ALL, including exposure to hazardous air pollutants associated with oil and gas development. This may have biased our associations toward the null [29, 53]. We note that between 2000 and 2013: (1) in rural Colorado counties, the mean annual incidence of ALL increased more

rapidly than the total cancer incidence with an annual mean increase of 2.9% per year compared to 0.51% per year; and (2) in urban Colorado counties, the mean annual incidence of ALL decreased by 0.5% [23]. In addition, our observed 5.9% proportion of ALL to other cancers in the unexposed group (no wells within 16.1 km) is similar to rural population proportions in the neighboring states of Nebraska (6.1% and Utah (4.6%) [54]. Finally, 82% of the children in the 0–4 year age group resided in a home within one of the IDW well count tertiles (one or more active oil and gas wells in a 16.1-kilometer radius) compared to 71% of children in the 5–24 year age groups.

Data on covariates obtained from the CCCR were limited to basic demographic information and median incomes at the zip code level. Our inability to adjust for early common infections, nutrition, family history of neoplasms, water source, proximity to other pollutants, and daycare attendance, as well as individual income, may have resulted in residual confounding. Meta analyses indicate that children with ALL and NHL are 10% and 22%, respectively, more likely than controls to have a mother who smoked during pregnancy [55, 56]. We also performed secondary analyses on the small subset of children with data on maternal smoking during pregnancy. It did not indicate substantial confounding in our ALL results, though we had limited power. Our inability to adjust for maternal smoking during pregnancy also may have resulted in residual confounding.

Because we did not have complete residential histories, we assumed that address at time of diagnosis represented a child's residence over the entire exposure period, so residential mobility during the exposure period may have obscured our results. A California study on residential mobility in children with leukemia found that 66% of children moved between birth and diagnosis, urban/rural status changed for 20%, and neighborhood SES changed for 35% [57]. The lack of information on residence across the entire exposure period prior to diagnosis likely introduced exposure misclassification for both controls and cases, most likely biasing our estimates toward the null.

Using IDW well counts in absence of information on O&G well activities, meteorology, and topography likely reduced temporal and spatial specificity in IDW well counts [36]. The overall effect of the resulting exposure misclassification is unknown, but it would most likely have biased our associations toward the null [58, 59]. The subset of oil and gas wells for which a spud-in date was not available, and for which we instead used the earliest available date of activity, may have resulted in an underestimate of IDW well counts for both cases and controls, and thus may have biased our results towards the null [60]. However, this bias is likely minimal: in the 72% of wells with spud dates, the median number of days between spud date and the next well activity is 13 days.

Conclusion

In this exploratory study, children aged 5–24 years diagnosed with ALL were more likely than children diagnosed with a non-hematologic cancer to live within 16.1-kilometers of an active oil and gas well, while children aged 0–4 years diagnosed with ALL were not more likely than children diagnosed with a non-hematologic cancer to live within 16.1-kilometers of an active oil and gas well. Children aged 0–24 years diagnosed with NHL were no more likely to live in areas with active oil and gas development than children diagnosed with a non-hematologic cancer. Because oil and gas development has potential to expose a large population to known hematologic carcinogens, such as benzene, further study is clearly needed to substantiate both our positive and negative findings. Future studies should incorporate information on oil and gas development activities and production levels near homes, schools, and day care centers; provide age-specific residential histories; compare cases to controls without cancer; and address other potential confounders, and environmental stressors.

Supporting information

S1 Table. Location coordinates for active oil and gas wells by year.

(ZIP)

S2 Table. Adjusted logistic regression model 1 for association between annual inverse distance weighted well count within 16.1-kilometer radius of residence at diagnosis averaged over exposure period and acute lymphocytic leukemia (ALL).

(PDF)

S3 Table. Adjusted logistic regression model 2 for association between annual inverse distance weighted well count within 16.1-kilometer radius of residence at diagnosis averaged over exposure period and acute lymphocytic leukemia (ALL).

(PDF)

S4 Table. Association between acute lymphocytic leukemia (ALL) and annual inverse distance weighted well count within 8-kilometer radius of residence at diagnosis averaged over exposure period.

(PDF)

S5 Table. Association between acute lymphocytic leukemia (ALL) and annual inverse distance weighted well count within 16.1-kilometer radius of residence at diagnosis averaged over exposure period: Subset of subjects with information on maternal smoking.

(PDF)

S6 Table. Adjusted logistic regression model 1 for association between annual inverse distance weighted well count within 16.1-kilometer radius of residence at diagnosis averaged over exposure period and non-Hodgkin lymphoma.

(PDF)

S7 Table. Adjusted logistic regression model 2 for association between annual inverse distance weighted well count within 16.1-kilometer radius of residence at diagnosis averaged over exposure period and non-Hodgkin lymphoma.

(PDF)

S8 Table. Association between non-Hodgkin Lymphoma (NHL) and annual inverse distance weighted well count within 8-kilometer radius of residence at diagnosis averaged over exposure period total study population (0–24 years).

(PDF)

S9 Table. Association between non-Hodgkin Lymphoma (NHL) and annual inverse distance weighted well count within 16.1-kilometer radius of residence at diagnosis averaged over exposure period: Subset of subjects with information on maternal smoking total study population (0–24 years).

(PDF)

S10 Table. Association between annual inverse distance weighted well count within 16.1-kilometer radius of residence at diagnosis averaged over exposure period and acute lymphocytic leukemia (ALL): Each year of cancer diagnosis treated separately.

(PDF)

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Congenital heart defects and intensity of oil and gas well site activities in early pregnancy

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ABSTRACT

Background: Preliminary studies suggest that offspring to mothers living near oil and natural gas (O&G) well sites are at higher risk of congenital heart defects (CHDs).

Objectives: Our objective was to address the limitations of previous studies in a new and more robust evaluation of the relationship between maternal proximity to O&G well site activities and births with CHDs.

Methods: We employed a nested case-control study of 3324 infants born in Colorado between 2005 and 2011. 187, 179, 132, and 38 singleton births with an aortic artery and valve (AAVD), pulmonary artery and valve (PAVD), conotruncal (CTD), or tricuspid valve (TVD) defect, respectively, were frequency matched 1:5 to controls on sex, maternal smoking, and race and ethnicity yielding 2860 controls. We estimated monthly intensities of O&G activity at maternal residences from three months prior to conception through the second gestational month with our intensity adjusted inverse distance weighted model. We used logistic regression models adjusted for O&G facilities other than wells, intensity of air pollution sources not associated with O&G activities, maternal age and socioeconomic status index, and infant sex and parity, to evaluate associations between CHDs and O&G activity intensity groups (low, medium, and high).

Results: Overall, CHDs were 1.4 (1.0, 2.0) and 1.7 (1.1, 2.6) times more likely than controls in the medium and high intensity groups, respectively, compared to the low intensity group. PAVDs were 1.7 (0.93, 3.0) and 2.5 (1.1, 5.3) times more likely in the medium and high intensity groups for mothers with an address found in the second gestational month. In rural areas, AAVDs, CTDs, and TVDs were 1.8 (0.97, 3.3) and 2.6 (1.1, 6.1); 2.1 (0.96, 4.5) and 4.0 (1.4, 12); and 3.4 (0.95, 12) and 4.6 (0.81, 26) times more likely than controls in the medium and high intensity groups.

Conclusions: This study provides further evidence of a positive association between maternal proximity to O&G well site activities and several types of CHDs, particularly in rural areas.

1. Introduction

Congenital heart defects (CHDs) are the most common type of birth defect in the United States (US) (Zoghbi and Jenkins, 2012). With an infant mortality rate of 41.46 per 100,000 live births, CHDs are the leading cause of death due to birth defects (Gilboa et al., 2010). Infants with a CHD are less likely to thrive, more likely to have developmental problems, and more vulnerable to brain injury (Gidding, 2012; Martinez-Biarge et al., 2013). Adults with a CHD are at increased risk of

pulmonary hypertension, arrhythmias, infective endocarditis, anticoagulation, and congestive heart failure (Bhatt et al., 2015). Of the 1.5 million US adults living with a CHD, at least 500,000 need lifelong specialized care, with death and disability rates rising dramatically after 30 years of age (Zoghbi and Jenkins, 2012). Colorado's rate of 18.9 CHDs per 1000 births is more than twice the national rate of 8.1 CHDs per 1000 births (Brook et al., 2004).

Polygenic inherited disease, noninherited risk factors, or gene-environment interactions can result in congenital heart defects during the

Abbreviations: AAVD, aortic artery and valve defect; CDPHE, Colorado Department of Public Health and Environment; CHDs, congenital heart defect; CRCSN, Colorado Responds to Children with Special Needs; CTD, conotruncal defect; IA-IDW, intensity adjusted inverse distance weighted; IDW, inverse distance weighted; NO₂, nitrogen dioxide; O&G, oil and natural gas; OR, odds ratio; PAVD, pulmonary artery and valve defect; PM_{2.5}, particulate matter ≤ 2.5 μm; ppbv, parts per billion by volume; SES, socioeconomic status; TVD, tricuspid valve defect

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first 20–60 days of embryonic development (Jenkins et al., 2007). Less than 20% of CHDs are attributed to a genetic etiology and the contribution of non-inherited risk factors and gene-environment interactions to CHD etiology is not well understood (Fung et al., 2013; Kuehl and Loffredo, 2006). Animal models demonstrate that CHDs can occur with a single environmental exposure during early gestation (Linask, 2013). Many environmental risk factors have been associated with CHDs including maternal exposures (Jenkins et al., 2007) to hazardous air pollutants, such as benzene (Desrosiers et al., 2012; McMartin et al., 1998; Wennborg et al., 2005) diesel exhaust (Dadvand et al., 2011; Vrijheid et al., 2010) and stress (Adams et al., 1989; Carmichael and Shaw, 2000; Zhu et al., 2013).

One source of environmental exposures to hazardous air pollutants, diesel exhaust, and non-chemical stressors is the close proximity of oil and natural gas (O&G) wells to maternal residences (Adgate et al., 2014). Numerous studies have attributed increased hazardous air pollutant levels to O&G activities and have observed that emissions increase significantly during specific activities, such as well completions and during maintenance (Allen et al., 2013; Gilman et al., 2013; Halliday et al., 2016; Helmig et al., 2014; McKenzie et al., 2012; Pétron et al., 2012; Pétron et al., 2014). Some of the most common hazardous air pollutants (e.g., benzene, toluene and xylenes) emitted from O&G well sites are suspected teratogens (Colborn et al., 2011) that are known to cross the placenta (Shepard, 1995). In the summer of 2014, continuous ambient benzene sampling in Colorado's Denver Julesburg Basin indicated that mean benzene concentrations at night, when people are most likely to be at home, were on average twice the daytime mean (Halliday et al., 2016). Daytime benzene concentrations reached 120 parts per billion by volume (ppbv) in grab samples collected within 500 ft of O&G sites (McKenzie et al., 2018). Additionally, O&G operators use trucks with diesel engines to transport supplies, water, and waste to and from O&G wells, with 40 to 280 truck trips per day per well pad during development (Allshouse et al., 2019; Witter et al., 2013). Generators equipped with diesel engines are used both to drill wells and for hydraulic fracturing (King, 2012). Air pollutants in the diesel exhaust emitted from these trucks and generators include nitrogen dioxide (NO₂) and particulate matter $\leq 2.5 \mu\text{m}$ (PM_{2.5}) (Birch and Cary, 1996; Sydbom et al., 2001). Reactions between NO₂ and volatile organic compounds produce lead to ground level ozone production (US Environmental Protection Agency, 2018). Finally, non-chemical stressors, such as traffic, noise, light, and psychological stress, associated with O&G development may increase maternal stress levels and the risk of CHDs (Allshouse et al., 2019; Blair et al., 2018a,b; Malin et al., 2018; Witter et al., 2013).

In our previous retrospective cohort study of 124,842 births in rural Colorado between 1996 and 2009, we observed that the birth prevalence of CHDs increased with increasing density of O&G wells around the maternal residence, with an odds ratio of 1.3 for the highest exposure group compared to the referent group (95% CI: 1.2, 1.5) (McKenzie et al., 2014). A second retrospective study of 476,000 births in Oklahoma observed positive, but imprecise, associations between density of natural gas wells and several specific CHDs (conotruncal, pulmonary valve and artery, aortic arch, and tricuspid valve defects) (Janitz et al., 2018). These previous studies had three major limitations. First, they were not able to provide sufficient spatial and temporal granularity to assign exposures to the three months prior to conception and the first two months of gestation – the critical period of development for the fetal heart. Second, they were not able to distinguish between well development and production phases or account for varying activities on O&G well sites. Third, they did not confirm specific types of CHDs by a medical record review.

Our objective in this study was to address the limitations of these previous studies in a new and more robust evaluation of the relationship between maternal proximity to O&G well site activities and births with CHDs.

2. Methods

We conducted a nested case-control study of 3324 mother-infant pairs born in Colorado between 2005 and 2011 using de-identified data provided by the Colorado Department of Public Health and Environment's (CDPHE) Center for Health and Environmental Data. CDPHE de-identified the data to maintain the confidentiality of registry records.

2.1. Study population

Our population includes all live singleton births occurring between 2005 and 2011 to mothers living in 34 Colorado counties with 20 or more wells drilled (well starts) from 2004 to 2011 per 10,000 births (Supplemental Table 1). The cut-point of 20 or more well starts best captures counties in areas of intense O&G activity. We selected these inclusion criteria to focus our analysis on growth of unconventional O&G development, characterized by the use of hydraulic fracturing and/or directional drilling (Haynes et al., 2017). It was necessary to restrict the cohort to Colorado counties with active O&G development because most Coloradans do not live near O&G wells: 6% of Coloradans live with one mile of a well that was drilled after the year 2000 (McKenzie et al., 2016). Restricting the cohort to births in counties with 20 or more well starts per 10,000 births reduces skewing the distribution of births towards unexposed mothers. We excluded siblings of cases and controls. From this cohort, CDPHE staff selected cases and controls as described in the next section and shown in Fig. 1.

2.2. Case and control selection

CDPHE staff used the Colorado Responds to Children with Special Needs (CRCSN) birth defects registry to select cases from the cohort described above and in Fig. 1. The CRCSN includes children with birth defects identified from hospital records, the Newborn Genetics Screening Program, the Newborn Hearing Screening Program, laboratories, physicians, and genetic, developmental and other specialty clinics up to age 3 years. Children in our cohort that also were in the CRCSN birth defects registry and confirmed via a medical record review to have one of the following four specific types of CHDs, without a chromosomal anomaly, were selected as cases. The four specific types of CHDs are: (1) pulmonary artery and valve defects (PAVDs) defined as pulmonary valve atresia and stenosis and pulmonary artery anomalies with and without ventricular defects (ICD-9-CM 746.01, 746.02, 747.3, 747.31, 747.32, 747.39); (2) aortic artery and valve defects (AAVD) defined as aortic valve stenosis and coarctation of aorta with and without ventricular defects (746.3, 747.10); (3) conotruncal defects (CTDs) defined as Tetralogy of Fallot and transposition of great vessels with and without ventricular defects (745.2, 745.10, 745.11, 745.12, 745.19); and (4) tricuspid valve defects (TVDs) defined as tricuspid valve atresia and stenosis and Ebstein's anomaly with and without other CHDs (746.1, 746.2). Based on previous studies, we grouped CHDs into these specific clinical diagnostic groupings to increase statistical power and to enable comparisons with previous studies (Gilboa et al., 2005; Janitz et al., 2018; McKenzie et al., 2014; Ritz et al., 2002). Children with multiple types of CHDs were selected as cases for each specific type of CHD present. For example, a child diagnosed with both a CTD and PAVD, would be selected as both a CTD and PAVD case. Based on these criteria and definitions, 187, 179, 132, and 38 children with an AAVD, PAVD, CTD, or TVD, respectively, were selected as cases.

For each case, CDPHE staff selected five controls from the birth certificate data in Colorado Vital Statistics Program frequency matching 1 to 5 on sex (Vereczkey et al., 2013), maternal cigarette use during pregnancy (yes or no) (Malik et al., 2008), and combined race and ethnicity (Jenkins et al., 2007). For children with multiple ICD-9-CM codes for the same type of CHD described above, five controls were selected for each ICD-9-CM code. Thus, 2860 children were selected as

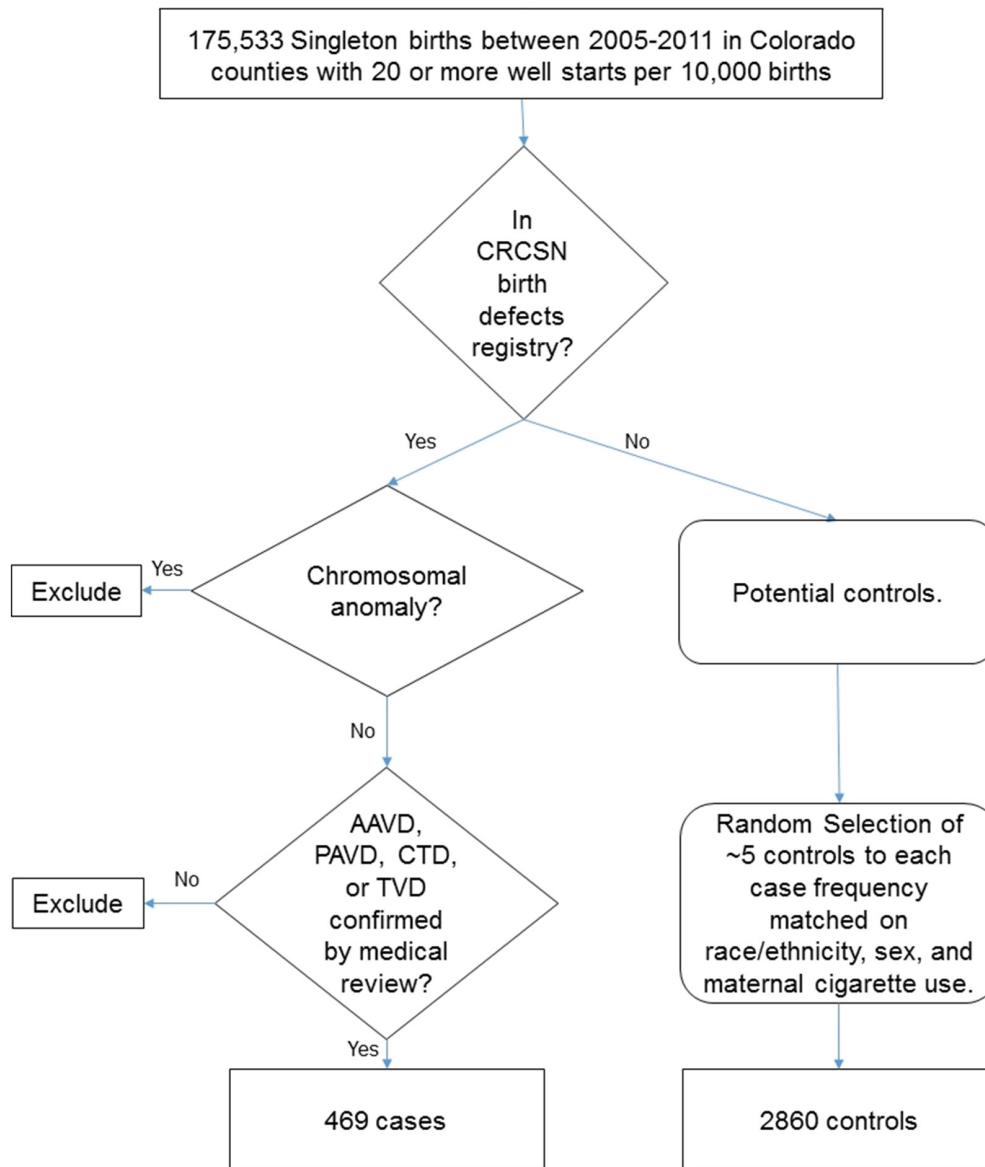


Fig. 1. Selection of cases and controls born between 2005 and 2011 in Colorado Countries with 20 or more active O&G wells.

AAVD: arterial artery or valve defect, CRCSN: Colorado Responds to Children with Special Needs, CTD: conotruncal defect; PAVD: pulmonary artery or valve defect; TVD: tricuspid valve defect.

controls. We compared each specific type of CHD to the entire control population.

2.3. Intensity of O&G well activity

Using information available in the publically accessible Colorado Oil and Gas Information System, we built a geocoded data set that contains the American Petroleum Institute well identification number, latitude, longitude, and status (development, producing, shut-in, and abandoned) of all O&G wells in Colorado between 2004 and 2011 (Colorado Oil and Gas Information System, 2015). To this data set, we added the latitude and longitude coordinates for O&G facilities other than wells (e.g. compressor stations, tank farms, and gathering lines) in the Colorado Oil and Gas Information System. We also added air pollution sources not associated with O&G activities in the US Environmental Protection Agency's Toxic Release Inventory program and Enforcement and Compliance History on-line data database (<https://echo.epa.gov/facilities/facility-search>); the US Geological Survey National

Mines Information Center; and the CDPHE's Concentrated Animal Feeding Operations, and Composting, Solid Waste, and Wastewater Treatment Facility data. The final data set was then parsed into months (84 months from 2004 to 2011) and provided to CDPHE staff.

For each case and control, CDPHE staff identified all O&G wells, O&G facilities other than wells, and air pollution sources not associated with O&G activities within 10 miles of the maternal residence provided on the birth certificate for each month in the three months prior to conception through the second month of gestation (five months). Based on associations observed with adverse health outcomes in previous studies, a 10-mile buffer represents a conservative geographic area of interest that could plausibly affect exposure (McKenzie et al., 2014, 2017; Stacy et al., 2015). We included the 3-months prior to conception in our exposure assessment because of the possibly mutation generation during ovum cell formation (Shi and Chia, 2001) or epigenetic modifications transmitted through sperm DNA, histones, and RNA (Braun et al., 2017). CDPHE staff determined the three months prior to conception through the second month of gestation period from the birth

date and gestational age recorded on the birth certificate. CDPHE staff also computed distances between the maternal residence and each O&G well, O&G facility other than a well, and air pollution source not associated with O&G activities using spherically-adjusted straight line distances and returned to us a de-identified data set.

Next, we applied our intensity adjusted inverse distance weighted (IA-IDW) model, as described in Allhouse et al. (2017), to estimate the monthly relative intensity of O&G well site activity around the maternal residence of each case and control for each month from three months prior to conception through the second month of gestation. Because the O&G wells included in our IA-IDW exposure metric are weighted by distance between the well and the residence, a well that is closer to the individual will contribute more to that individual's metric than a well with the same intensity that is further away. Our IA-IDW metric differs from other methods that define an individual as exposed if they have a well within a given buffer without adjustment for phase of well development or intensity of operations that occur at the well site (Currie et al., 2017; Hill, 2018).

2.4. O&G facilities other than wells

For O&G facilities other than wells, we used an inverse distance weighted (IDW) approach, commonly used to estimate individual air pollutant exposures from multiple fixed locations (Brauer et al., 2008; Ghosh et al., 2012; McKenzie et al., 2014, 2017) to estimate maternal exposure. We separately calculated the IDW count of all existing O&G facilities that were not on a well site for each month between three months prior to conception through the second month of gestation within a 10-mile radius of each maternal residence:

$$IDW \text{ count} = \sum_{i=1}^n \frac{1}{d_i^2} \quad (1)$$

where

- d_i = distance of the i th individual well from maternal residence.
- n = number of O&G facilities other than well sites within a 10-mile radius.

2.5. Air pollution sources not associated with O&G activities

For air pollution sources not associated with O&G activities, we calculated an intensity adjusted inverse distance weight (IA-IDW) count for each month between three months prior to conception through the second month of gestation within a 10-mile radius of each maternal residence:

$$IA - IDW \text{ count} = \sum_{i=1}^n \frac{I}{d_i^2}$$

where:

- d_i = distance of the i th individual well from maternal residence.
- n = number of air pollution sources not associated with O&G activities within a 10-mile radius.
- I = relative intensity of emissions or activities.

We assigned concentrated animal feeding operations an intensity of 1–5 based on the percentile of animal units; mining sources an intensity of 1–4 based on the type of mine (Supplemental Table 2); and Toxic Release Inventory and Solid Waste, and Wastewater Treatment Facility sources an intensity of 1–5 based on the percentile of annual air emissions and waste flow, respectively. We assigned Composting and Enforcement and Compliance History sources an intensity of 1 due lack of information on emissions and activity.

2.6. Maternal residence in three months prior to conception through second week of gestation

We conducted all residential history searches on the CDPHE campus under the supervision of CDPHE staff. CDPHE released no personal identifiers to our research team. We used the mother's and father's (if available) name and birth date recorded on the birth certificate to perform a maternal residential history search for the year preceding the child's birth date in the LexisNexis® Accurint® for Government data system (LexisNexis®) and provided the results of the search to CDPHE staff. LexisNexis® uses data linking technologies that enable searches of current comprehensive and authoritative public records information. If the residential history search found the maternal address did not change between three months prior to the pregnancy to the birth date or if we could not determine the maternal residence in this time-period, CDPHE staff used the address on the birth certificate to calculate the IDW-metrics. If the residential history search found the maternal address differed from the address on the birth certificate at any point during the three months prior to conception through the second month of gestation, the address(es) found in the residential history search were used to calculate IDW-metrics.

2.7. Statistical analysis

We log-transformed All IDW-metrics because the distribution of each of our IDW metrics were highly skewed with long tails towards large values. Based on multi-modal log transformed distributions for IA-IDW and IDW counts of O&G facilities other than wells, we divided the distributions of these IDW-metrics into low, medium, and high exposure groups based on modal cut points for subsequent statistical analysis. We divided the final IA-IDW well distribution into low, medium, and high exposure groups using cut points of 1 and 403 intensity well counts per square mile (mile²) (Supplemental Fig. 1). We divided the final IDW count for O&G facilities other than wells into low, medium, and high groups using cut points of 1 and 6 IDW counts/mile² (Supplemental Fig. 2). We used the continuous log-transformed data for IA-IDW count of air pollution sources not associated with O&G activities for subsequent statistical analysis because the log-transformed data approximated a Gaussian distribution (Supplemental Fig. 3).

We used data from the 2007–2011 American Community Survey 5-year estimates to calculate a composite socioeconomic status (SES) index at the zip-code level, based on a principal component analyses method presented in Yost et al., 2001 and applied in other studies (Cheng et al., 2010; Ghosh et al., 2012, 2013; Yost et al., 2001). We included seven indicator variables in the principle component analysis: percent in food stamps or Supplemental Nutrition Assistance Program, percent below poverty level, percent on public cash assistance, percent unemployed, median household income, median house value, and educational attainment for adults > 25 years. We divided educational attainment into three groups: no high school degree, high school degree and some college, and bachelor degree or higher. The first two components captured 60% of the variability with eigenvalues > 1. Because the first component best reflected SES disadvantage, we used the first component to create our SES index. The first component captured 42% of the variability with each indicator loading as follows (correlation coefficient of each indicator with the SES index in parentheses): percent on food stamps or Supplemental Nutrition Assistance Program (0.48); percent below poverty (0.41); percent public cash assistance (0.34); percent unemployed (0.30); median household income (–0.44); median household value (–0.37); and educational attainment (–0.28). Therefore, a larger SES index represents a lower SES level. Lastly, we grouped the SES indices into quantiles (Yost et al., 2001).

For each of the five months between three months prior to conception through the second month of gestation, we used unconditional logistic regression (Jewell, 2004; Mansournia et al., 2018) to evaluate associations between each dichotomous outcome (combined CHDs,

AAVD, PAVD, CVD, and TVD) and IA-IDW group with the low group as the referent. First, we estimated the crude odds ratio (OR) associated with IA-IDW exposure group for each binary outcome. We further used logistic regression to investigate for associations by adjusting for potential confounders, as well as child covariates, based on a priori knowledge of their association with both exposure and/or outcome. Specifically, we considered the following co-variables: maternal age (continuous) (Reefhuis and Honein, 2004), parity (0, 1, 2, > 2) (Vereczkey et al., 2013), SES index (quantile), sex (Vereczkey et al., 2013), IDW count of O&G facilities other than wells (low, medium, high), and IA-IDW count for air pollution sources not associated with O&G activities (continuous). Because our previous study excluded urban populations (McKenzie et al., 2014), we tested for effect modification of residence in a rural zip code. Additionally, we tested for effect modification by infant sex, evaluated a 2-mile buffer, evaluated an analysis of IA-IDW > 0 divided into tertiles with a referent group with no O&G wells in the 10-mile buffer, and evaluated year of birth as a confounder. We performed sensitivity analyses on two subsets of our study population: mother's address in the second gestational month found in LexisNexis® and exclusion of births to mothers in the O&G facilities other than wells high group. We conducted tests to evaluate linear trends in binominal proportions with increasing IA-IDW by treating the categorical IA-IDW variable as ordinal and used the Wald Chi-Square parameter to test for statistical significance (Carlton et al., 2015). With the exception of effect modification, we considered the statistical significance of the association, as well as the trend, in evaluating results, at an alpha of 0.05. We evaluated effect modification based on differences in effect size in stratified analyses. The Colorado Multi-Institutional Review Board approved our study protocol (Protocol Number: 14-1343).

3. Results

Table 1 summarizes the characteristics of our population by case and control status. A higher proportion of infants with an AAVD were male, had a white non-Hispanic mother, or had a mother living in a more advantaged SES group than controls. A higher proportion of infants with a PAVD were female, first born, had a mother living in a less advantaged SES group, or had fewer O&G facilities other than wells in the 10-mile buffer than controls. A higher proportion of infants with a CTD were first born, had a mother living in a less advantaged SES group, and a higher density of O&G facilities other than wells in the 10-mile buffer around the mother's residence than controls. A higher proportion of infants with a TVD were female, had older siblings, had mothers living in a rural area, had less intensity of air pollution sources not associated with O&G activity, or less density of O&G facilities other than wells in the 10-mile buffer around the mother's residence than controls. Additionally, we were more likely to find a residential history for mothers of infants with a CHD than controls.

Table 2 summarizes our study population's characteristics by exposure status (IA-IDW well count within a ten mile buffer of the mother's residence in the second gestational month). Most infant-mother pairs (59%) were in the medium exposure group, followed by the low (25%) and high (15%) exposure groups. Estimated exposures, as represented by IA-IDW well counts, tended to be lower for male infants and mothers in a higher SES group, in a rural area, or with lower densities of O&G facilities other than wells or air pollution sources not associated with O&G activities in the 10-mile buffer around their residence. Additionally, we were less likely to find a residential history for mothers in the low exposure group.

3.1. Overall results

Both crude and adjusted estimates indicate an increase in odds of maternal exposure to O&G well site activities in the second gestational month, as represented by IA-IDW well counts, in births with any CHD

Table 1

Study population characteristics for cases and controls born between 2005 and 2011 in Colorado counties with 20 or more O&G well starts per 10,000 births.

Maternal or infant characteristic	AAVD cases ^c	PAVD cases ^c	CTD cases ^c	TVD cases ^c	Controls
Total N	187	179	132	38	2860
Maternal age (years)					
Median	29	27	27	28	27
25th Percentile	23	23	22	24	23
75th Percentile	34	32	32	33	32
Maternal combined race and ethnicity (%) ^b					
White – Non-Hispanic	63	57	58	58	59
White – Hispanic	28	34	31	32	32
Other	5.4	7.3	10	11	7.7
Missing	3.2	1.7	1.5	0	1.2
Male (%)	59	48	56	47	54
Maternal smoking (%)					
No	91	91	86	92	89
Missing	0	0	0	0	< 1
Change in maternal address between 3 months prior to conception to birth of child (%)					
No	74	69	70	71	67
Yes	8.0	5.6	9.1	7.9	9.0
Unknown	18	25	21	21	24
Parity (%)					
0	37	41	46	34	39
1	29	32	27	34	33
2	21	16	13	16	18
> 2	13	10	13	16	10
Rural (%)					
60	60	55	68	62	
SES Index Percentile (%)					
20	23	17	17	21	20
40	21	13	13	24	20
60	21	21	18	13	21
80	19	28	27	13	20
100	16	21	25	29	20
Missing	0	< 1	0	0	< 1
IDW Group of O&G Facilities other than wells (%) ^a					
Low	36	39	42	42	36
Medium	27	27	23	21	28
High	36	35	36	37	37
IA-IDW count of air pollution sources not associated with O&G activities (intensity/mile ²)					
Median	5.1	6.7	6.2	5.4	5.9
25th Percentile	3.2	3.6	3.3	3.6	3.3
75th Percentile	11	12	11	7.9	11
IA-IDW group (%) ^b					
Low	21	25	26	29	26
Medium	64	59	56	58	58
High	14	16	18	13	15

AAVD = Aortic artery and valve defects, CTD = conotruncal defects, IA-IDW = intensity adjusted inverse distance weighted well count, IDW = inverse distance weighted count, N = number, O&G = oil and natural gas, PAVD = Pulmonary artery and valve defects, TVD = tricuspid valve defects.

^a Low = < 1 O&G facilities per square mile, medium = 1 to 6 other types of O&G facilities per square mile, high = > 6 other types of O&G facilities per square mile.

^b Low = < 1 intensity wells per square mile, medium = 1 to 403 intensity wells per square mile, high = > 403 intensity wells per square mile.

^c The sum of AAVD, PAVD, CTD, and TVD cases is > 469 because a few infants had multiple CHDs.

(Table 3). Congenital heart defects were 1.4 (95% CI: 1.0, 2.0) and 1.7 (95% CI: 1.1, 2.6) times more likely than controls in the medium and high exposure groups, respectively, compared to the least exposed group after adjustment (p for trend = 0.0230). Similarly, both crude and adjusted estimates indicate an increase in odds of maternal exposure to O&G well site activities in the second gestational month, as represented by IA-IDW well counts, in births with a CTD or PAVD. Births with a CTD were 1.5 (95% CI: 0.87, 2.6) and 2.0 (95% CI: 0.97,

Table 2

Study population characteristics for cases and controls born between 2005 and 2011 in Colorado counties with 20 or more O&G well starts per 10,000 births by IA-IDW group.

	IA-IDW group		
	Low ^a	Medium ^a	High ^a
Total (N)	864	1945	515
Maternal age (years)			
Median	26	28	27
25th Percentile	22	23	23
75th Percentile	31	32	32
Maternal combined race and ethnicity (%)			
White – Non-Hispanic	57	61	56
White – Hispanic	34	30	37
Other	7.4	8.1	6.2
Missing	1.3	1.4	1.4
Male (%)	52	55	55
Maternal smoking (%)			
No	88	90	89
Missing	0	< 1	< 1
Change in maternal address between 3 months prior to conception to birth of child (%)			
No	57	72	69
Yes	14	7.0	8.4
Unknown	29	21	22
Parity (%)			
0	36	41	38
1	33	33	30
2	20	16	19
> 2	11	8.8	13
Rural (%)	75	61	42
SES Index Percentile (%)			
20	17	21	18
40	13	22	23
60	18	21	26
80	22	22	10
100	31	14	24
Missing	< 1	0	0
IDW group of O&G facilities other than wells (%) ^b			
Low	94	20	< 1
Medium	5.6	38	22
High	< 1	42	78
IA-IDW Count of Air Pollution Sources not associated with O&G activities (source/mile ²)			
Median	4.5	6.1	7.8
25th Percentile	1.4	3.3	4.9
75th Percentile	8.2	10	14

IA-IDW = intensity adjusted inverse distance weighted well count, IDW = inverse distance weighted count, N = number, O&G = oil and natural gas, SES = social-economic status.

^a Low = < 1 intensity wells per square mile, medium = 1 to 403 intensity wells per square mile, high = > 403 intensity wells per mile.

^b Low = < 1 O&G facilities per square mile, medium = 1 to 6 other types of O&G facilities per square mile, high = > 6 other types of O&G facilities per square mile.

4.3) times more likely than controls in the medium and high exposure groups, respectively, compared to the least exposed group (p for trend = 0.0599). Births with a PAVD were 1.4 (95% CI: 0.87, 2.3) and 1.7 (95% CI: 0.87, 3.2) times more likely than controls in the medium and high exposure groups, respectively, compared to the least exposed group (p for trend = 0.1234). While both crude and adjusted estimates indicate increased odds of births with AAVDs and TVDs with increasing maternal exposure to O&G well site activities in the second gestational month, we did not observe a trend from low to high exposure.

We observed similar associations for AAVDs and attenuated associations for CTDs and TVDs with exposure to O&G well site activities in each of the three months prior to conception through the first

gestational month for AAVDs (Supplemental Tables 3–6). For PAVDs, we observed the strongest association with exposures in the two months prior to conception (Supplemental Table 4).

In our evaluation of a 2-mile buffer zone around the maternal residence in the second month of gestation, we observed similar results for AAVDs, stronger associations for CTDs and TVDs, and attenuation towards the null for PAVDs (Supplemental Table 7). In our evaluation of IA-IDW well count > 0 divided into tertiles with a referent group as no O&G wells in the 10-mile buffer, we observed some bias towards the null for the AAVD and TVD outcomes and potentially some bias away from the null for the CTD and PAVD outcomes (Supplemental Table 8). Further adjustment of our models for year of birth did not change our results (Supplemental Table 9).

3.2. Effect modification and stratified results

Our finding of stronger associations between odds of a birth with a CHD and maternal exposure to O&G well site activities for mothers with a residence in a rural zip code compared to an urban zip code indicates effect modification (Table 4). In rural zip codes, CHDs, AAVDs, CTDs, and TVDs in the medium and high exposure groups were 1.6 (95% CI: 1.0, 2.4) and 2.4 (95% CI: 1.3, 4.4, p for trend = 0.0033); 1.8 (95% CI: 0.97, 3.3) and 2.6 (95% CI: 1.1, 6.1, p for trend = 0.0276); 2.1 (95% CI: 0.96, 4.5) and 4.0 (95% CI: 1.4, 12, p for trend = 0.0108); and 3.4 (95% CI: 0.95, 12) and 4.6 (95% CI: 0.81, 26, p for trend = 0.0846) times more likely, respectively, than controls compared to the least exposed group after adjustment for co-variables. With the exception of PAVDs, we observed no associations between O&G exposure and CHDs in births to mothers residing in an urban zip code. While we did not observe effect modification between exposure and infant sex, we did observe stronger associations between maternal exposure to O&G well activity and AAVDs, PAVDs, and CTDs in female infants (Supplemental Table 10).

3.3. Sensitivity analyses

In our sensitivity analyses of births to mother's for whom we found a residential address in the second gestational month and exclusion of births to mother's in the O&G facilities other than wells high group, we observed results similar to the whole population, with the following exception (Supplemental Tables 11 and 12). With exclusion of births for which we could not find the mother's address in the second gestational month, the association between exposure to O&G well activities and PAVDs increased. Compared to controls, births to mothers in the medium and high exposure groups had a 1.7 (95% CI: 0.93, 3.0) and 2.5 (95% CI: 1.1, 5.3, p for trend = 0.0243) times higher prevalence of PAVDs, respectively, for mothers with a found address in the second gestational month after adjusting for co-variables.

4. Discussion

We observed positive associations between odds of a birth with a CHD and maternal exposure to O&G well activities, as represented by IA-IDW well counts, in the second gestational month. The odds of a birth with any type of CHD increased from the low to high exposure group. In rural areas, odds of a birth with an AAVD, CTD, or TVD were 2.6–4.6 times more likely than controls in the high exposure group compared to the low exposure group. In urban areas, we did not observe associations between odds of a birth with an AAVD, CTD, or TVD. In the subset of births for which we were able to find the maternal address in the second gestational month, odds of a birth with a PAVD were 2.5 times more likely than controls in the high exposure group.

Interestingly, we observed associations between maternal exposures to O&G well site activities and AAVDs, CTDs, and TVDs in rural areas and not in urban areas. The 62% of mothers in our study living in a rural area differed from mothers living in urban areas in several ways.

Table 3

Association between intensity adjusted O&G well site activity within ten-mile radius of maternal residence in second month of pregnancy and congenital heart defects for cases and controls born between 2005 and 2011 in Colorado counties with 20 or more O&G well starts per 10,000 births.

IA-IDW group ^a	Low	Medium	High	Trend test p-value ^c
Controls (N)	751	1669	438	
Any CHD				
Cases (N)	110	276	77	
Crude OR	Referent	1.1 (0.89, 1.4)	1.2 (0.88, 1.6)	
Adjusted OR (95% CI) ^b	Referent	1.4 (1.0, 2.0)	1.7 (1.1, 2.6)	0.0230
AAVDs				
Cases (N)	40	120	27	
Crude OR	Referent	1.4 (0.93, 2.0)	1.2 (0.70, 1.9)	
Adjusted OR (95% CI) ^b	Referent	1.6 (1.0, 2.6)	1.5 (0.79, 3.0)	0.2373
PAVD				
Cases (N)	43	106	29	
Crude OR	Referent	1.1 (0.77, 1.6)	1.2 (0.71, 1.9)	
Adjusted OR (95% CI) ^b	Referent	1.4 (0.87, 2.3)	1.7 (0.87, 3.2)	0.1234
CTD				
Cases (N)	34	74	24	
Crude OR	Referent	0.98 (0.65, 1.5)	1.2 (0.71, 2.1)	
Adjusted OR (95% CI) ^b	Referent	1.5 (0.87, 2.6)	2.0 (0.97, 4.3)	0.0599
TVD				
Cases (N)	11	22	5	
Crude OR	Referent	0.90 (0.43, 1.9)	0.78 (0.27, 2.3)	
Adjusted OR (95% CI) ^b	Referent	1.4 (0.49, 4.1)	1.1 (0.25, 4.8)	0.9478

AAVD = Aortic artery and valve defects, CHD = congenital heart defects, CTD = conotruncal defects, IA-IDW = intensity adjusted inverse distance weighted well count, N = number, O&G = oil and natural gas, PAVD = Pulmonary artery and valve defects, TVD = tricuspid valve defects.

^a Low = 0 to < 1 intensity wells per square mile; medium = 1 to < 403 intensity wells per square mile, high = \geq 403 intensity wells per square mile.

^b Adjusted for IDW count of oil and gas facilities other than wells in 10-mile buffer, IA-IDW count of air pollution sources not associated with O&G activities, maternal age, and SES group, as well as infant parity and sex.

^c Trend tests performed by treating categorical inverse-distance well count as an ordinal.

In rural areas, mothers were younger and a higher proportion were white non-Hispanic, in a less advantaged SES group, and had less density of O&G facilities other than wells and less intensive O&G well site activities around their home (Tables 1 and 2). Additionally, the median IA-IDW count of air pollution sources not associated with O&G activities within 10 miles of the mother's home was lower in rural areas, even though we observed the maximum IA-IDW count for these air pollution sources in a rural zip code. Because we would expect more air pollution sources in urban areas than rural areas, we performed an exploratory analysis for effect modification of IA-IDW counts of air pollution sources not associated with O&G activities on IA-IDW well count. Our exploratory analysis indicates that the intensity of air pollution sources not associated with O&G activities modifies the effect of the intensity of O&G well site activity on CHD prevalence. Stratifying our population by tertile of IA-IDW count of air pollution sources not associated with O&G activities indicates a possible additive effect: the association between CHDs and intensity of O&G well site activities strengthens in areas with higher densities of other air pollution sources (Table 5). Therefore, we suspect that both residual confounding and confounding from air pollution sources not considered in our study (e.g. traffic related pollution and gasoline stations) may have obscured associations particularly in urban areas. We did not observe effect modification between IA-IDW exposures groups and other covariates (ethnicity, SES group, and O&G facilities other than wells).

Previous retrospective cohort studies of mother-infant pairs in Oklahoma and rural Colorado also indicated positive associations between CHDs and maternal proximity to O&G well sites (Janitz et al., 2018; McKenzie et al., 2014) albeit the associations were smaller than observed in our study. Our ability to confirm the maternal residence, estimate the intensity of O&G well activities, and confirm contributions from other O&G facilities and sources of air pollution, around the maternal residence during the critical period for CHD development likely reduced exposure misclassification that may have attenuated these previous study results towards the null. Additionally, our CHD cases

were confirmed by medical record review and did not include CHDs with a known genetic origin, thus reducing the potential for outcome misclassification. Finally, we adjusted our results for SES using an SES index for the mother's zip code. While an SES index is a more robust approach than use of maternal education as a proxy for SES, there is likely some misclassification due to aggregation to the zip code level.

O&G well site activities are a known source of PM_{2.5}, NO₂, and hazardous air pollutants (Allshouse et al., 2019; Collett et al., 2016; Duncan et al., 2016; Evanoski-Cole et al., 2017; Helmig et al., 2014; Hildenbrand et al., 2016; McCawley, 2015; Roy et al., 2013) and are known to have short periods of high emissions (Allen et al., 2017; Halliday et al., 2016). Our results are in general agreement with epidemiological studies suggesting associations between maternal exposures to these air pollutants and CHDs (Stingone et al., 2017; Dadvand et al., 2011; McMartin et al., 1998; Wennborg et al., 2005). Studies evaluating specific types of CHDs suggest relationships between maternal NO₂ exposures with AAVDs (coarctation of the aorta), PAVDs (pulmonary valve stenosis) and CTDs (tetralogy of Fallot) (Schembari et al., 2014; Stingone et al., 2014; Vrijheid et al., 2010). Studies also indicate and association between maternal PM_{2.5} exposures and AAVDs, PAVDs, and CTDs (Tanner et al., 2015; Warren et al., 2016; Padula et al., 2013; Zhang et al., 2016). Other studies suggest an association between maternal occupational exposures to Stoddard solvents and CTDs (transposition of the great arteries), AAVDs (aortic valve stenosis), and PAVDs (pulmonary valve stenosis) (Gilboa et al., 2012).

While the biological mechanism between maternal exposures to environmental stressors such as air pollutants and CHDs is not entirely understood, the available evidence indicates that environmental stressors may create oxidative stress in embryonic cells during formation of the cardiac neural crest in the second gestational month, ultimately resulting in teratogenesis (Badham et al., 2010; Hansen, 2006; Wu et al., 2016). Most non-genetic CTDs are a direct result and most non-genetic PAVDs and AAVDs are an indirect result of perturbations in cardiac neural crest formation (Rosenquist, 2013). Because of rapid

Table 4
 Association between intensity adjusted O&G well site activity within ten-mile radius of maternal residence in second month of pregnancy and congenital heart defects for cases and controls born between 2005 and 2011 in Colorado counties with 20 or more O&G well starts per 10,000 births stratified by rural and urban zip codes.

IA-IDW ^a	Rural zip codes				Urban zip codes				Effect modification between rural and IA-IDW group p-value	
	Low	Medium	High	Trend test p-value ^c	Low	Medium	High	Trend test p-value ^c		
	N	OR (95% CI) ^b	N	OR (95% CI) ^b	N	OR (95% CI) ^b	N	OR (95% CI) ^b		
Controls (N)	571	1032	178		180	637	260			
Any CHD										
Cases (N)	73	160	39		37	116	38			
Crude OR	Referent	1.2 (0.90, 1.6)	1.7 (1.1, 2.6)		Referent	0.89 (0.59, 1.3)	0.71 (0.44, 1.2)			
Adjusted OR (95% CI) ^b	Referent	1.6 (1.0, 2.4)	2.4 (1.3, 4.4)	0.0033	Referent	1.2 (0.68, 2.1)	0.94 (0.47, 1.9)	0.7582		0.0119
AAVDs										
Cases (N)	30	66	16		10	54	11			
Crude OR	Referent	1.2 (0.80, 1.9)	1.7 (0.91, 3.2)		Referent	1.5 (0.76, 3.1)	0.76 (0.32, 1.8)			
Adjusted OR (95% CI) ^b	Referent	1.8 (0.97, 3.3)	2.6 (1.1, 6.1)	0.0276	Referent	1.3 (0.52, 3.4)	0.73 (0.23, 2.3)	0.4547		0.1592
PAVD										
Cases (N)	30	63	13		13	43	16			
Crude OR	Referent	1.2 (0.74, 1.8)	1.4 (0.71, 2.7)		Referent	0.94 (0.49, 1.8)	0.85 (0.4, 1.8)			
Adjusted OR (95% CI) ^b	Referent	1.2 (0.61, 2.2)	1.5 (0.62, 3.9)	0.3650	Referent	1.8 (0.76, 4.2)	1.7 (0.59, 4.7)	0.3562		0.3958
CTD										
Cases (N)	18	43	11		16	31	13			
Crude OR	Referent	1.3 (0.76, 2.3)	2.0 (0.91, 4.2)		Referent	0.55 (0.29, 1.0)	0.56 (0.26, 1.2)			
Adjusted OR (95% CI) ^b	Referent	2.1 (0.96, 4.5)	4.0 (1.4, 12)	0.0108	Referent	1.0 (0.41, 2.5)	0.91 (0.30, 2.8)	0.8555		0.0238
TVD										
Cases (N)	6	16	< 5		< 5	< 5	< 5			
Crude OR	Referent	1.5 (0.57, 3.8)	2.1 (0.59, 7.7)		Referent	NC	NC			NC
Adjusted OR (95% CI) ^b	Referent	3.4 (0.95, 12)	4.6 (0.81, 27)	0.0846	Referent	NC	NC			NC

AAVD = Aortic artery and valve defects, CHD = congenital heart defects, CTD = conotruncal defects, IA-IDW = intensity adjusted inverse distance weighted well count, N = number, O&G = oil and natural gas, NC = Not calculated because low counts result in unstable estimates, PAVD = Pulmonary artery and valve defects, TVD = tricuspid valve defects.

^a Low = 0 to < 1 intensity wells per square mile; medium = 1 to < 403 intensity wells per square mile, high = ≥403 intensity wells per square mile.

^b Adjusted for IDW count of oil and gas facilities other than wells in 10-mile buffer, IA-IDW count of air pollution sources not associated with O&G activities in 10-mile buffer, maternal age, and SES group, as well as infant parity and sex.

^c Trend tests performed by treating categorical inverse-distance well count as an ordinal.

Table 5

Association between intensity adjusted O&G well site activity within ten-mile radius of maternal residence in second month of pregnancy and congenital heart defects for cases and controls born between 2005 and 2011 in Colorado counties with 20 or more O&G well starts per 10,000: births stratified by tertile of IA-IDW count for air pollution sources not associated with O&G activities.

	Low other air pollution sources ^a			Medium other air pollution sources ^a			High other air pollution sources ^a		
	Low ^b	Medium ^b	High ^b	Low ^b	Medium ^b	High ^b	Low ^b	Medium ^b	High ^b
Controls (N)	346	530	76	213	588	147	197	546	215
Any CHD									
Cases (N)	56	84	14	35	95	27	20	99	36
Crude OR	Ref	0.99 (0.69, 1.4)	1.2 (0.61, 2.2)	Ref	0.98 (0.65, 1.5)	1.1 (0.65, 1.9)	Ref	1.8 (1.1, 3.0)	1.6 (0.92, 2.9)
Adjusted OR (95% CI) ^c	Ref	1.2 (0.69, 2.1)	1.8 (0.73, 4.3)	Ref	1.3 (0.69, 2.4)	1.7 (0.73, 3.8)	Ref	2.4 (1.3, 4.5)	2.5 (1.2, 5.4)
AAVDs									
Cases (N)	23	38	7	11	40	9	6	42	11
Crude OR	Ref	1.1 (0.63, 1.8)	1.4 (0.57, 3.3)	Ref	1.3 (0.66, 2.6)	1.2 (0.48, 2.9)	Ref	2.5 (1.1, 6.0)	1.7 (0.61, 4.6)
Adjusted OR (95% CI) ^c	Ref	1.1 (0.48, 2.3)	1.6 (0.46, 5.3)	Ref	1.2 (0.43, 3.4)	1.3 (0.33, 4.8)	Ref	4.4 (1.6, 12)	3.5 (1.0, 12)
PAVD									
Cases (N)	20	27	< 5	14	39	10	10	41	16
Crude OR	Ref	0.92 (0.51, 1.7)	0.72 (0.21, 2.5)	Ref	1.0 (0.54, 1.9)	1.0 (0.45, 2.4)	Ref	1.5 (0.73, 3.0)	1.5 (0.65, 3.3)
Adjusted OR (95% CI) ^c	Ref	1.4 (0.55, 3.6)	1.6 (0.31, 8.2)	Ref	1.4 (0.56, 3.6)	1.9 (0.55, 6.4)	Ref	2.1 (0.91, 5.0)	2.4 (0.84, 6.8)
CTD									
Cases (N)	14	23	< 5	14	23	8	6	28	12
Crude OR	Ref	1.0 (0.53, 2.1)	1.3 (0.41, 4.0)	Ref	0.60 (0.30, 1.2)	0.83 (0.34, 2.0)	Ref	1.7 (0.69, 4.1)	1.8 (0.68, 5.0)
Adjusted OR (95% CI) ^c	Ref	1.5 (0.55, 4.2)	2.7 (0.54, 13)	Ref	1.1 (0.40, 3.2)	2.0 (0.48, 8.0)	Ref	2.5 (0.88, 7.1)	3.5 (0.97, 13)

AAVD = Aortic artery and valve defects, CHD = congenital heart defects, CTD = conotruncal defects, IA-IDW = intensity adjusted inverse distance weighted well count, IDW = inverse distance weighted count, N = number, O&G = oil and natural gas, PAVD = Pulmonary artery and valve defects, Ref = referent, TVD = tricuspid valve defects.

^a Low = 0 to < 4.14 intensity air pollution sources per square mile; medium = 4.14 to < 8.18 intensity air pollution sources per square mile, high = \geq 8.18 air pollution sources wells per square mile.

^b Low = 0 to < 1 intensity wells per square mile; medium = 1 to < 403 intensity wells per square mile, high = \geq 403 intensity wells per square mile.

^c Adjusted for IDW count of oil and gas facilities other than wells in 10-mile buffer, IA-IDW count of air pollution sources not associated with O&G activities in 10-mile buffer, maternal age, and SES group, as well as infant parity and sex.

cellular division during cardiac neural crest formation, an acute environmental exposure during cardiac neural crest formation could induce teratogenesis (Linask, 2013;). The air pollutants emitted from O&G operations have been associated with increased oxidative stress in animal models and humans (Amin et al., 2018; Ferguson et al., 2017; Sun et al., 2012, 2018). While it is plausible that an acute maternal exposure to one or more these stressors during embryonic cardiac neural crest formation could initiate a CHD, further study will be necessary to elucidate this biological mechanism.

Our study benefited from our selection of cases and controls from the same population. Because our cohort included all births in Colorado counties with O&G activities, it is representative of Colorado's population in these areas. Using our IA-IDW model, we were able to estimate the individual level of relative O&G well activity around the mother of each case and control. In addition to SES, density of O&G facilities other than wells, and intensity of air pollution sources not associated with O&G activities, we considered other potentially important confounders (maternal age, smoking, ethnicity, and residence in a rural area as well as infant sex and infant parity) in our study design. Because adjustment for birth year did not change our results, it is unlikely that changes in Colorado's population during the study period would affect our results.

The use of the LexisNexis® database to determine maternal residence during critical periods for development of CHDs is an improvement on previous studies, but it is not without limitations. Young, non-married, and Hispanic mothers were less likely to be found in the LexisNexis® database. The sensitivity analysis of births to mother's with an address found in the second gestational month indicates that this had minimal effect on our results. Similarly, accounting for the density of other O&G facilities and intensity of air pollution sources not associated with O&G activities is an improvement on previous studies, but limitations remain. Small scale fixed air pollution sources, such as gasoline stations, and mobile air pollution sources were not included in our analysis. This may be obscuring our ability to observe associations in

urban areas, such as Greeley CO, where these air pollution sources are more prevalent than in rural areas.

Our evaluation with zero wells in the 10-mile buffer as the referent and grouped IA-IDW > 0 into tertiles (see Supplemental Table 8) indicates that our choice of cut-points based on the multi-modal distribution of the IA-IDW well may have introduced some bias. However, we note that defining the referent group as IA-IDW equal to zero, results in a smaller referent group and loss of precision. Additionally, assigning cut-points based tertiles rather than the multi-modal distribution masks the effects of the highly exposed group indicated in Supplemental Fig. 1.

There also are limitations inherent to our study design and nature of the available data. CHDs remain undercounted, because data on non-live births, terminated pregnancies, and later life diagnoses (after age 3 years) is not available. Data on covariates were limited to information on the birth certificates and thus we were not able to adjust for maternal health and nutrition that may have resulted in residual confounding of unknown bias. A recent study suggests that methionine intake may modify the effect of maternal NO₂ exposures during pregnancy and CHD outcomes in offspring (Stingone et al., 2017) and offspring of mothers with pre-pregnancy diabetes are at a higher risk for CHDs (Correa et al., 2008). We were not able to account for the mother's time away from her residence, such as work and recreation, which may have led to exposure misclassification. This potential exposure error likely does not differ by cases/control status and thus has the potential to attenuate the reported results towards the null.

Our IA-IDW model estimated the average monthly intensities of O&G well site activities around the maternal residence, which may have obscured acute events on a shorter time scale (e.g. one-day). A recent study indicates that the developmental exposure window of concern could be as short as one day (Warren et al., 2016). Our inability to capture and evaluate short-time scale acute exposures may have attenuated the reported results towards the null. The small number of CTD

and TVD cases and in the stratified analyses for all CHD types led to wide confidence intervals and further attenuation towards the null.

5. Conclusion

This study provides further evidence of a positive association between maternal proximity to O&G well site activities and several types of CHDs, particularly in rural areas and in areas with high densities of air pollution sources not associated with O&G activity. At least 17 million people in the U.S and 6% of Colorado's population live within 1 mile of an active O&G well site. Taken together, our results and expanding development of O&G well sites underscore the importance of continuing to conduct comprehensive and rigorous research on the health consequences of early life exposures to O&G activities.

Declaration of Competing Interest

The authors declare they have no competing financial interests.

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Appendix A. Supplementary data

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Relationships between Indicators of Cardiovascular Disease and Intensity of Oil and Natural Gas Activity in Northeastern Colorado

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Structured Abstract

Background: Oil and natural gas (O&G) extraction emits pollutants that are associated with cardiovascular disease, the leading cause of mortality in the United States.

Objective: We evaluated associations between intensity of O&G activity and cardiovascular disease indicators.

Methods: Between October 2015 and May 2016, we conducted a cross-sectional study of 97 adults living in Northeastern Colorado. For each participant, we collected 1–3 measurements of augmentation index, systolic and diastolic blood pressure (SBP and DBP), and plasma concentrations of interleukin (IL)-1 β , IL-6, IL-8 and tumor necrosis factor alpha (TNF- α). We modelled the intensity of O&G activity by weighting O&G well counts within 16 km of a participant's home by intensity and distance. We used linear models accounting for repeated measures within person to evaluate associations.

Results: Adjusted mean augmentation index differed by 6.0% (95% CI: 0.6, 11.4%) and 5.1% (95%CI: -0.1, 10.4%) between high and medium, respectively, and low exposure tertiles. The

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greatest mean IL-1 β , and α -TNF plasma concentrations were observed for participants in the highest exposure tertile. IL-6 and IL-8 results were consistent with a null result. For participants not taking prescription medications, the adjusted mean SBP differed by 6 and 1 mm Hg (95% CIs: 0.1, 13 mm Hg and -6, 8 mm Hg) between the high and medium, respectively, and low exposure tertiles. DBP results were similar. For participants taking prescription medications, SBP and DBP results were consistent with a null result.

Conclusions: Despite limitations, our results support associations between O&G activity and augmentation index, SBP, DBP, IL-1 β , and TNF- α . Our study was not able to elucidate possible mechanisms or environmental stressors, such as air pollution and noise.

Introduction

Cardiovascular disease (CVD) is the leading cause of mortality in the United States (U.S.), accounting for more than 900,000 deaths and 3,000 per 100,000 persons age-standardized disability-adjusted life years (DALYS) in 2016 (Global Burden of Cardiovascular Diseases 2017; Global Burden of Cardiovascular Diseases 2018). While behavioral and genetic factors contribute to the burden of CVD, exposure to environmental stressors, such as air pollution, noise, and psychosocial stress, also contribute to cardiovascular morbidity and mortality (Brook 2017; Cuffee et al. 2014).

One increasingly common source of these environmental stressors is the extraction of oil and natural gas (O&G) in residential areas (Adgate et al. 2014; Czolowski et al. 2017; McKenzie et al. 2016). In the early 21st century, advances in hydraulic fracturing (fracking), horizontal drilling, and micro-seismic imaging opened up previously inaccessible petroleum reserves that resulted in an extensive dispersion of O&G well sites across populated areas (Haynes et al. 2017). More than 17.4 million people in the U.S. now live within 1.6 kilometers (km) (1-mile) of an active O&G well (Czolowski et al. 2017). In Colorado, this population is growing at a faster rate and may be at an economic disadvantage compared to Colorado's general population (McKenzie et al. 2016).

Populations living in areas with O&G development may be exposed to several environmental stressors that have been associated with CVD. The modern extraction of O&G is a complex industrial process that requires diesel-powered equipment, trucks, and generators that continuously emit noise and exhaust (King 2012; Blair et al. 2018; Brown et al. 2015; Hays et al. 2017; McCawley 2015; Radtke et al. 2017; Witter et al. 2013). Furthermore, normal operations, maintenance activities, and leaks at on-site storage tanks, valves, and pipes result in emissions of volatile organic compounds (VOCs) (Halliday et al. 2016; Helmig et al. 2014; Collett and Hecobian 2016; Collett et al. 2016).

Diesel exhaust from O&G operations contributes to increased levels of ambient particulate matter of < 2.5 microns (PM_{2.5}) (Brown et al. 2015, McCawley 2015). Numerous studies have provided evidence that increased short-term and long-term exposure to PM_{2.5} is associated with increases in cardiovascular morbidity and mortality (Brook et al. 2010; U.S. Environmental Protection Agency 2009). Noise levels measured in communities near O&G development sites have exceeded levels that have been associated with increased risk of CVD and hypertension (Blair et al. 2018, McCawley 2015, Radtke et al. 2017, Eriksson et

al. 2012, van Kempen et al. 2012). Additionally, co-exposures to noise and PM_{2.5} have been associated with indicators of CVD, including increases in systolic and diastolic blood pressure (SBP, DBP) (Brook and Rajagopalan 2009; Chang et al. 2009; Münzel et al. 2014; Urch et al. 2005; van Kempen and Babisch 2012; Zanobetti et al. 2004), vasoconstriction (Brook et al. 2002; Foraster et al. 2017; Laurent et al. 2001; Nurnberger et al. 2002; Dales et al. 2007; Rundell et al. 2007) and systemic inflammation (Delfino et al. 2008; Delfino et al. 2009; Nemmar et al. 2010), as well as morbidity and mortality (Brook et al. 2010).

The VOCs emitted from O&G activity are primarily aliphatic and aromatic hydrocarbons (Collett and Hecobian 2016; Collett et al. 2016; McKenzie et al. 2012). Inhalation exposure to hydrocarbons has been associated with alterations in cardiovascular physiology (Shin et al. 2015), increases in cardiovascular emergency department visits (Ye et al. 2017), and cardiovascular morbidity and mortality (Bard et al. 2014; Harrison et al. 2016; Villeneuve et al. 2013; Xu et al. 2009). Additionally, individuals living in communities where modern O&G wells sites are located may also experience increases in psychosocial stress (Malin 2014; Malin et al. 2018; Perry 2012; Powers et al. 2014; Sangaramoorthy et al. 2016; Shelley 2014; Wilber 2012, Casey et al. 2018a, Casey et al. 2018b, Fisher et al. 2018) that could also adversely affect SBP, DBP, vascular function, and systemic inflammation (Lu et al. 2013; Hänsel et al. 2010; Ranjit et al. 2007; Sparrenberger et al. 2008; von Känel et al. 2008; Yasui et al. 2007).

Epidemiological studies using administrative health data sources and indirect measures of exposure have observed associations between density of O&G wells and prevalence rates of cardiology inpatient hospital admission and congenital heart defects (Jemielita et al. 2016; McKenzie et al. 2014), as well as childhood leukemia, low birthweight, preterm birth, asthma, fatigue, migraines, and chronic rhinosinusitis (Casey et al. 2016; McKenzie et al. 2017; Rasmussen et al. 2016; Stacy et al. 2015; Tustin et al. 2016; Whitworth et al. 2017; Whitworth et al. 2018, Willis et al. 2018, Currie et al. 2017, Hill 2018, Koehler et al. 2018). While studies on the health impacts of O&G development have indicated increases in self-reported cardiovascular and other types of symptoms (Ferrar et al. 2013; Rabinowitz et al. 2015; Saberi et al. 2014; Weinberger et al. 2017) and cardiovascular related hospital admissions (Jemielita et al. 2016), we are not aware of any studies that have directly measured markers of cardiovascular morbidity in a population near active O&G development. The objective of this study was to evaluate the association between indicators of CVD and the intensity of O&G development and production activity in Northeastern Colorado.

Methods:

We conducted a cross-sectional study to evaluate associations between indicators of CVD and the intensity of O&G development and production activity within 16 km (10 miles) of a participant's home. The 16-km buffer was selected based on previous studies (McKenzie et al. 2014; McKenzie et al. 2017; Stacy et al. 2015).

Study Population

Between October 2015 and May 2016, we measured indicators of CVD in 97 men ($n = 28$) and non-pregnant women ($n = 69$) ≥ 18 years who did not smoke tobacco or marijuana, were not taking statins or other anti-inflammatory medication; were not occupationally exposed to dust, fumes, solvents, or O&G development activities; were not frequently exposed to environmental tobacco or marijuana smoke; and without a history of diabetes, chronic obstructive pulmonary disease, or chronic inflammatory diseases (such as asthma, arthritis, or severe allergies), and resided full-time in the city of Fort Collins, CO ($n = 46$), or in the cities of Windsor or Greeley, ($n = 51$) CO. As shown in Figure 1, most O&G wells were located in Greeley and Windsor; very few were located in Fort Collins. We obtained informed consent from all participants. The Colorado Multiple Institutional Review Board approved our study protocol (COMIRB protocol number 14–1880)

Each participant completed up to three visits to our clinics between October 2015 and May 2016. At each visit, participants completed a questionnaire on their recent level of exercise, food, caffeine, medication, and alcohol intake; exposure to air pollutants and stress; and overall health (Supplemental Material). We measured the participant's augmentation index, SBP, DBP, height, and weight and collected a blood sample for measures of systemic inflammation. Body mass index (BMI) was calculated as the weight (kg)/[height (meters)]².

Measures of Cardiovascular Health

We measured augmentation index and blood pressure with the SphygmoCor System (Atcor Medical Australia). To obtain these measures, the participant's dominant arm was extended onto a flat surface, ensuring that the bend in the elbow was at heart level. For blood pressure, three measurements were collected and the reported SBP and DBP is the average of the 2nd and 3rd measurements. Augmentation index is a non-invasive method that reasonably approximates carotid-femoral pulse wave velocity, which is the gold standard for measuring arterial stiffness (Laurent et al. 2006; Yao et al. 2017). For the augmentation index, a micro-nanometer flattened the radial artery with gentle pressure and ten seconds of sequential pulse pressure waveforms were recorded and transformed into central aortic waveforms. The augmentation index was then calculated by dividing the augmented pressure by the pulse pressure and was expressed as a percentage. The reported augmentation index is the average of three measures that have an operator index $>90\%$ and are within 10 % of each other. Because augmentation index is inversely proportional to heart rate, augmentation indices were normalized to a standard heart rate of 75 bpm (Wilkenson 2000, Wilkenson 2002). Because heart rate may also mediate augmentation index, we also evaluated augmentation index without normalizing for heart rate (Stoner et al. 2014).

Measures of Systemic Inflammation

We measured a suite of inflammatory markers that have been associated with psychosocial stress and short-term air pollution exposure: Interleukin (IL)-1 β , IL-6, IL-8 and tumor necrosis factor alpha (TNF- α) (Lu et al. 2013, Hänsel et al., 2010, Yasui et al. 2007, von Känel et al. 2008, Ranjit et al. 2007, Delfino et al. 2008, Delfino et al. 2009, Panasevich et al. 2009, Delfino et al. 2010). Venous blood was collected into EDTA tubes and centrifuged for 15 minutes at 2500 RPMs to separate the plasma, which was then stored at -80°C prior

to analysis. An analyst blinded to the participant's exposure measured IL-1 β , IL-6, IL-8 and TNF- α in duplicate using the commercially available R&D Biosystems (Minneapolis, Minnesota) Human Magnetic Luminex Performance Assay, High Sensitivity Cytokine kit, according to the manufacturer's protocol ((Vasunilashorn et al. 2015). Plates were read using a Luminex MagPix System (Luminex Corporation, Austin Texas).

Exposure Assessment

We used the Google Maps Geocoding Application Programming Interface to geocode each participant's street address with "Rooftop" accuracy. Google "Rooftop" accuracy indicates that the returned result is a precise geocode for which we have location information accurate down to street address precision (Google 2018). We obtained the latitude and longitude for all O&G wells within 16 km of each participant's home (McKenzie et. al. 2012, Stacy et. al. 2015, McKenzie et al., 2017, Whitworth 2017) from the Colorado Oil and Gas Information System. The 16-km buffer allows us to incorporate the density of O&G operations into the exposure metric which can be relevant for additional stresses on a community with a high density of operations such as trucking traffic, population influx, and allocation of resources. The 16-km buffer also captures the geographical extent of Fort Collins, Windsor, and Greeley. Extending the buffer beyond 16 km would create overlap in community level stressors, such as increased traffic and community cohesion. Using the latitude and longitude coordinates of the O&G wells and each participant's home, the distance between the participant's home and each O&G well in the 16-km buffer was calculated with MATLAB 8.3 software. We then applied our intensity adjusted inverse distance weighted (IA-IDW) model, as described in Allshouse et al. (2017), to estimate the monthly relative intensity of O&G activity around the home of each participant from August 2015 through April 2016 (Allshouse et al. 2017) and used the mean of monthly intensities over the 9-month period to represent the estimated intensity. To evaluate CVD responses to chronic O&G related exposure, we began our exposure assessment two months prior to the first collection of biomarkers.

Because the wells included in our IA-IDW exposure metric for an individual are weighted by distance between the well and the residence, the wells that are closest to the individual will contribute the most to that individual's metric. Our IA-IDW metric differs from methods that define an individual as exposed if they have a well within a given buffer without adjustment for distance or intensity of operations that occur at the well site (Currie et al. 2017 and Hill 2018). The final IA-IDW distribution was divided into tertiles (low, medium, and high) using cut points of 14.5 and 1242 well intensity per square km (km²) for subsequent statistical analysis.

Statistical Analysis

For each biomarker, adherence to assumptions of the linear random intercept model was assessed visually using scatter plots, histograms, and QQ-plots of the standardized residuals. Cytokine levels were log-10 transformed to better align with the model's assumption of Gaussian-distributed residuals (Diggle et. al. 2002). Because the systemic inflammation (IL-1 β , IL-6, IL-8 and TNF- α) results did not meet assumptions for linear regression, we log-10-transformed the systemic inflammation concentrations prior to statistical analysis.

The augmentation index, SBP, and DBP measurements met all assumptions for linear regression and were not transformed.

We used separate linear mixed models with random intercepts for each participant to evaluate the association between each health measurement (augmentation index, SBP, DBP, IL-1 β , IL-6, IL-8 and TNF $-\alpha$) and categorized intensity of O&G well activity (IAIDW) within 16 km of each participant's home (low, medium, high). The medium and high tertiles were compared to the low tertile (the referent group). Linear mixed models allow for unbalanced data (i.e., unequal number of repeated measures assuming data points missing at random) (Fitzmaurice et al. 2004). All models were adjusted for age, sex, race/ethnicity (white non-Hispanic vs. other/missing), BMI, education level (less than Bachelor's degree vs. Bachelor's degree or higher), income level (less than \$50,000/year vs. \$50,000/year or higher), and employment status (full-time employment vs. other). We evaluated our final models for residual spatial autocorrelation using semivariograms and found no evidence of residual spatial autocorrelation.

We performed sensitivity analysis on subsets of participants living only in Greeley or Windsor (no participants in the low IA-IDW tertile), reporting no illness in the past 24 hours, no alcohol use in the past 10 hours, no relocation of home in the past 3 months, or participants without an outlier result (defined as more than 1.5 times the IQR below and above the lower and upper bounds of the IQR, respectively). Based on participant questionnaire responses on their recent level of exercise, food, caffeine, medication, and alcohol intake, exposure to air pollutants and stress, and overall health, we evaluated interactions by the following categorical variables: the participant's sex, age (18–27, 28–52, 53–80 years), unusual stress (yes, no), vigorous physical activity in the past 7-days (none, 75 or more minutes), moderate physical activity in the past 7-days (none, at least 150 minutes), use of prescription medications (none, 1 or more), exposure to other sources of VOCs (yes, no), and ingestion of food or drink 60 minutes prior to health measurement (yes, no) to evaluate for effect modification. Unusual stress was determined to be yes if the participant indicated in the past 7-days that they had experienced unusual stress or in the past 3-months they had relocated their home, changed jobs, had someone close to them die, or experienced a major change in their family. Sources of VOCs included paint or cleaning fumes, fires, burning fireplaces, candles or incense.

Data analysis was conducted using R v3.4.3(R core Team 2017). The mixed effect models were fitted using the nlme v3.1–131 package (Pinheiro et al. 2017).

Results

Characteristics of our study population are presented in Table 1. Participants were approximately evenly divided between residing in Fort Collins (47%), with limited O&G activity, or in Greeley or Windsor (53%), which are areas of active O&G development. The participants in the low exposure tertile resided exclusively in Fort Collins, while those in the high exposure tertile resided in Greeley or Windsor. Participants in the high exposure tertile were older and less educated than participants in the other tertiles. Participants in the low

exposure tertile had lower incomes and were more likely to be working part-time than participants in the other tertiles.

Both crude and adjusted estimates indicate that augmentation index is associated with greater O&G activity around a participant's residence, as represented by IA-IDW (Table 2). Mean augmentation index, adjusted for only sex and age differed by 8.7% (95% CI: 4.1, 13.4%) and 6.9% (95%CI: 2.1, 11.7%) between the high and medium, respectively, and low IA-IDW tertiles. Further adjustment for race/ethnicity, BMI, education, income and employment status attenuated the results. Fully adjusted mean augmentation index differed by 6.0% (95% CI: 0.6, 11.4%) and 5.1% (95%CI: -0.1, 10.4%) between the high and medium, respectively, and low IA-IDW tertiles. We observed similar results for the mean augmentation index not normalized for heart rate, although the difference between tertiles was attenuated (Supplemental Table 1).

Systolic blood pressure, adjusted for only sex and age differed by 5 mm Hg (95%CI: 0, 10 mm Hg) and -1 mm Hg (95% CI: -6, 4 mm Hg) between the high and medium, respectively, and low IA-IDW tertiles. Further adjustment slightly attenuated the results. Fully adjusted mean SBP differed by 3 mm Hg (95% CI: -3, 8 mm Hg) and -1 mm Hg (95% CI: -6, 4 mm Hg) between the high and medium, respectively, and low IA-IDW tertiles.

Diastolic blood pressure, adjusted for only sex and age differed by 4 mm Hg (95%CI: 0, 7 mm Hg) and -1 mm Hg (95% CI: -4, 3 mm Hg) and between the high and medium, respectively, and low IA-IDW tertiles. Further adjustment slightly attenuated the results. Fully adjusted mean DBP differed by 2 mm Hg (95% CI: -1, 6 mm Hg) and -1 mm Hg (95%CI: -4, 3 mm Hg) (Table 2).

The greatest crude and adjusted mean IL-1 β , and α -TNF measurements were observed for participants in the highest exposure tertile (Table 3). We did not observe an association between IL-6 and IL-8 plasma concentrations and IA-IDW.

In a sensitivity analysis for participants living in Greeley or Windsor, reporting no illness in the past 24 hours, no alcohol use in the past 10 hours, no relocation of home in the past 3 months, or with participants with outliers removed, we observed results similar to the results for the whole population (Supplemental Tables 2–6), with one exception. With the exclusion of participants with outliers, the highest adjusted mean TNF- α plasma concentration was still observed in the high exposure tertile; however, the adjusted mean in the medium exposure tertile was lower than in the low exposure tertile.

We did not observe interactions between IA-IDW and the participant's sex, age, level of stress, level of physical activity, use of prescription medications, exposure to other sources of VOCs, and ingestion of food or drink 60 minutes prior to measurement of cardiovascular indicators with one exception. We found that use of prescription medications attenuated the difference in SBP (p-value for interaction = 0.113) and DPB (p-value for interaction = 0.564) between exposure tertiles (Table 4). For participants not taking any type of prescription medication, the adjusted mean SBP differed by 6 mm Hg (95% CI: 0.1, 13 mm Hg) and 1 mm Hg (95% CI: -6, 8 mm Hg) between the high and medium, respectively, and

low exposure tertiles. The adjusted mean DBP differed by 4 mm Hg (95%CI: -1, 8 mm Hg) and 0.4 mm Hg (95%CI: -5, 6 mm Hg) between the high and medium, respectively, and low exposure tertiles. For participants taking prescription medications, the differences between the exposure tertiles were smaller and consistent with a null result. While we did not observe interactions between IA-IDW and the participant's sex, we did observe larger differences between high, medium, and low IA-IDW tertiles for augmentation index, SBP, and DBP in men than women (Supplemental Table 7).

Discussion

In this population, we observed positive associations between the intensity of O&G activity within 16 km of a participant's homes and some indicators of cardiovascular disease. Augmentation index was highest in participants living in areas with the greatest O&G activity. Similarly, both SBP and DBP were highest in the subset of participants experiencing the greatest levels of O&G activity and who were not taking prescription medications. While IL-1 β and TNF- α plasma concentrations also were highest in participants living in areas with the greatest O&G activity, wide confidence intervals that include zero warrant caution in interpretation. In this population, we did not observe an association between IL-6 and IL-8 plasma concentrations and intensity of O&G activity.

Because this is the first study to evaluate the association between indicators of CVD and intensity of O&G activities, there are no previous results available for a direct comparison. However, our results are consistent with the observed increase in prevalence rates of cardiology inpatient hospital admission in areas of O&G activity (Jemielita et al. 2016). Additionally, because O&G activities are associated with increases in noise (Blair et al. 2018; Hays et al. 2017; Radtke et al. 2017; Witter et al. 2013), air pollution (Brown et al. 2015; Helmig et al. 2014; Collett and Hecobian 2016; Collett et al. 2016; McCawley 2015) and psychosocial stress (Hirsch et al. 2018; Malin et al. 2018; Mayer 2017; Fisher et al. 2018, Casey et al. 2018a, Casey et al. 2018b), we can compare our results to previous studies on exposure to these environmental stressors.

Our augmentation index results are similar to the 5.1–7.8% increases that have been reported following exposure of welders to an 8-hour time-weighted average PM_{2.5} concentration of 390 $\mu\text{g}/\text{m}^3$ or exposure of volunteers to diesel exhaust concentrations in an exposure chamber of 350 $\mu\text{g}/\text{m}^3$ (Fang et al. 2008; Lundback et al. 2009). The one study that evaluated the association between augmentation index and noise did not find evidence for an association (Khoshdel et al. 2016). Studies evaluating the cumulative impact of noise, stress, and PM_{2.5} experienced by our participants are lacking.

For participants not taking a prescription medication, our blood pressure results are similar to what has been reported for exposure to PM_{2.5}, noise, and psychosocial stress. Following 5–10 $\mu\text{g}/\text{m}^3$ increases in modelled or direct measures of personal ambient PM_{2.5} exposures in non-occupational adult populations, studies have reported increases in SBP ranging from 0.2 to 1.42 mm Hg and DBP ranging from 0 to 0.44 mm Hg (Auchincloss et al. 2008; Brook et al. 2010; Chan et al. 2015; Honda et al. 2018). In one study that considered the modifying effect of taking blood pressure medication, SBP and DBP increased by 6.01 and 3.42 mm

Hg four days following a $10 \mu\text{g}/\text{m}^3$ increase $\text{PM}_{2.5}$ exposure measured at central locations (Dvornch et al. 2009). Further study of this population found that self-reported levels of stress modified the association between exposure to $\text{PM}_{2.5}$ and blood pressure (Hicken et al. 2014). For each $10 \mu\text{g}/\text{m}^3$ increase in 2-day prior $\text{PM}_{2.5}$ exposure, participants reporting low stress showed a 2.94 mm Hg increase in SBP and those reporting high stress showed a 9.05 mm Hg increase in SBP (Hicken et al. 2014). Studies of adult volunteers exposed to noise have observed 1.43 and 1.40 mm Hg increases SBP and DBP, respectively, per 5-dBA increase in 24-hour noise exposure (Chang et al. 2009), and a 4.1 to 6.2 mm Hg and 7.4 mm Hg increases in SBP and DBP, respectively, following exposure to nighttime noise (Haralabidis et al. 2008; Schmidt et al. 2015). Studies on the effect of exposure to job strain and psychosocial stress have observed increases in SBP and DBP ranging from 1.2 to 7.7 mm Hg and 0.8 to 7 mm Hg, respectively (Ford et al. 2016; GilbertOuimet et al. 2014).

The increases in TNF- α plasma concentrations in participants in the highest exposure tertile are in the range of what has been reported following exposure to $\text{PM}_{2.5}$ and other air pollutants and stress (Delfino et al. 2008; Delfino et al. 2009; Grossi et al. 2003; Panasevich et al. 2009; Steptoe et al. 2002; Yasui et al. 2007). Studies have observed increases in TNF- α ranging from 0.36 to 1.06 pg/mL following exposure to several components of diesel air pollution (particles, EC, Organic Carbon, CO, and NO $_x$) for participants in the upper 25th percentile of TNF- α levels (Delfino et al. 2008; Delfino et al. 2009). Additionally, 1.8 to 15.7% increases in TNF- α levels have been observed to follow exposure to NO $_2$ and PM_{10} (Panasevich et al. 2009). Increases in TNF- α levels ranging from 5.4 to 6.5% have been observed following acute stress and burnout (Grossi et al. 2003; Steptoe et al. 2002). The differences we observed in plasma concentrations of IL-1 β between exposure tertiles are less than an 88% increase observed in women with psychological symptoms (Yasui et al. 2007). We did not observe the elevations in IL-6, that have been observed in previous studies on air pollutants and psychosocial stress (Delfino et al. 2008; Delfino et al. 2009; Delfino et al. 2010; Panasevich et al. 2009).

Biological Plausibility and Clinical Implications

Acute exposure to $\text{PM}_{2.5}$, noise, and psychosocial stress all can promote activation of the sympathetic nervous system, systemic inflammation, and oxidative stress, which, in turn, can result in autonomic nervous imbalance and enhance thrombotic and blood coagulation. This can result in acute (short-term) to chronic (longer term) elevation of blood pressure (Brook 2009, Brook 2017, Cuffee et al. 2014).

While the clinical implications of our results are uncertain, the CVD indicators explored in our study are important markers of cardiovascular health and the observed responses in our population are in the range that have been associated with increased risk of CVD. Augmentation index is a measure of atrial stiffness and is predictive of all cause and overall cardiovascular mortality as well as CVD (Laurent et al. 2006). Differences in augmentation index of 4.3% have been associated with a 20% increase in cardiovascular events in hypertensive diabetics (Yang et al. 2017). Cardiovascular mortality doubles for each 20 mm Hg and 10 mm Hg increase in SBP and DBP, respectively (Whelton et al. 2017) and each 10 mm Hg increase in DBP and SBP increases the risk of CVD and stroke (Franklin et al. 2001;

McCarron et al. 2000) Because associations between blood pressure and risk of CVD are on a continuous gradient (Whelton et al. 2017) and because millions of people may be affected given the growing intersection of O&G development and residential areas (Czolowski et al. 2017; McKenzie et al. 2016), the relatively small increases in SBP and DBP observed in this study could indicate substantial adverse impacts on overall cardiovascular risk at the national and possibly global public health level (Brook 2017).

Strengths and Limitations

Because our participants provided information on co-exposures and potential confounders each time they provided samples for biomarker measurements, we were able to assess the impact of many potential confounders and effect modifiers on these results, although residual confounding may remain. We were able to estimate the level of intensity of O&G activities within 16 km of each participant's home by applying a spatiotemporal industrial model developed to address this issue and that incorporates region-specific, data-driven activity and production information to estimate the relative intensity of air pollution emissions across four distinct phases of O&G activity (i.e., construction, drilling, completions, and production) (Allshouse et al. 2017). This model's O&G intensity estimates are strongly correlated with measured VOCs over all phases of well development and yields a 19-times greater dynamic range in exposure intensity estimates than other proximity-based methods (Allshouse et al. 2017). Therefore, we have confidence that this model is able to better categorize exposure among individuals, and therefore reduce exposure misclassification. However, the model has not been validated with noise or psychosocial stressor measures.

Our cross sectional study design, small sample size, the potential for residual confounding, and lack of direct measures of noise and air pollution are important limitations of this analysis. Because of the small sample size, and potential for residual confounding and exposure misclassification, our results for IL-6 and IL-8 may be biased towards the null. The participants who volunteered for our study may be different from nonparticipants in many ways, so our results may not be applicable to the general population. Our study population of mostly female, healthy, adult, English-speakers in Northeast Colorado may further limit the generalizability of our results. There is limited evidence that blood pressure and inflammatory responses to chronic stress, noise, and PM_{2.5} may be more pronounced in men than women (Gilbert-Ouimet et al. 2014, Hicken et al 2014, Hajat 2015, van Kempen and Babisch 2012) and our results stratified by sex support this observation (Supplemental table 7). Therefore, the over representation of women in our study may have attenuated the results towards the null. Because we did not directly measure exposure to noise and air pollution, our study was not able to elucidate possible mechanisms or environmental stressors that might be involved. Additionally, limitations in our exposure estimate and sample size prevent us from evaluating dose-response effects. Lastly, because we conducted numerous statistical tests, we recognize that we could observe statistically significant associations by chance. These limitations can be addressed in the future by using more robust study designs in larger, population-based studies of residents exposed to oil and gas development.

Conclusion

In this cross-sectional study of 97 participants living in Northeast Colorado in 2016, we observed evidence supporting an association between the intensity of O&G activity and several indicators of cardiovascular disease.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights:

- Augmentation index increased as O&G activity intensity increased.
- SBP increased with O&G activity intensity in participants not taking medication.
- DBP increased with O&G activity intensity in participants not taking medication.
- IL-1 β plasma concentrations peaked in the highest O&G activity intensity area.
- TNF- α plasma concentrations peaked in the highest O&G activity intensity area.

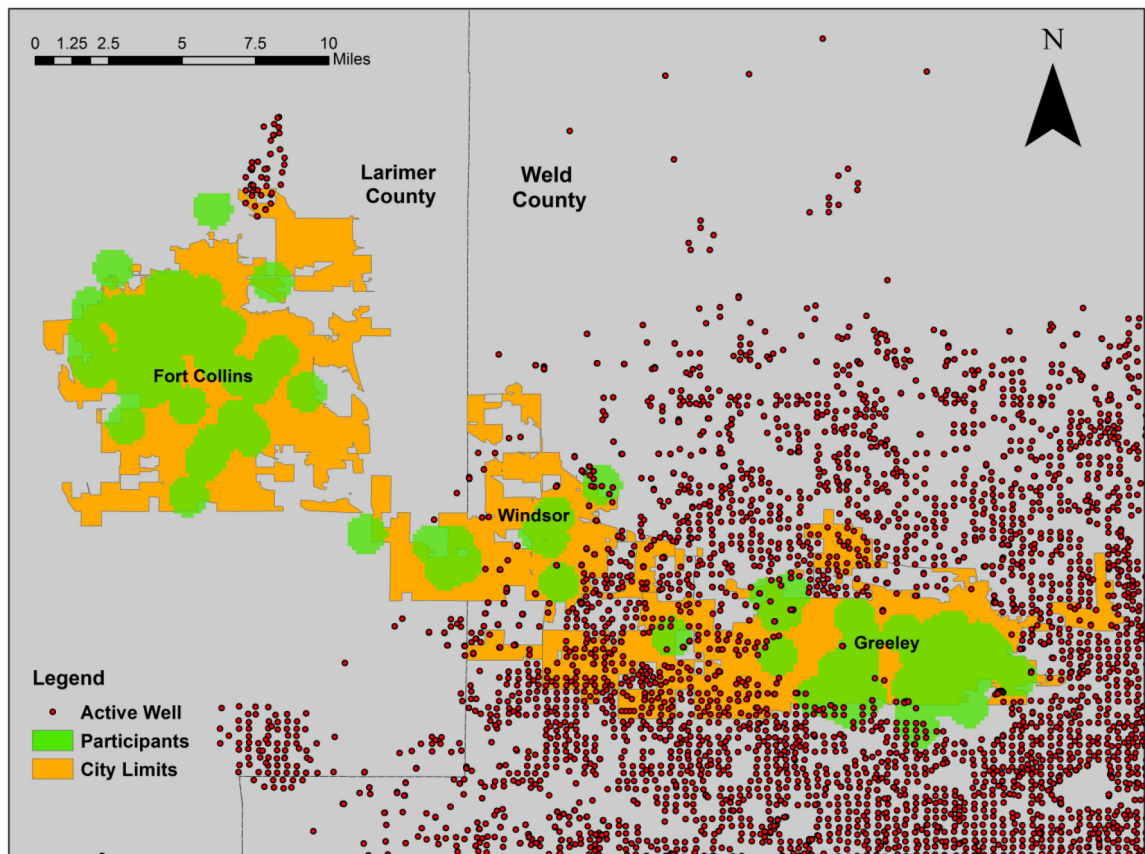


Figure 1.

Study area is located in Northeastern Colorado: 46 participants from Fort Collins with little oil and gas activity in 2016, 51 participants from Windsor and Greeley where active oil and gas development was ongoing as of June 2016.

Table 1.

Study population characteristics categorized by tertiles of intensity adjusted inverse distance weighted (IA-IDW) oil and gas well count within 16.1 kilometers of residence of each participant in 2016.

Characteristic	IA-IDW		
	Low (0 –14.5 well intensity/kilometer ²)	Medium (14.6–1242 well intensity/kilometer ²)	High (High > 1242 well intensity/kilometer ²)
Number of Participants (N)	32	33	32
Community (N, percent)			
Ft. Collins	32 (100)	14 (42)	0
Greeley & Windsor	0	19 (58)	32 (100)
Female (N, percent)	23 (72)	21 (64)	25 (78)
Age (mean ± SD years)	39 ± 19	37 ± 18	50 ± 17
Race/Ethnicity (N, percent)			
Non-Hispanic White	24 (75)	26 (79)	27 (84)
Other	8 (25)	6 (18)	5 (16)
Missing	0	1 (3)	0
Body Mass Index (mean ± SD kg/m ²)	24 ± 4	25 ± 4	26 ± 6
Annual Income (N, percent)			
Less than \$50,000	25 (78)	11 (33)	16 (50)
\$50,000 or greater	7 (22)	21 (63)	16 (50)
Missing	0	1 (3)	0
Education bachelor's degree or higher (N, percent)	30 (94)	26 (79)	21 (66)
Employment (N, percent)			
Full-Time	11 (34)	11 (33)	11 (34)
Part-Time	17 (53)	8 (24)	8 (25)
Not Working	4 (13)	14 (42)	13 (41)
Participants completing each visit (N, percent)			
1	32 (100)	33 (100)	32 (100)
2	30 (94)	27 (82)	25 (78)
3	28 (88)	25 (76)	28 (88)

IA-IDW = intensity adjusted inverse distance weighted count of oil and gas wells within 16.1 kilometers of residence N = number, SD = standard deviation

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Table 2.

Biomarker means and differences for each tertile of intensity adjusted inverse distance weighted oil and gas well count (IA-IDW) within 16.1 kilometers of residence of each participant in 2016. Differences between means compared to low IA-IDW tertile for each measure of cardiovascular health, i.e., augmentation index, systolic blood pressure, diastolic blood pressure.

Biomarker (N)	Mean (95% Confidence Interval)				Difference between means (95% Confidence Interval)		
	Low ¹ N = 92	Medium ¹ N = 81	High ¹ N = 81		Low ¹ N = 92	Medium ¹ N = 81	High ¹ N = 81
Augmentation Index (percent at HR 75)							
Crude	5.0 (0.7, 9.3)	16.8 (12.5, 21.0)	14.7 (10.4, 19.0)	Referent	11.8 (5.7, 17.9)	9.7 (3.5, 15.9)	
Adjusted ²	9.1 (5.6, 12.6)	15.9 (12.4, 19.5)	17.8 (14.4, 21.0)		6.9 (2.1, 11.7)	8.7 (4.1, 13.4)	
Adjusted ³	10.9 (5.3, 16.5)	16.0 (11.0, 21.1)	16.9 (11.8, 22.0)		5.1 (-0.1, 10.4)	6.0 (0.6, 11.4)	
Systolic Blood Pressure (mm Hg)							
Crude	119 (115, 122)	120 (116, 124)	123 (119, 127)	Referent	1 (-4, 7)	5 (-1, 10)	
Adjusted ²	117 (113, 121)	116 (112, 120)	122 (118, 126)		-1 (-6, 4)	5 (0, 10)	
Adjusted ³	117 (112, 123)	116 (112, 121)	120 (115, 125)		-1 (-6, 4)	3 (-3, 8)	
Diastolic Blood Pressure (mm Hg)							
Crude	73 (70, 75)	73 (70, 75)	77 (74, 79)	Referent	0 (-4, 3)	4 (0, 7)	
Adjusted ²	72 (70, 74)	71 (68, 74)	76 (73, 78)		-1 (-4, 3)	4 (0, 7)	
Adjusted ³	74 (70, 78)	73 (70, 77)	76 (73, 80)		-1 (-4, 3)	2 (-1, 6)	

¹ Tertile of IA-IDW = intensity adjusted inverse distance weighted count of oil and gas wells within 16.1 kilometers of residence: Low = 0 – 14.5 well intensity/kilometer², Medium 14.6 – 124.2 well intensity/kilometer², High > 124.2 well intensity/kilometer².

² Adjusted for age and sex

³ Adjusted for age, sex, race/ethnicity, BMI, education, income, and employment.

HR= heart rate, mm Hg = millimeters of mercury, N = number

Table 3

Biomarker means and differences for each tertile of intensity adjusted inverse distance weighted oil and gas well count (IA-IDW) within 16.1 kilometers of residence of each participant in 2016. Difference between means compared to low IA-IDW tertile, and each individual marker of inflammation, i.e., interleukins -1β , -6 , -8 , and TNF $-\alpha$.

Biomarker	Mean (95% Confidence Interval)			Low ²	Difference between means (95% Confidence Interval)	
	Low ²	Medium ²	High ²		Low ²	High ²
Observations (N)	92	81	81	92	81	81
Interleukin-1 β (pg/ml)						
Crude	0.552 (0.504, 0.604)	0.560 (0.510, 0.614)	0.623 (0.567, 0.684)	Referent	0.008 (-0.063, 0.080)	0.071 (-0.005, 0.149)
Adjusted ¹	0.546 (0.465, 0.637)	0.557 (0.481, 0.642)	0.610 (0.527, 0.701)		0.012 (-0.070, 0.091)	0.064 (-0.022, 0.149)
Interleukin-6 (pg/ml)						
Crude	0.815 (0.695, 0.950)	0.889 (0.757, 1.04)	0.934 (0.794, 1.09)	Referent	0.075 (-0.114, 0.266)	0.119 (-0.076, 0.318)
Adjusted ¹	0.964 (0.774, 1.19)	0.842 (0.689, 1.02)	0.902 (0.740, 1.09)		-0.122 (-0.311, 0.056)	-0.062 (-0.256, 0.125)
Interleukin-8 (pg/ml)						
Crude	5.03 (4.42, 5.71)	4.95 (4.34, 5.61)	5.41 (4.74, 6.16)	Referent	-0.082 (-0.991, 0.826)	0.384 (-0.570, 1.35)
Adjusted ¹	5.67 (4.54, 6.99)	4.71 (3.85, 5.69)	5.59 (4.58, 6.76)		-0.963 (-2.08, 0.070)	-0.079 (-1.25, 1.05)
Tumor Necrosis Factor- α (pg/ml)						
Crude	4.57 (4.02, 5.17)	5.13 (4.53, 5.81)	5.19 (4.56, 5.88)	Referent	0.568 (-0.289, 1.44)	0.622 (-0.245, 1.50)
Adjusted ¹	4.70 (3.79, 5.75)	4.82 (3.99, 5.78)	5.03 (4.15, 6.04)		0.124 (-0.799, 1.02)	0.329 (-0.632, 1.27)

¹ Adjusted for age, sex, race/ethnicity, BMI, education, income, and employment.

² IA-IDW = intensity adjusted inverse distance weighted count of oil and gas wells within 16.1 kilometers of residence: Low = 0 – 14.5 well intensity/kilometer², Medium 14.6 – 1242 well intensity/kilometer², High > 1242 well intensity/kilometer².

% = percent, pg/ml = picograms per milliliter, TNF = tumor necrosis factor

Table 4.

Biomarker means and differences for each tertile of intensity adjusted inverse distance weighted oil and gas well count (IA-IDW) within 16.1 kilometers of residence of each participant in 2016. Difference between systolic and diastolic blood pressure (SBP and DBP, respectively) means compared to low IA-IDW tertile, and SBP and DBP results stratified by prescription medication use¹.

Biomarker	Mean (95% Confidence Interval)			Difference between means (95% Confidence Interval)		
	Low ²	Medium ²	High ²	Low ²	Medium ²	High ²
Observations (N)	87	81	81	87	81	81
Systolic Blood Pressure (mm Hg) p= 0.113 ³						
No prescription medications (N=108)	115 (109, 120)	115 (109, 122)	121 (116, 126)	Referent	1 (-6, 8)	6 (0.1, 13)
One or more prescription medications (N=141)	119 (113, 124)	117 (112, 122)	119 (114, 125)		-2 (-8, 3)	-0.6 (-7, 5)
Diastolic Blood Pressure (mm Hg) p = 0.564 ³						
No prescription medications (N=108)	72 (68, 77)	73 (68, 77)	76 (72, 80)	Referent	0.4 (-5, 6)	4 (-1, 8)
One or more prescription medications (N=141)	75 (71, 79)	73 (70, 77)	76 (72, 80)		-2 (-6, 3)	1 (-3, 6)

¹ All results adjusted for age, sex, race/ethnicity, BMI, education, income, and employment.

² IA-IDW = intensity adjusted inverse distance weighted count of oil and gas wells within 16.1 kilometers of residence: Low = 0 – 14.5 well intensity/kilometer², Medium 14.6 – 124.2 well intensity/kilometer², High > 124.2 well intensity/kilometer².

³ p-value for interaction between prescription medication use and IA-IDW tertile.

mm Hg = millimeters of mercury, N = number of observations

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Thank you, all of you for your tremendous efforts on giving Coloradans the best healthiest lifestyles. I appreciate everything you've accomplished on bills, when you're ensuring the safety and healthiest outcome for your residences and you are making them the first priority.

I am an El Paso County resident and a recreational enthusiast. I know there are many bills for you to address but today I feel that the HB24-159 is setting the pace for the rest of the year and I need you to consider passing this bill so we can continue to enjoy the outside. I moved from the pollutants in California so that my family could increase their appreciate for the outdoors with cleaner air.

Recently, I've noticed that the air pollution has increased and the warning days have been taking away from our time to be outdoors. I can't expose my kids and ill family members to that kind of pollutants. My ill family members want to live healthy lives by being active outside to help their immune system and help them release stress, but they can't increase their chances of getting sicker by being outside on those days. Colorado needs to stand by the limitations set by the Clean Air Act requirements. I feel that when the permitting process comes in for a certain company wanting to start drilling for oil and gas operations, the APCD is splitting up the oil and gas operations into many different minor source permits, allowing them to be excluded from air permitting considerations. This tactic is not just, for a company to act this way. Consider passing this bill so there can be accurate account of the emissions of a project. This bill will also help in requiring minor sources in the Denver Metro\North Front Range nonattainment area to meet all applicable regulations, including that it will not cause or contribute to the exceedance of any applicable ambient air quality standard. This demonstration must be based on air quality modeling of at least the 1 hour NOx standard.

Thank you for your time.



HB24-159 - Mod to Energy & Carbon Management Processes

Dear bill sponsors,

One of the major points of concern about the bill is O&G workforce, assets, and knowledge abandonment over time.

Last year **HB23-1074** - Study Workforce Transitions To Other Industries was approved. It focuses on "Evaluate the skill transferability of workers in the oil and gas industry and in occupations in Colorado that are facing the most disruption due to automation". The study is not due until the end of this year.

One major element of this study is enhanced geothermal systems which shows real promise, not only to transition skills from O&G, but to also transition energy supply itself. Deep geothermal is emission free, abundant, steady, resilient, and equitable. New technologies for deep rock drilling will be fully developed within the time frame of HB24-159 (www.quaise.energy for example). Additionally, Gov. Polis is an advocate of geothermal. He introduced his "Heat Beneath Our Feet" initiative at last year's WGA conference.

I recommend that HB14-159 be delayed until the context of this study can be fully addressed.

Thank you for your consideration.

Peace and Strength,

Eric Darst (eric@civilution.org)



INDIVISIBLE COLORADO

March 28, 2024

**Members of the Colorado Senate Agriculture and Natural Resources Committee
Re: SB 159 Modifications to Energy and Carbon Management Processes**

Dear Chair and Committee Members,

We urge your support of SB 159. Indivisible Colorado consists of dozens of grassroots Indivisible groups throughout the state including over 32,000 Coloradans. We are teachers, architects, priests, planners, civil servants, small business owners, artists, retirees, nurses, contractors, and many more. We are Coloradans, and we are concerned by the tepid commitment shown so far in the state's leadership to address the climate crisis.

We deeply regret that so far Republicans cannot be counted on to help unite our state in pursuit of a better future for Colorado. We are grateful that most Democrats have done "more than ever" to fight climate change, but as we know that's a bar far too low for the scale of the crisis we face. We ALL must do ALL we can and you are in a position to do more than most.

SB 159 makes common sense changes to tackling two critically important aspects of our inevitable transition away from fossil fuels; it provides a timeline to phase-out new drilling permits in Colorado, and ensures that taxpayers are not left to clean-up the devastation more than 100,000 wells will cause, indefinitely.

Other states and federal agencies are ahead of us in addressing these problems, why not Colorado? Because without reform, orphan wells will cost our state hundreds of millions of dollars, at a minimum, possibly billions. That is not acceptable while our teachers are paid some of the lowest salaries in the nation, where housing, senior care, child care and so many other needs go unmet. We cannot afford to clean -up after the oil and gas industry, we do not have this money. Nor is it for the common good to continue to pay for fossil fuel extraction, when we clearly know the very activities we subsidize do us harm.

Please be mindful that the corporate welfare we provide the oil and gas industry comes at a high cost to the welfare of your constituents.

Pass SB159. Have a plan to stop burning our future.

Elizabeta Stacishin
Indivisible Colorado, Climate Policy

I see no reason, no common good in using taxpayer money to perpetuate the use of a fuel that is polluting our air and destroying our planet. Stop the corporate welfare already. Building more gas lines locks ratepayers into the use of gas or methane, whose pollution and volatile price swings can be easily avoided with cheap modern technology.

Reform the Oil & Gas Conservation Act to hold prior owners financially liable as many federal agencies and other states already do. Without reform, orphan wells will cost the state hundreds of millions of dollars at a minimum.

(I) Regulate the development and production of the natural resources of oil and gas in the state of Colorado in a manner that protects public health, safety, and welfare, including protection of the environment and wildlife resources;

(II) Protect the public and private interests against waste in the production and utilization of oil and gas

Update liability provisions of the Act to include new technologies including carbon capture and geothermal.

The climate crisis is accelerating and Americans are feeling the impact. Dramatically reducing methane emissions is one of the quickest, highest-impact actions we can take to begin stemming the climate and pollution crisis today.

We thank you for your work and urge the EPA to support the strongest, most comprehensive methane rules possible to protect our health from all sources of oil and gas methane pollution, to slow down the degradation of our environment and minimize harm to ourselves and future generations.

Indivisible Colorado is a statewide coalition of over 30,000 individuals in local groups across the state. We are teachers, architects, priests, planners, civil servants, school administrators, small business owners, artists, retirees, healthcare administrators, nurses, landscape architects, contractors, painters and many, many more. We are Coloradans, and we are concerned by the tepid commitment shown so far in our state to address the climate crisis. We deeply regret that so far Republicans cannot be counted on to help unite our state in pursuit of a better future for a livable Colorado. We are grateful that most Democrats have done “more than ever” to fight

climate change, but as we know that's a bar far too low for the scale of the crisis we face. We ALL must do ALL we can and you are in a position to do more than most.

We are here, Indivisible Colorado is here today to urge you to support SB-159. We must have a plan to phase out new permits for drilling oil and gas. This bill does not stop Colorado from continuing to be a major polluter and producer of fossil fuels. It simply puts a cap

We urge those of you who are lobbying on behalf of the fossil fuel industry to think about the wellbeing of all of us, not just your financial gain or political influence of a few. Use your influence for the common good, we need your help. We are in this together, be creative.

A better builder than this one would accomplish all of this sooner, SB 159 is already a compromise we have no time to waste this is an emergency Mr. Robert what is your plan if not now when under what conditions what are your deadlines what are your threshold what's the critical measures, or is this not your problem? I urge you to support this bill. You know this is needed and it's needed now, later is too late.

We are here to speak of protect our near future we all share. Present profits vs

While these bills aren't perfect, they take meaningful steps in the right direction towards reducing our GHG emissions, protecting habitat, modernizing power transmission, encouraging EV ownership, protecting people from air pollution, cleaning-up oil and gas operations, exploring new sources of renewable energy, encouraging transit use and more. Individually these bills aren't enough, but together they can take us closer to where we need to go

Members of the Senate Agriculture and Natural Resources Committee,

I am writing to express my strong support for Senate Bill 24-159. My support for this bill is deeply personal. My child suffers from a heart condition, and our family has endured significant financial strain due to the medical expenses associated with managing health conditions exacerbated by air pollution.

The current situation is fundamentally unjust. The costs of pollution are real and tangible, affecting the health and financial stability of families across our state. Yet, the burden of these costs is unfairly paid by individuals. This is nothing short of freeloader shifting the costs of their actions onto others.

It is well-established in business that the correct allocation of costs is essential for making informed decisions. By preventing the true costs of operation from being accounted for, Oil producers are unable to make appropriate business decisions. This lack of transparency distorts the market and hinders the ability of companies to operate responsibly, let alone ethically. Furthermore, as a conservative, I also believe in the principles of self-responsibility, and it is frustrating to witness our conservative representatives enabling this form of freeloading by hiding the costs producers create, and harm they cause. This morally indefensible.

Senate Bill 24-159 represents a crucial step towards rectifying this imbalance. By requiring gas and oil companies to cover the costs of maintaining and closing wells that pollute our air, we ensure externalities are cost accounted. This is not only fair but also essential for promoting responsible business practices, not freeloaderism.

I urge you to support Senate Bill 24-159 and take a stand against freeloading. Through correct cost accounting, we can protect the health of our families, promote economic fairness, and uphold conservative principles of responsibility and accountability.

Thank you for considering my testimony.

Kyle Prawel
Fort Collins, CO

SB24-159 - No New Permits by 2030

My name is Kathleen J Graves. I am a constituent.

It is time. The frustration we all feel when problematic issues are great, serves us today. We can work together to make change to improve our Colorado environment. By Phasing Out New Oil and Gas Permits by 2030, the bill SB24-159 recognizes, in this time of transition to greener energy, that Colorado can take on a leadership role. A leadership role! New oil and gas adds to the pollution here at home. We, the people living in Colorado, have more than enough wells for our own needs and to sell gas and oil for profit.

I am an artist. Yes, I articulate both beauty and allegory about environmental and landscape issues in my work. We are at a Threshold looking out towards our future and our children's and grandchildren's future. We have this opportunity to create a lever of change.

Oil and gas pollution is a public health issue that causes heart and lung diseases, asthma and intestinal problems. People die prematurely!

This bill, SB24-159 allows for a reasonable amount of time to plan and prepare to end the permits.

The transition to renewables is already underway globally. This bill provides time for industry to reorganize and pays attention to workers and communities to resolve their needs.

Air pollution in our state is a danger to each one of us. Do you run in a park, bike ride, walk to work? Think about this for yourselves and your family.

We see now that climate change brings on harsher wildfires, flooding and higher yearly temperatures that harm us all.

This is an opportunity! An opportunity to personally handle a piece of our future. This is your opportunity with our backing to act. I urge you to put aside frustration and act to pass this No New Permits Bill. If you are not yet convinced may I remind you we currently have 50,000 active wells in Colorado that will not be phased out. They produce 4 times the amount of fossil gas and twice as much oil as Colorado uses.

These facts prove it is a logical step. This bill will increase the quality of our air and keep our mountains healthy to enjoy. Let us work together to end frustration and make these changes. Thank you.

SB24-159 - No New Permits by 2030

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These facts prove it is a logical step. This bill will increase the quality of our air and keep our mountains healthy to enjoy. Let us work together to end frustration and make these changes. Thank you.

Dear Colorado Legislators,

I support SB24-159, which is integral to reducing greenhouse gases in Colorado, improving the public health of Coloradans, and providing for increased efficiency in well clean-up while protecting taxpayers.

This bill is necessary for reducing greenhouse gases in Colorado and keeping the planet from warming more than 1.5 degrees Celsius. For too long now, governments and corporations have danced around the issue of climate change, when it has been clear to scientists for years that the only way to prevent climate change is to phase out oil and gas. This bill is incredibly important to the fight against climate change and could have a big impact, since Colorado is the fifth largest oil producer and eighth largest natural gas producer in the country. This bill would require that no new oil and gas permits be issued after January 1, 2030. It does not impact the 50,000 active wells, which will continue to produce more than Colorado needs for decades. This bill is essential for preventing the worst impacts of climate change. Coloradans have already been impacted through droughts, wildfires, flooding, and extreme heat, and continuing the use of oil and gas will exacerbate these issues. With the phase out of oil and gas we can hopefully slow or maybe even revert these effects.

Ending the expansion of oil and gas development is vital for public health and environmental justice. Oil and gas pollution is known to cause premature death, heart and lung disease, neurological issues, and gastrointestinal problems. While oil and gas pollution impacts over half of Coloradans, it disproportionately impacts certain communities. For that reason, I am glad that this bill will prioritize the reduction of oil and gas permits in disproportionately impacted communities.

Finally, this bill provides reforms to the clean-up and plugging of orphan wells. Currently, orphan wells are the state's responsibility. However, orphan wells can cost upwards of \$100,000 to plug. Colorado has 500 orphan wells that need to be plugged at the moment and another 1,200 are expected. The state is only able to plug about 60 wells a year, meaning that it will take 8 years to plug the existing 500 orphan wells. Unplugged wells contaminate soil and groundwater and leak methane gas, which contributes to climate change. Currently, all excess liability for orphan wells lies with the state instead of the prior owner. This bill would shift the liability to the prior owners and allow the state to recover its costs from the operators, protecting taxpayers.

As a Coloradan, I greatly appreciate the efforts of SB24-159 to mitigate the impacts of climate change, improve public health for Coloradans, and provide much needed reform for orphan well clean up. Over my lifetime, I have seen the wildfire season extend, temperatures rise, and erratic weather in my home state due to the continued use of oil and gas. I am hopeful that a phase out of new oil and gas permits under SB24-159 will significantly improve the lives of Coloradans. Please approve bill SB24-159.

Sincerely,

Shelby Behr

Good afternoon. Thank you for letting me speak today.

My name is Sandra Covelli and I am a married 75 year old native of Colorado and a retired small business owner

In December of 2022 our home heater went out. Since the country is headed for zero carbon emissions and phasing out natural gas stoves and heaters, my husband and I decided to go with electric heaters. This year my bill for February was over \$500.00. When we were using natural gas our gas bills were always under \$200.00 a month during the winter.

At our ages it makes no fiscal sense to take out a 20 year loan to put in a solar system. Nor do we wish to purchase an electric vehicle.

Beside my own monetary concerns I am also concerned about the state losing over 34 billion dollars a year and over 50 thousand direct jobs and over 250 thousand indirect jobs.

I don't know whether any of you remember or know about Black Sunday during the 1980's when Exxon pulled out of Colorado. At that time Colorado lost over 1 million dollars a day and thousands of jobs. I only mention this because at the time I was selling my father's house and foreclosures were advertised in the weekend newspapers and there were pages of them. Which made it very difficult to get a decent price for single family homes. I would hate to see that happen again.

I have a few questions for you.

1. How is the state planning on replacing the 34 billion dollars of lost revenue?
2. What is the state going to do for the 50 thousand plus people that will be unemployed?
3. What is the state going to do for the senior citizens and others on fixed incomes to soften the economic impact?

March 12, 2024

RE: SB24-159 (Mod to Energy & Carbon Management Processes)

Dear Senate Agriculture and Natural Resources Committee

Your action in support of SB24-159 is important. It really matters for the physical health of employees and businesses on the Front Range and the economic health of communities and businesses statewide which are vulnerable to increasing heat, drought, fires, and floods.

The oil and gas industry harms and takes from Colorado far more than it helps, as multiple studies have shown. Leadership is needed now to phase out permitting in our state and to ensure Colorado's 100,000 active and closed wells don't continue polluting, it is also crucial that polluters pay the cost of plugging and remediation that has too often been pushed off to the taxpayers.

This bill will phase out the approval of new oil and gas permits by 2030 (something other states have done already, sooner) prioritizing permit reductions in disproportionately impacted communities first, and hold oil and gas operators responsible for the costs to cleanup dead and dying wells. This is just and the least we can do. It would not affect production from current wells. It also requires follow up on the in-progress study required by HB23-1074 to determine how to support oil and gas workers and communities impacted by the transition away from oil & gas expansion.

We need to set an end date to the fracking industry's relentless expansion by phasing out new permits. A transition is already underway and this is responsible policy to manage it. Industries such as agriculture and outdoor recreation are already suffering damages from climate change and we need to do everything we can to avert further disaster. Drought is expected to worsen in Colorado and new oil and gas wells use billions of gallons of surface water and groundwater. According to the National Academy of Science, for each 1°C temperature rise crop yields decline by 7.4% for corn, 6% for wheat, 3.2% for rice, 3.1% for soy. Temperatures have already risen more than 2°C in 15 of our counties.

Science Daily says 80% of world's croplands will be affected by water scarcity due to climate change. In 2019 20 million acres couldn't be planted in the US due to flooding and heavy rainfall - USDA. New invasive pest species proliferate under warmer conditions (like the corn ear worm that hit our Olathe sweet corn and the grasshopper 'invasion' last year) — CABI Ag and Bioscience. Also, more CO2 causes loss of nutritional value so lowers commodity prices (impacting levels of zinc, iron, copper, magnesium and calcium in rice, wheat and soybeans) - National Inst. of Health. Let's protect our and our children's future. Later is too late!

Thank you for your service,

Marie Venner, **Colorado Small Business Alliance** and Steve Douglas, Mayor, as **former CO City Council Members and Planning Commissioners**

Fran Aguirre, President, **Unite North Metro Denver**

Thomas Lundy, Co-Chair of the **CDP Energy & Environment Initiative**

Dr. David Mintzer, Hospitalist, on the board of **Colorado Physicians for Social Responsibility**

Dr. Velma Campbell & Jamie Valdez, Colorado Lead, **Mothers Out Front**

Emmett Hopley, Co-Chair, **Montbello Neighborhood Improvement Association**
Maura Stephens, Coordinating Committee, **System Change Not Climate Change**
Jan Brown, **Citizens' Alliance for a Sustainable Englewood**
J.D. Ruybal, **COCRN Colorado Community Rights Network**
Kristi Douglas, Co-chair, **North Range Concerned Citizens**
Trupti Suthar, **Sunnyside United Neighbors, Inc (SUNI)**
Philip Beck and Elizabeta Stacishin, Co-founders, **Indivisible Ambassadors**
Bridget Walsh, **Greater Park Hill Community**
Paddy McClelland, Co-Chair, **Wall of Women**
Shannon Francis, Director, **Spirit of the Sun**
Moshe Kornfeld, Coordinator, **CO Jewish Climate Action**
Fred Kirsch, Director, **Community for Sustainable Energy**
Stefanie Klass, Co-Chair, **Colorado Call to Action** and **CatholicNetwork**
Debbie Thornburg James, **Mayfair Park Neighborhood Association Board**
Nic Venner, **Metro State Student** and **Our Children's Trust *Juliana* Plaintiff**
Amy Petré Hill, Founder and Community Chaplain, **Mental Health & Inclusion Ministries**
Rachael Lehman, Healthy Communities Chair, **I-70/Vasquez Blvd Citizens Advisory Committee**
Paolo C. Solorzano of the **Transit Riders Alliance** and **Colorado Cross Disabilities Coalition**
Anna Ramirez, **Working for Racial Equity** and **Southwest Organization for Sustainability**
Patrick Santana, **Vibrant Littleton** and **Littleton Business Alliance**
Yadira Sanchez, mother and longtime Denver resident **Elyria Swansea community**
Renée M. Chacon, Executive Director/Co Founder, **Womxn from the Mountain**
Karen Bueno, Leaders Team, **Accelerate Neighborhood Climate Action**
Harmony Cummings, Co-Founder, **Green House Connection Center**
Jeff Hart, **former EPA staff member** and Co-Founder of Save EPA
Rev. Mark Meeks, Pastor, **Capitol Heights Presbyterian Church**
Rabbi Eliot J Baskin, D Min, with Together Colorado

RE: SB24-159
March 26, 2024

Dear Senate Committee Members:

Thank you for considering Coloradans' concerns about approving new permits for oil and gas in our beautiful state

I have been a resident of Colorado for over 20 years and urge the committee to vote YES on SB24-159.

Colorado has an outsized impact on carbon emissions locally, nationally, and internationally. It exports 40% of gas and 75% of oil from over 50,000 wells currently in operation. A direct result of oil and gas production, our population suffers the health consequences -from ground level ozone to toxic air and water pollution.

Carbon emissions must fall by 1/2 of what they are now and within the next six years if we are to avoid the worst devastations of the climate crisis. Making the internationally agreed upon limit of 1.5C rise in temperature out of reach because of a failure to phase out fossil fuel production within this timeframe means our failure to do so will bake in irrevocable damage to the ecosystems. And each fraction of a degree beyond that imperils survivability further.*

To prevent additional tons of CO2 going into the atmosphere, phase out the approval of new oil and gas permits by 2030 that SB24-159 proposes.

Vote YES for a sustainable future for the next generations.

Thank YOU

Colleen McGovern
3929 S Sherman St
Englewood CO 80113

*<https://www.theguardian.com/environment/2023/mar/20/ipcc-climate-crisis-report-delivers-final-warning-on-15c>

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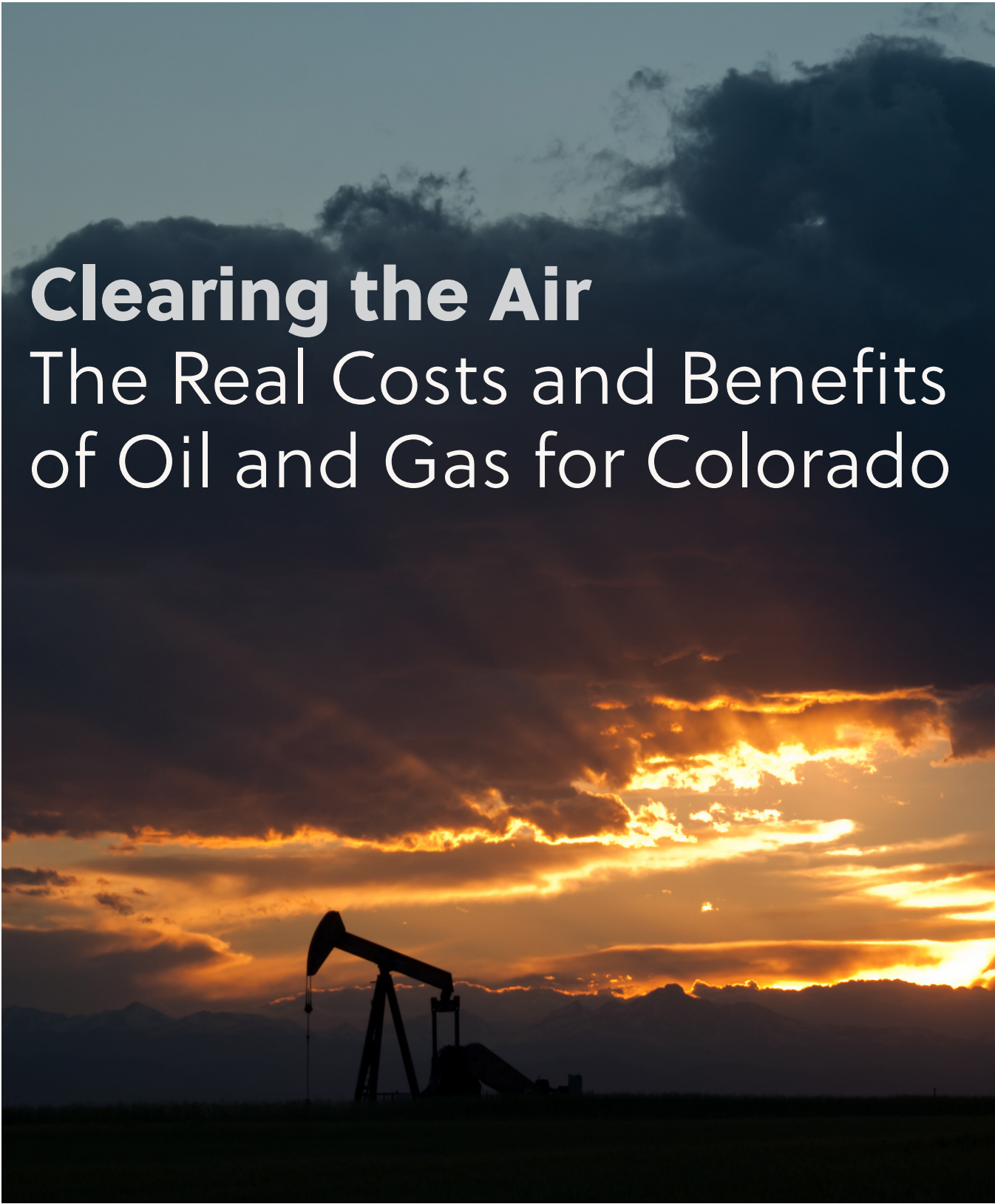
Colleen McGovern
3929 S Sherman St
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*<https://www.theguardian.com/environment/2023/mar/20/ipcc-climate-crisis-report-delivers-final-warning-on-15c>

Reports for Senate Agriculture and Natural Resources Committee
March 28, 2024
SB24-159

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Clearing the Air

The Real Costs and Benefits of Oil and Gas for Colorado

Executive summary

Given the United States' commitment to the Paris Agreement and global, federal, and state greenhouse gas emissions reduction targets, states with communities that produce oil and gas are forced to consider how they will diversify economically. One of the biggest barriers to these goals is the perception that Colorado is so economically reliant on the oil and gas industry that our state's economy will prohibitively suffer if production declines.

While our climate goals are reliant on a transition to clean energy, which carries costs, pollution created by oil and gas operations comes with costs to our health and our environment. Therefore, it's important for policymakers to have a clear picture of just how much oil and gas factors into Colorado's economy.

To properly gauge this, we must look at both the benefits of the industry and its economic impact, as well as the costs of oil and gas production. Unfortunately, most economic impact analyses of the oil and gas industry tend to ignore the negative economic effects of pollution, and may overstate the industry's total employment, income, and tax base.

A clearer picture of the role of oil and gas in Colorado's economy can support policymakers and elected officials in determining how we responsibly transition from burning climate-harming fuels to a carbon-neutral energy economy. This report aims to quantify both the economic benefits of Colorado's oil and gas industry as well as the costs.

Our analysis found:

- The oil and gas extraction industry, along with the pipeline construction and transportation industries and support industries for oil and gas make up just 1.8% of total wages in the state, 3.4% of total personal income, 3.3% of GDP and less than 1% (0.7%) of total employment.
- While oil and gas operations in Colorado generate local, federal and state tax revenue, some of these taxes and fees are not a net benefit to the state because they go directly toward regulating the industry, including cleaning up pollution or compensating for losses caused by development. Additionally, a significant amount of these taxes are based on self-reporting by the industry. Recent state audits showed the industry paid only about 20% of what they would have owed without exemptions, credits, and undercharging.
- The most significant government revenue from oil and gas operations comes from property taxes, including \$621 million in 2021. While this makes up 3.5% of total local school funding in Colorado, it is not evenly distributed. 70% of school districts receive less than 1% of total funding from oil and gas property taxes, and just a handful get more than 10% of their total funding from oil and gas property taxes.
- The industry creates significant health, environmental, and other costs that are paid by Coloradans, not the industry. While some serious impacts of oil and gas development are not quantifiable, many are. Pollution emitted by oil and gas operations in Colorado will cause well over \$13 billion of damages between 2020 and 2030, based on calculations of the social cost of oil and gas pollution that are set in state law.
- Other health and environmental costs include emissions of volatile organic compounds (VOC) and Nitrogen Oxides (NOx), which lead to dozens of deaths in Colorado each year, high amounts of water usage, lower property values near oil and gas drilling sites, habitat fragmentation, and costs related to cleaning and plugging abandoned oil and gas wells, much of which is paid for by Colorado communities instead of the companies that made the mess.

- Pollution from oil and gas in Colorado contributes to climate change, which is already causing billions of dollars in damage to Colorado, harming the agriculture and recreation industries, and causing natural disasters. Climate-caused disasters alone have cost the state between \$20 billion and \$50 billion since 1980.

This report found that oil and gas development, while creating some economic benefits, also carries significant costs. While some communities will have a harder time than others during the transition from pollution-causing fuels to clean energy, this analysis shows it is entirely feasible for Colorado to diversify its economy, move away from oil and gas development, and come together to support the specific towns and counties that will be in most need of support.



Colorado Oil and Gas Jobs and Wages

As of March 2022, there were 20,475 oil and gas jobs in Colorado, which made up 0.7% of total jobs in the state. The oil and gas industry paid \$948 million in total wages which comprised 1.8% of total wages in Colorado during the first quarter of 2022.

Oil and Gas Jobs and Total Wages in Colorado		
	March 2022 Employment	Total Quarterly Wages (Q1 2022) in \$
Oil and gas extraction	6,653	572,675,151
Drilling oil and gas wells	1,023	24,653,221
Support activities for oil and gas operations	8,030	232,004,199
Oil and pipeline construction	3,705	70,975,715
Pipeline transportation	1,064	47,789,866
Oil and Gas	20,475	948,098,152
Total	2,767,893	52,086,837,500
Oil and Gas Share of Total in Colorado	0.7%	1.8%

Source: Quarterly Census of Employment and Wages

As a comparison, the car dealers and auto parts and car tire industry in Colorado paid \$550 million in wages in the first quarter of 2022 which represented 1.1% of total wages. Colorado’s hotel and restaurant industry makes up 3.8% of wages.

Lost 12,000 Jobs in the Oil and Gas Sector Since 2019		
	March 2019 Employment	March 2022 Employment
Oil and gas extraction	9,228	6,653
Drilling oil and gas wells	1,679	1,023
Support activities for oil and gas operations	13,738	8,030
Oil and pipeline construction	6,633	3,705
Pipeline transportation	1,420	1,064
Oil and Gas	32,698	20,475
Total	2,693,297	2,767,893
Oil and Gas Share of Total Jobs in Colorado	1.2%	0.7%

Source: Quarterly Census of Employment and Wages

The median wage of an oil rig laborer in Colorado in 2021 was \$46,740. Drill operators make more, with a median wage in 2021 of \$75,910. For comparison the median wage in Colorado for all occupations was \$47,940.

Managers, Supervisors, and Business Operations Employees in the oil and gas industry make much more. The median salary for a Financial Operations employee was \$103,460 in 2021. Engineers in the oil and gas industry have a median wage of \$131,100. The average oil and gas office worker doing administrative support has a median wage of \$60,160.

Jobs and Wage Distribution of Common Oil and Gas Jobs in Colorado						
	Total Employment in CO 2021	10th Percentile Salary	25th Percentile Salary	Median Salary	75th Percentile Salary	90th Percentile Salary
Derrick Operators, Oil and Gas	470	\$35,820	\$38,520	\$39,750	\$49,840	\$74,680
Rotary Drill Operators, Oil and Gas	300	\$44,840	\$48,890	\$75,910	\$75,940	\$96,460
Service Unit Operators, Oil and Gas	2,150	\$37,840	\$46,910	\$51,390	\$65,240	\$79,190
Excavating and Loading Machine and Dragline Operators, Surface Mining	480	\$37,840	\$46,140	\$59,180	\$75,920	\$75,920
Roustabouts, Oil and Gas	1,350	\$36,750	\$37,300	\$46,740	\$50,240	\$76,390
Helpers--Extraction Workers	230	\$35,370	\$37,130	\$37,700	\$43,280	\$60,800
First-Line Supervisors of Construction Trades and Extraction Workers	160	\$84,600	\$100,700	\$122,330	\$128,550	\$137,040
Business and Financial Operations Occupations (Oil and Gas)	1,220	\$63,960	\$80,930	\$103,460	\$131,920	\$167,270
Architecture and Engineering Occupations (Oil and Gas)	1,060	\$77,930	\$101,230	\$131,100	\$166,660	#
Sales and Related Occupations (Oil and Gas)	390	\$61,400	\$97,320	\$125,110	\$154,260	\$202,110
Office and Administrative Support Occupations (Oil and Gas)	420	\$44,210	\$47,770	\$60,360	\$78,020	\$99,790

Source: Bureau of Labor Statistics Occupational Employment Statistics industry-level (OES) 2021 Colorado data

Share of Oil and Gas in Colorado's Economy

Oil and Gas made up 3.3% of Colorado's economy measured by GDP in 2021. This includes oil and gas extraction, support activities for oil and gas, drilling oil and gas wells, pipeline construction, and pipeline transportation.

The oil and gas industry was a smaller part of the economy in 2021 than it was from 2018-2020. In 2018, oil and gas represented \$18.5 billion in GDP in Colorado—5% of the economy. In 2021, oil and gas represented \$14.5 billion in GDP in Colorado—3.3% of the economy. During the same period, Colorado's GDP increased by 17.2% while the oil and gas sector shrank by 21.4%. The overall positive trendline of Colorado's economy during a time of decline for the oil and gas industry lends credibility to the idea that the state is not economically dependent on oil and gas.

Gross Domestic Product (millions of current dollars)	2018	2019	2020	2021
All industry total	372,212	394,535	391,263	436,360
Oil and gas extraction	12,141	10,479	5,775	10,510
Support activities for mining	3,123	2,943	1,710	1,753
Portion of Support Activities from "Oil and Gas Wells" and "Oil and Gas Operations"	97.1%	97.0%	96.2%	95.3%
Construction	21,719	23,352	23,517	24,528
Portion of Construction from "Pipeline Construction"	3.35%	4.20%	2.52%	2.11%
Pipeline transportation	2,628	1,794	1,799	1,856
Total Oil and Gas Industry	18,528	16,109	9,809	14,554
Percent of Colorado's GDP	5.0%	4.1%	2.5%	3.3%

Source: Bureau of Economic Analysis State GDP; Quarterly Census of Employment and Wages "Total Annual Wage" by NAICS 237120 as portion of NAICS 23 and NAICS 213111 and NAICS 213112 as portion of NAICS 2131.

Taxes and Fees Charged to the Oil and Gas Industry

Fees and taxes that are specific to Oil and Gas are 1) leases and royalties for operations on state and federal lands, 2) fees that go into the Environmental Response Fund, and 3) Severance Taxes. These fees and taxes comprise a large portion of what industry groups claim is a benefit to the state, although a large portion of that public money goes toward offsetting social, environmental, and economic costs of the oil and gas industry.

A portion of revenue from leases and royalties goes toward funding schools. As discussed below, nearly all revenue from oil and gas leases on state lands goes to schools, and 50% of the money coming to Colorado from Federal Mineral Leases (FML) goes to schools. 10% of FML disbursements go to the Water Conservation Board, and 40% goes to the Local Government Mineral Impact Fund. 50% of that is disbursed directly to local governments who are affected by oil and gas development, and 50% goes to the Energy Impact Assistance Fund (EIAF), the purpose of which is to "assist political subdivisions that are socially and/or economically impacted by the development, processing, or energy conversion of minerals and mineral fuels." In total, 40% of Federal Mineral Lease disbursements from oil and gas go toward compensating communities for the negative social and economic impact of oil and gas development.

It's hard to count the Environmental Response Fund as a benefit to the state, because like the EIAF, it simply offsets some of the costs associated with the oil and gas industry. The Environmental Response Fund is funded

through certain fees and penalties collected from oil and gas operators. By law this fund can only be spent to fund the regulation of the oil and gas industry and the remediation of environmental damage caused by oil and gas operations. C.R.S. § 30-60-124.

In addition to the costs of community compensation for damage costs, the industry also has regulation costs. Regulatory costs come in four main forms: the Colorado Oil and Gas Conservation Commission (COGCC) budget, the failure of the COGCC to charge adequate fees, the costs of plugging or reclaiming orphaned wells (PROW) and staffing specific to oil and gas in the Colorado Department of Natural Resources.

Additionally, the PROW program has nowhere near the resources required to plug and fill all the abandoned wells in the state. This is largely because it is cheaper for producers to keep wells barely producing oil (making them into so-called “stripper wells”) than to properly plug them. In 2018, 58% of oil wells and 73% of gas wells qualified as stripper wells.¹ The cost of plugging and cleaning up a well can range from an average of \$20,000 per well, to over \$1 million depending on the type and age of the site.²

The biggest state revenue source that the oil and gas industry pays comes in the form of severance taxes. Severance taxes are a graduated tax imposed on ‘severing’ natural resources such as coal, oil, and minerals from the ground. For perspective, In FY2021-22 severance tax was \$308.7 million, which is only about 1.7% of gross general fund revenue (including State Education Fund transfer) of \$18.7 billion. This revenue was during a good year, and severance taxes closely track the boom-and-bust cycle of oil and gas prices (see chart below). A closer look at the 2020 report from the state auditor’s office and comparison to other states reveals that the industry is getting off easy when it comes to severance taxes.³



State auditors estimated the underpayment of tax by the operator with the highest number of incomplete or missing reports. In 2016 alone, this operator missed 1,123 monthly reports, failing to report more than 850,000 barrels of oil and 4 million MCF of gas, which could have resulted in approximately \$2.6 million worth of severance taxes, prior to other fees or credits. Accounting for the delinquent reports of every operator in the state for the past six years would be nearly impossible, but this single case from 2016 goes to show just how much under-reporting is costing Colorado.

The COGCC has the power to enforce the submission of monthly reports with a \$200-per-day-per-well late fee, increasing after 30 days of tardiness. However, even though an estimated 316 well operators were out of compliance with reporting, the commission imposed no fees on any operators. Had the commission imposed the \$200-per day fee for 30 days on each of the 51,264 delinquent reports (assuming they turned in their reports after 30 days), operators could have been liable for more than \$300 million in fines from 2016-2018. Had the commission only enforced this penalty in the case of the three worst offenders during this period, those three operators could have been held accountable for more than \$120 million in fines. Each of those operators had more than 5,000 missing reports.

In addition to chronic underreporting by well operators, there are two main routes through which the oil and gas industry in Colorado pays significantly less in taxes than they would in other states. The first of these is the ad valorem tax credit, a law passed in 1977 which allows oil and gas companies to claim 87.5% of the ad valorem property taxes as a credit on their severance tax liability.⁴ This tax credit can go unnoticed because it shares a name and value with the assessment rate for oil and gas property but in fact can reduce severance bills by up to 92.8%. This tax credit alone was responsible for \$149 million in severance tax refunds in 2021 and even more in 2019 when the credit was worth \$430 million.

Tax Year	Gross Liability	Ad Valorem Credit	Percent of Gross Liability	Net Tax Liability
2008	430,590,389	167,703,452	38.9%	262,912,030
2009	190,979,702	160,991,461	84.3%	30,007,579
2010	278,418,846	133,581,819	48.0%	144,839,008
2011	307,839,571	154,736,951	50.3%	153,112,212
2012	272,855,723	163,920,883	60.1%	108,948,651
2013	388,121,572	191,045,636	49.2%	197,077,279
2014	543,794,057	284,876,842	52.4%	258,927,136
2015	325,109,120	301,843,159	92.8%	23,268,339
2016	260,674,621	214,726,300	82.4%	45,952,977
2017	378,724,058	249,453,562	65.9%	129,429,438
2018	561,574,826	374,857,470	66.8%	186,766,212
2019	506,104,659	430,778,139	85.1%	75,358,079
2020	281,747,126	265,691,162	94.3%	16,063,439
2021	290,724,229	149,059,933	51.3%	141,683,611
Average	358,375,607	231,661,912	65.8%	126,738,999

Source: Colorado Department of Revenue, Legislative Council Staff calculations

Colorado oil and gas producers also pay less than producers in other states due to what is known colloquially as the ‘stripper well exemption.’ This exemption states that wells with an average daily production of less than 15 barrels or 90k MCF are not charged a severance tax. The ad valorem credit and stripper well exemption reduced the effective severance tax rate from a statutory 2-5% (graduated, depending on the output of the well) to an average of 1.5% in FY 2018-19. The effective rate across the nine states compared in the report prepared for the Colorado Legislature was 4.8%.

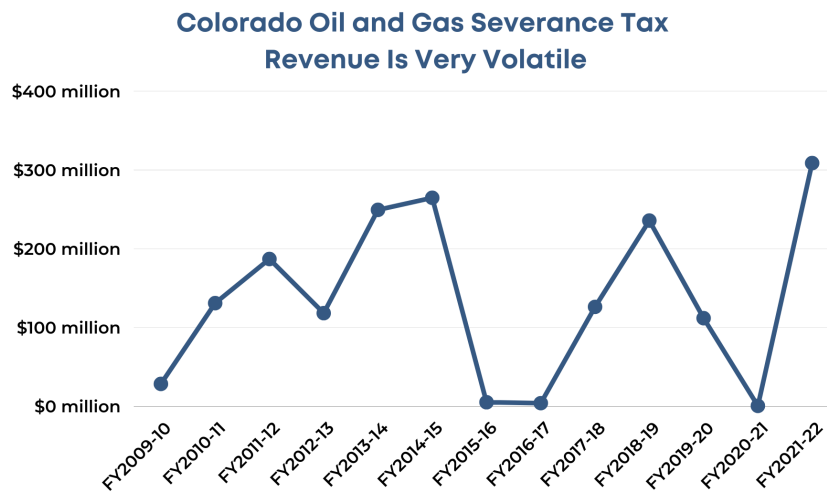
Tax Year	Net Severance Tax Liability	Percent Exempt	Value of Exemption
2008	262,912,030	16.1%	79,137,055
2009	30,007,579	17.8%	10,624,561
2010	144,839,008	18.7%	45,538,108
2011	153,112,212	20.4%	50,426,087
2012	108,948,651	20.7%	35,802,436
2013	197,077,279	16.7%	49,736,857
2014	258,927,136	12.4%	43,471,438
2015	23,268,339	10.6%	3,464,881
2016	45,952,977	11.1%	8,179,947
2017	129,429,438	9.7%	17,986,670
2018	186,766,212	7.7%	20,035,078
2019	75,358,079	6.8%	7,379,403
2020	16,063,439	7.6%	2,001,786
2021	141,683,611	8.6%	35,729,047
Average	126,738,999	13.2%	29,250,954

Source: Colorado Department of Revenue, Colorado Oil & Gas Conservation Commission, Legislative Council Staff calculations

Severance tax collections are incredibly volatile in large part because of oil and gas price volatility. Because severance taxes are paid on the value of oil and gas produced, big swings in prices cause big swings in revenue collections even if production levels remain relatively constant.

In 2020, energy prices fell significantly from pandemic-related travel restrictions and people choosing not to travel for health reasons. This led to a collapse in demand for oil and gas and nearly zero severance tax collections in FY2020-21. Demand for oil and gas jumped back rapidly when travel resumed and supply couldn't keep up. This resulted in large spikes in gas prices. As those prices rose, the value of oil and gas produced in Colorado jumped and therefore severance tax revenue jumped.

The ad valorem credit also contributes to Colorado's severance tax collection volatility. Because there is a misalignment between the production year used to calculate the credit and the production year used to calculate severance tax owed, a big credit can be used to offset a year that might be a down year in energy prices. This can amplify swings in severance tax collections.



Source: Colorado Legislative Council

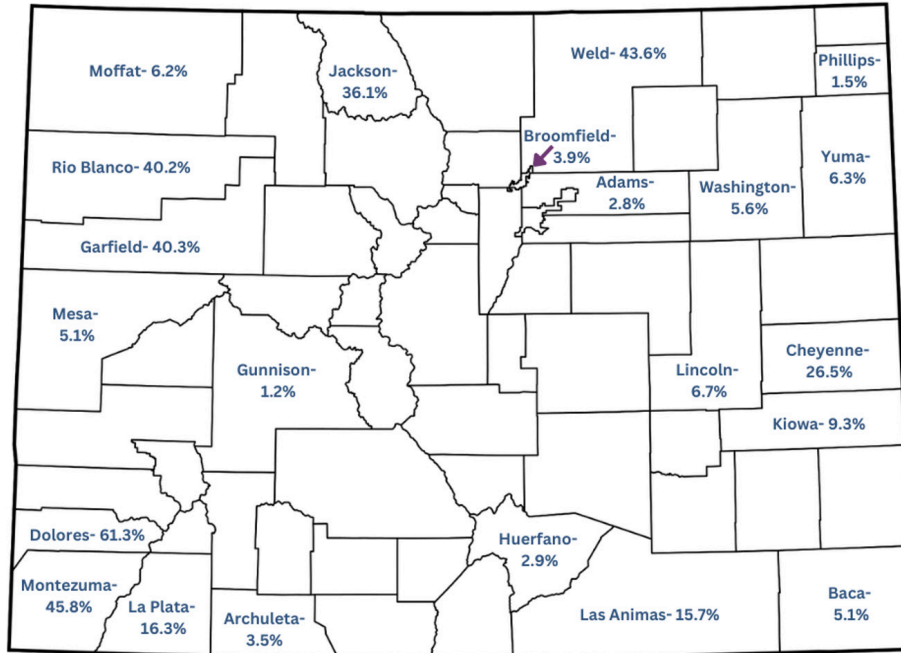
Property Taxes Paid by Oil and Gas Companies

In 2021, total property tax in Colorado was \$11.9 billion. Of this total, \$621 million, or 5.2%, came from property taxes on oil and gas property (see appendix for full breakdown of oil and gas property taxes paid by county).

36 of Colorado's 64 counties had oil and gas assessed property value in 2021. Just nine of those counties get more than 10% of their property tax from oil and gas property. Dolores County has the highest portion of its assessed value coming from oil and gas property at 61.3%, followed by Montezuma (45.8%), Weld (43.6%), Garfield (40.3%), and Rio Blanco (40.2%). Of the \$621 million generated for total local governments (schools, counties, cities, and special districts) \$128 million went to county budgets.



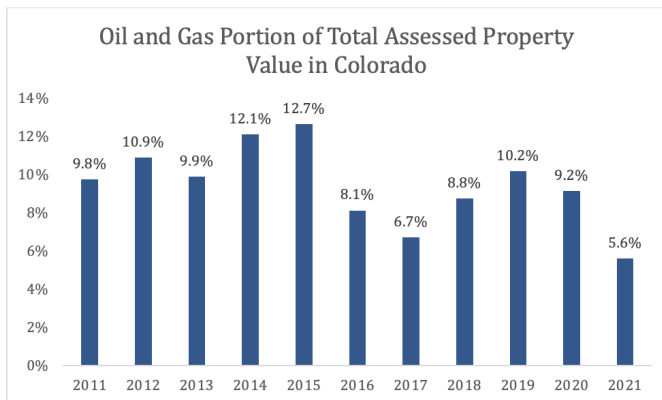
Percentage of County's Assessed Property From Oil & Gas



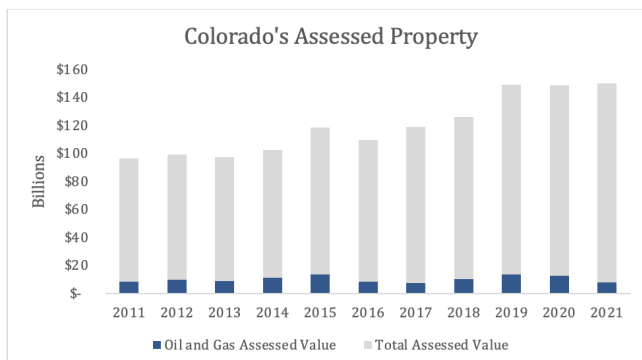
Any counties not labeled have less than 1% oil and gas property

Source: Colorado Department of Local Affairs 2021 Assessed Value by Property Class

Oil and Gas Assessed Property Value has average 9.5% of total assessed property in Colorado over the past 10 years. Like GDP and employment, the share of oil and gas has shrunk over the past several years while totals continue to grow. For example, oil and gas assessed value fell by 42% between 2019 and 2021 while total assessed value grew by 5%.



Source: Colorado Department of Local Affairs Assessed Value by Property Class



Source: Colorado Department of Local Affairs Assessed Value by Property Class

36 of Colorado's 64 counties had oil and gas assessed property value in 2021. Just nine of those counties get more than 10% of their property taxes from oil and gas property.

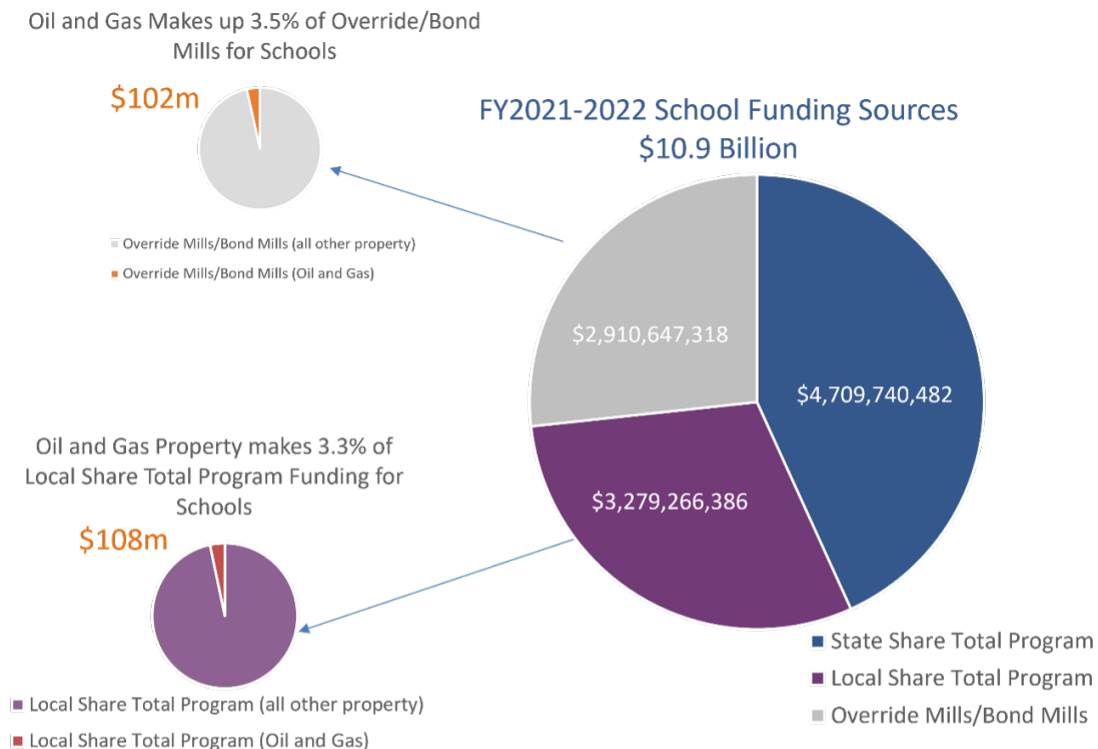
School Funding from Oil and Gas Operations

Of the \$621 million in property tax revenue generated from oil and gas property in 2021, \$210 million of it went to school district budgets. About half of that (\$108 million) contributed to “Total Program” funding and a little less than half (\$102 million) went to school districts through extra override mills and bond mills. As a share of total property tax that funds schools in Colorado in 2021, oil and gas made up 3.5%. However, only a handful of communities are reliant on oil and gas property to fund schools. 84 of 178 school districts have zero oil and gas property. 94 out of 178 school districts have some oil and gas assessed value. Of those 94 districts, 41 of them get less than 2% of property tax from oil and gas. On the other hand, 15 of those school districts get more than half their property tax from oil and gas.

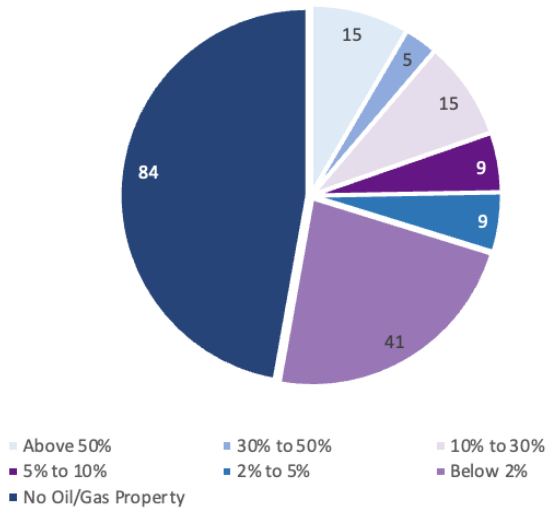
The state essentially already has a backfilling mechanism for about half of property taxes that would be lost if oil and gas went away. The school finance formula is designed to compensate for property wealth disparities across school districts, so if the local share of school funding falls in a district, the state makes up the difference. In 2021, \$108 million in local property tax dollars contributed to “total program” funding. If that suddenly went away, the state would backfill that \$108 million.

In addition to total program funding, school districts have asked voters to approve “override” mills. These are additional property taxes that all stay local to the school district and do not impact total program funding. Of the \$2.9 billion in override revenue, 3.5% of it comes from oil and gas property (\$102 million). This means the real dollar amount needed to make schools that are reliant on oil and gas property whole is \$102 million that would not automatically be backfilled with state sources.

The school finance formula’s backfill method could act as a model for a mechanism to backfill local governments who lose property tax revenue as we transition away from oil and gas. This would be especially important for counties like Dolores, Montezuma, Weld, Garfield, and Rio Blanco.



School Districts by Oil/Gas Property as a Share of Total Property



Platte Valley RE-7 in Weld County has the most reliance on oil and gas property—86% of their assessed property value comes from oil and gas. Their district gets \$17.1 million in total funding from that property, \$6.8 million of which comes from taxes but would get backfilled by state sources, and another \$5.8 million comes from override property taxes from oil and gas that wouldn't get backfilled by the state when we transition away from oil and gas. Statewide, 15 of 178 school districts' override revenue from oil and gas exceeds 10% of their total funding.

A percentage of mineral leases and royalties on oil and gas produced on state and federal lands also goes to fund schools. Approximately 70% of State Land Board Trust revenue comes from

oil and gas leases and royalties, and nearly 99% of this goes to fund education.⁵ In 2021, the State Land Board Trust received \$81,755,676 in revenue from oil and gas royalties and leases, \$80.7 million of which went to education. The federal government also collects fees and royalties from mineral leases on federal lands, returning 49% back to the states.

According to Colorado's Department of Local Affairs, 50% of the Federal Mineral Lease (FML) disbursements Colorado receives from the federal government goes to schools.⁶ In fiscal year 2021, the federal government collected \$165.9M in Federal Mineral Leasing royalties and fees from oil and gas.⁷ 49% (\$81.3M) was returned to Colorado, of which \$1M is 'bonus.' 50% of the non-bonus federal disbursements, or \$40.2M, goes to the State Public School Fund or is disbursed directly to school districts.



Total Revenue Generated from Oil and Gas in Colorado

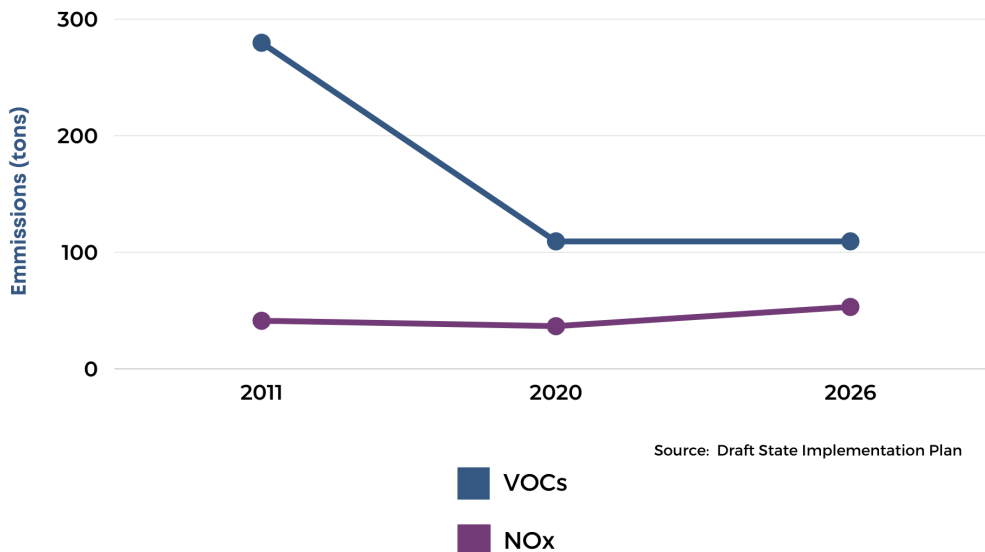
Total Revenue Generated from Oil and Gas in Colorado			
	Amount (millions)	Time Period	Primary Uses for Funds
Property Tax	\$621	2021	School, County, City, Special District Budgets
State Severance Tax	\$154.6	2021 (Average of FY2020-21 and FY2021-22)	Local Government Grants, water projects, fire mitigation
State Land Board	\$81.8	FY2020-21	Schools, Parks, Public Buildings
Federal Mineral Lease	\$81.3	FY2020-21	Schools, Water Board, Local Governments
Oil and Gas Conservation and Environment Response Fund	\$19.6	FY2020-21	Industry regulation
Total Revenue from Oil and Gas	\$958.7	FY 2021	

In 2020, Colorado state and local governments collected \$79.6 billion in revenue.⁸ So the \$958.7 million represents 1.2% of total revenue in Colorado for all levels of government.

Costs of Oil and Gas to Colorado

Air quality

Emission Trends (TPD)



Anyone who lives on the front range knows how poor air quality affects our views of the mountains, but pollution is also particularly hazardous to public health. The oil and gas industry is the largest industrial source⁹ of emissions of what are called volatile organic compounds (VOCs), which contribute to ground level ozone pollution.

The draft State Implementation Plan¹⁰ (SIP) states that in 2020 the oil and gas industry emitted 109.42 tons per day (tpd) of VOCs and 36.7 tpd of NOx. This inventory represents emissions estimates for an average episode day during the peak summer ozone season of June through September.

VOCs from drilling and fracking operations, together with nitrogen oxides, are responsible for 17 percent of locally produced ozone in Colorado’s heavily drilled Front Range.¹¹ The oil and gas sector is also a large contributor to particulate matter emissions. The PM can either be emitted directly from the source (primary particles) or formed through chemical reactions (secondary particles) of different gases. These gases include Sulfur Dioxide (SO2), Oxides of Nitrogen (NOx), and certain organic compounds.

The table below shows that in 2025,¹² the total cost of ozone precursors NOx and VOCs from the oil and gas sector is estimated to be between \$100 million and \$180 million (in 2015 dollars). These significant costs are borne by Coloradans, especially those communities sited nearest the oil and gas developments, which research shows are more likely to be communities of color and places where people are more likely to earn low incomes.¹³

Damages per ton of oil and gas related pollutants in Colorado (\$2015)					
	Ozone Precursors		PM_{2.5} Precursors		
	VOCs	NOx	SO ₂	EC/OC	NOx
Health damages	\$300–\$500	\$4,600–\$8,200	\$27,000–\$62,000	\$140,000–\$320,000	\$2,800–\$6,300

Source: Fann et al. (2018)

By 2025, the average number of PM2.5 and ozone related premature deaths attributable to oil and gas emissions in Colorado is estimated to be 70 deaths which is the equivalent of 1.9 premature deaths per 100,000 people. This is 210% of the national population-adjusted premature death rate.¹⁴

Those same researchers estimate that by 2026, the total economic damages from the oil and gas sector in the United States will be between \$13 billion-\$29 billion, which is mostly due to health damages from premature deaths. Since their premature death estimates for Colorado is about 3.7% of the national estimates, we can infer that total damages for Colorado will be between \$480 million and \$1 billion.

There are many more unquantified costs associated with drilling and fracking activities. A 2022 Physicians for Social Responsibility (PSR) report¹⁵ reviews about 2000 studies on health impacts of fracking and drilling. They find that more than 200 airborne chemicals have been detected near drilling and fracking operations, as well as significantly higher toxic levels near these sites. Cancers, asthma, respiratory diseases, skin rashes, heart problems, and mental health problems are among the health conditions linked to drilling, fracking, and their infrastructures.

since 2008, PFAS have been used in fracking operations in at least ten counties in Colorado, mostly in Weld and Garfield counties. PFAS are long lasting chemicals, components of which break down very slowly over time. Exposure to some PFAS may be linked to harmful health effects in humans and animals.¹⁶

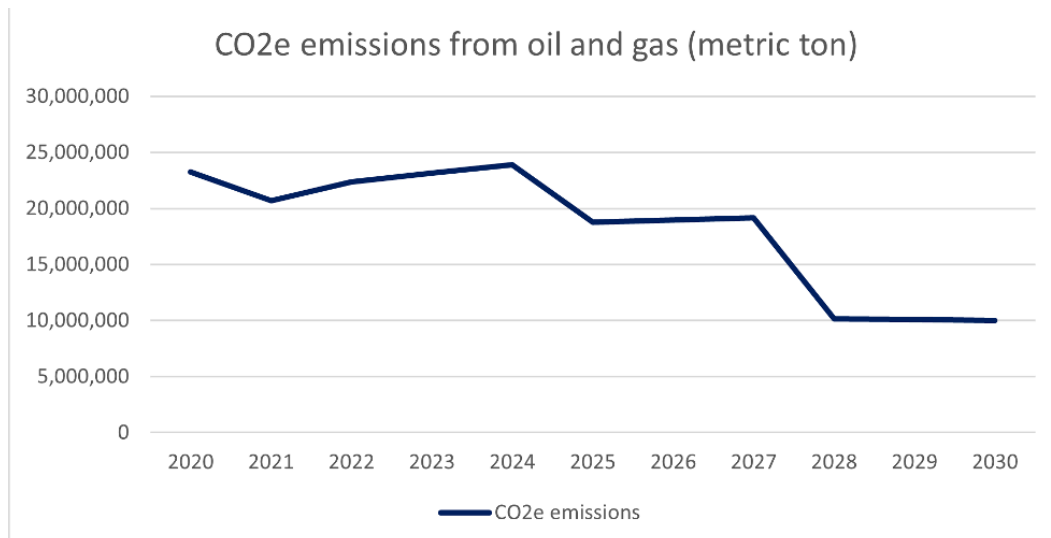
Moreover, fracking in northeastern Colorado has been a significant source of toxic pollutants, including benzene and toluene.¹⁷ Studies have found higher rates of leukemia among children and young adults living in areas dense with oil and gas wells.¹⁸ For people living within 500 feet of a well, lifetime cancer risks are estimated to be eight times higher than the EPA’s upper threshold.¹⁹

In addition to benzene and toluene, ethylbenzene, and xylene (BTEX) are two common air pollutants from drilling and fracking. sperm abnormalities, reduced fetal growth, cardiovascular disease, respiratory dysfunction, and asthma are among the health conditions linked to BTEX air pollutants.²⁰

Greenhouse Gas Pollution

The social cost of carbon is a dollar estimate of the economic cost resulting from emitting one additional ton of carbon dioxide (CO2) into the atmosphere. Assessments of damages from climate change are influenced by projections of population, economic growth, and emissions. A recent study by RFF²¹ incorporates socioeconomic uncertainty and stochastic discounting in deriving estimates of the SCC and finds mean estimates of between \$61 and \$168 per ton of CO2 in 2020 dollars (depending on the discount rate). Per Colorado law, the social cost of carbon is calculated at \$68 per ton.²²

The Colorado greenhouse gas reduction roadmap provides annual estimates of CO2 equivalent emissions from the oil and gas sector between 2020 and 2030. The graph below shows these estimates under HB1261 targets. Using these estimates, the total emissions from this sector between 2020 and 2030 is 200.5 million metric tons. Using the estimates of the social cost of carbon, total economic damages from these emissions would be between \$12.2 billion (based on RFF low estimates) and \$33.7 billion (based on RFF high estimates) by 2030. Using the \$68 social cost of carbon in Colorado law, total economic damages over this period would be \$13.6 billion.



Cost of Plugging Abandoned Wells

Oil and gas companies are legally obligated to plug wells once they are no longer producing oil. In reality, many operators abandon wells they profit from without paying for their cleanup and closure. The EPA’s estimate shows that in 2019, there were about 2 million unplugged abandoned oil and gas wells across the United States.²³ According to the orphan well program, Colorado has at least 215 orphaned wells and 454 associated sites, which can include well pads, storage tanks, flowline locations and other facilities. Moreover, nearly half of the state’s unplugged wells are stripper wells—low-producing operations with small profit margins often at the end of their lifespans.

So far, the costs of plugging these wells have been paid through the orphan well program, which uses fees from the oil and gas industry to plug and abandon orphan wells and reclaim orphan well sites.²⁶ Colorado has about 60,000 unplugged wells (including currently producing wells, stripper wells, injection wells, temporarily abandoned wells, and zombie wells), and Carbon Tracker’s estimates show that the costs of cleaning and plugging them are about \$7 billion.²⁷ If the funds collected by the orphan well program are not sufficient, the state will have to pay for these cleaning and plugging costs.

Housing Prices

Oil and gas production can drive housing prices up through increasing employment and subsequently higher demand for housing in the area. On the other hand, environmental and health risks associated with extraction and distribution, including air, water and noise pollution could push housing prices down. Those not nearby active drilling at the time of sale may benefit from the fracking boom, while those near wells being actively drilled at the time of sale suffer loss in property value due to environmental pollution. Overall, they find a reduction in property value of about 1%.²⁴

The Western Slope of Colorado (Garfield, Mesa, and Rio Blanco counties) is one of the primary locations of hydraulic drilling in the state. In this region, the houses within one mile of the drill site sell for 34.8% less than comparable properties without proximate drilling.²⁵ Treated properties are affected by highly intensive drilling (on average 16 wells drilled within a mile). These are properties that do not have mineral rights and do not financially benefit from drilling and are only negatively impacted).

Effect of oil and gas production on housing prices		
Location	Type of property	Percent change in property value
Weld County	Drilling within ½ mile of property	-1%
Western Slope	Drilling within 1 mile, no mineral rights	-35%

Water Use and Quality

According to the COGCC, hydraulic fracturing, which has occurred in approximately 90% of oil and gas wells since the 1970s, uses about 1.6 million gallons of water per well (or about 80,000 gallons per year over the average 20-year life of a well).²⁸ The sourcing of water leads to reductions in its availability for other local requirements. A study by WRA finds that the volume of water required annually for new oil and gas development is enough to serve up to 296,100 people.²⁹

Oil and gas development can also impact surface and ground water quality through stormwater runoff and spills, surface spills, leaking waste pits, or poor disposal practices. Some studies have found significantly higher levels of arsenic, selenium, strontium, and total dissolved solids (TDS) in water wells less than 3 km from shale-gas

Habitat Loss and Fragmentation

Oil and gas drilling activities require extensive use of land. Production of oil and gas is associated with direct and indirect impacts to biodiversity and habitat availability (well pads, access roads and other infrastructure including tanks for holding fluids). While renewable energy production can be sustained indefinitely on the same land base, oil and gas extraction requires continuous drilling and use of new land for production. It is estimated that habitat fragmentation damages from oil and gas production in the U.S. amounts to \$4.11 billion.³¹

Costs of Climate-Related Disasters

Estimates by the National Center for Environmental Information (NCEI) show that between 1980 and 2022, Colorado has experienced 63 climate-related billion-dollar disasters, 52 of which have happened since 2000 and 38 have happened since 2010. It is estimated that these events have cost Colorado between \$20 billion and \$50 billion.³² Drought, flooding, severe storms, and wildfire are among the most damaging climate disasters in Colorado.

It should be noted that these estimates refer to the overall costs of climate related disasters and cannot be attributed to oil and gas production in Colorado only. Rather, these disasters are the result of extraction and burning of all fossil fuels everywhere around the world since the industrial revolution. However, United States is the second largest producer of greenhouse gases in the world and oil and gas sector is responsible for 80 percent of greenhouse gas emissions in the U.S., so oil and gas industry's share in these climate events is not negligible.³³ The Colorado greenhouse gas inventory estimates that in 2019, greenhouse gas emissions in oil and natural gas production has been about 20 million metric tons of CO2 equivalent, which is 16 percent of total greenhouse gas emissions in Colorado.³⁴



Conclusion

The oil and gas industry in Colorado represents a small fraction of the economy, contributing 3.3% of Colorado's Gross Domestic Product (GDP) in 2021. In comparison, manufacturing contributed twice as much (6.6%), and the Professional and Business Services sector contributed about 5 times as much (15.5%). As of March, 2022, oil and gas industry employees represented only 0.7% of Colorado's workforce, and they received 1.8% of wages paid in Colorado.

Revenue from oil and gas comes from severance taxes, leases and royalties from oil and gas use of public lands, fees and penalties, and severance taxes. All these taxes, fees, leases, and royalties, along with income tax from oil and gas workers, totals only 1.7% of total state and local revenue in Colorado. The largest portion of tax revenue from oil and gas in Colorado comes from local property taxes. In 2021, Oil and gas represented 5.2% of total property tax, with about half of counties receiving zero property tax revenue from oil and gas and an additional one-sixth receiving less than 1%. Nine counties received over 10% of property tax revenue from oil and gas. Some of the revenue from oil and gas goes toward school funding, making up about 3.5% of local school funding in Colorado.

The costs of the oil and gas industry to the state include lowered property values, lowered air quality and the associated health impacts, habitat loss and fragmentation, water use and quality, and greenhouse gas emissions and the costs associated with those emissions. The social cost of carbon for all of the emissions created during drilling, production, and transmission of oil and gas in Colorado is 1.5 times greater than the revenue the state collects from the oil and gas industry. Climate disasters associated with global production and consumption of fossil fuels have cost Colorado between \$20B and \$50B.

If the oil and gas industry in Colorado gradually declines due to market forces, regulation, or a combination of these, we can expect the economy to evolve and develop to accommodate these changes. Historically, the economy has shown that over time it has absorbed large changes without adverse affects. Some counties would be disproportionately affected by this change, and Colorado will need to come together to find a solution that will support these communities.

Appendix

Analysis by Oil and Gas Industry Includes “Indirect” and “Induced” Impacts

Public perception that oil and gas is a huge part of the economy could be due in part to information long circulated by industry-funded public relations campaigns and trade groups like the Colorado Oil and Gas Association (COGA). Their current fact sheet is based on a 2018 report prepared for COGA by Global Energy Management Program (henceforth “COGA Report”).³⁵ The fact sheet says that the industry supports 89,000 workers, and the economic impact of the oil and gas sector on the state is \$19 billion. These conclusions are based on a method of calculation that includes “induced effects” and differ significantly from the direct jobs and GDP numbers reported earlier in this report. The COGA report explains that “well operators, water supply truck drivers, and contract welders, among others, spend much of their income in Colorado. The share of employment spent, for example, at hardware stores and restaurants and ski resorts attributable to direct and indirect oil and gas industry workers is ‘induced’ by activities in the oil and gas sector.”

This argument relies on the idea that because oil and gas workers spend money, like all of us do, the oil and gas industry should get credit for the jobs of the workers in the establishments where money is spent. If applied to all workers and industries, this method would result in massive double-counting and have an absurd result: it would give the appearance of a Colorado job market that is several times its true size.

Including induced effects can also be misleading because it implies these economic benefits would be irreparably lost if Colorado undergoes a managed transition off oil and gas. Under a gradual, managed transition away from oil and gas production, the workers currently employed in oil and gas would have comparable employment in other jobs and would still be spending the same amount of money as they were when employed in oil and gas, leading to a reapportioning of those jobs and taxes into other sectors.

Inclusion of individual income taxes in the economic contribution of the oil and gas sector is erroneous for the same reason. Under a gradual, managed transition, displaced workers would not be unemployed, but employed in other comparably paid jobs. Income taxes would be coming from the same people, who would be employed in different industries. While it is true that the taxes of oil and gas workers contribute economically to the state, it is not revenue that would necessarily be lost under a transition.

Finally, employment and other data shows the economic condition of the oil and gas industry isn’t as tied to the state’s overall economy as these groups claim. Because so much of the industry is tied to global economic factors (e.g. the price of oil), there are several examples of the industry cutting jobs while Colorado’s overall employment and economy grew. If the industry is really responsible for “inducing” and indirectly creating so many jobs, it stands to reason Colorado would face a recession every time the industry loses jobs, but this is not the case.



Local Property Tax Revenue from Oil and Gas in Colorado

	Local Property Tax Revenue from Oil and Gas	Total Local Property Tax Revenue
Adams	\$31,297,798	\$1,135,729,345
Alamosa	\$0	\$15,422,506
Arapahoe	\$7,109,557	\$1,289,716,020
Archuleta	\$865,598	\$24,808,896
Baca	\$107,189	\$9,284,028
Bent	\$24,303	\$6,737,059
Boulder	\$287,821	\$886,443,782
Broomfield	\$8,901,788	\$230,838,540
Chaffee	\$0	\$31,468,556
Cheyenne	\$1,794,589	\$6,821,828
Clear Creek	\$0	\$29,297,874
Conejos	\$0	\$6,248,494
Costilla	\$0	\$9,109,808
Crowley	\$0	\$3,848,654
Custer	\$0	\$8,256,413
Delta	\$91,768	\$23,578,349
Denver	\$0	\$1,913,598,684
Dolores	\$3,825,677	\$6,233,310
Douglas	\$0	\$822,291,773
Eagle	\$0	\$241,281,878
El Paso	\$0	\$732,241,401
Elbert	\$60,523	\$41,436,684
Fremont	\$32,813	\$40,716,970
Garfield	\$61,177,151	\$151,893,498
Gilpin	\$0	\$16,423,767
Grand	\$0	\$64,395,091
Gunnison	\$617,696	\$52,198,016
Hinsdale	\$0	\$3,184,430
Huerfano	\$348,553	\$12,032,750
Jackson	\$1,420,686	\$3,927,623
Jefferson	\$0	\$1,067,799,559
Kiowa	\$333,225	\$3,591,788
Kit Carson	\$5,124	\$16,885,978
Lake	\$26,186,239	\$21,004,414
La Plata	\$0	\$80,495,096
Larimer	\$2,445,092	\$677,356,099
Las Animas	\$2,266,969	\$14,402,716
Lincoln	\$834,143	\$12,466,157
Logan	\$222,127	\$26,461,347

Mesa	\$8,171,343	\$160,488,878
Mineral	\$0	\$3,537,556
Moffat	\$1,781,818	\$28,683,841
Montezuma	\$14,476,352	\$31,616,168
Montrose	\$0	\$46,362,638
Morgan	\$520,174	\$55,636,299
Otero	\$0	\$11,298,389
Ouray	\$0	\$12,150,291
Park	\$0	\$34,483,776
Phillips	\$132,716	\$9,026,747
Pitkin	\$0	\$155,561,871
Prowers	\$35,265	\$10,014,469
Pueblo	\$0	\$205,627,293
Rio Blanco	\$12,042,489	\$29,973,296
Rio Grande	\$0	\$14,213,229
Routt	\$73,381	\$84,950,255
Saguache	\$0	\$30,246,976
San Juan	\$0	\$2,214,391
San Miguel	\$189,945	\$44,508,585
Sedgwick	\$4,111	\$4,849,143
Summit	\$0	\$146,138,626
Teller	\$0	\$37,072,494
Washington	\$617,862	\$11,057,747
Weld	\$431,765,682	\$989,330,571
Yuma	\$1,421,405	\$22,716,048
Colorado Total	\$621,488,970	\$11,921,688,758

Source: Colorado Fiscal Institute's analysis of Department of Local Affairs 2021 Assessed Valuation Data by Class and Average Mill Levies.

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- 2 <https://pubs.acs.org/doi/pdf/10.1021/acs.est.1c02234>
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- 4 https://leg.colorado.gov/sites/default/files/2020-te24_ad_valorem_credit.pdf
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- 22 C.R.S. § 40-3.2-106(4) “Starting in 2020, the commission shall use a social cost of carbon dioxide of not less than sixty-eight dollars per short ton”
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Climate Change in Colorado

A report for the Colorado Water Conservation Board

Climate Change in Colorado

A report for the Colorado Water Conservation Board

Third Edition | 2024

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The Colorado Water Conservation Board and Colorado Climate Center hope this report can be used to support climate adaptation and water planning efforts across Colorado. The report describes recent trends in Colorado's climate and hydrology and interprets the model-based projections of future climate and hydrology. This information can be used by local, state, and federal partners to inform planning efforts across Colorado.

The Colorado Water Conservation Board is committed to continued work across all types of communities, including those which are disproportionately impacted by environmental injustice and climate impacts. This also includes a commitment to ongoing meaningful consultation with tribal nations on water and climate change issues. Integrating Indigenous knowledge and multiple perspectives into state water planning can enhance and advance climate adaptation efforts.

This commitment to collaboration is also embodied in the Colorado Water Plan which acknowledges the need for not just state action but local action, tribal coordination, and cross-sector leadership. By working together Colorado can realize a more sustainable and resilient future.

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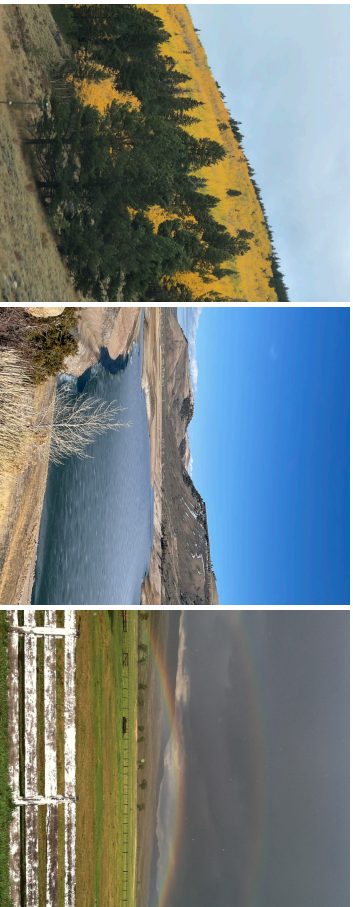


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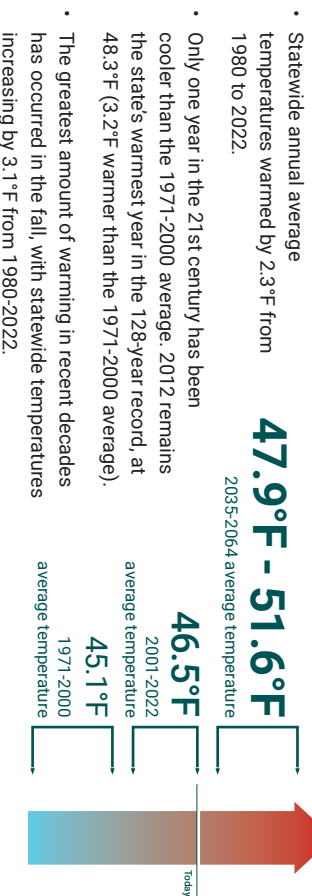
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 Visit our website for the expanded report, interactive charts, and access to data.

Temperature



- Statewide annual average temperatures warmed by 2.3°F from 1980 to 2022.
- Only one year in the 21st century has been cooler than the 1971-2000 average. 2012 remains the state's warmest year in the 128-year record, at 48.3°F (3.2°F warmer than the 1971-2000 average).
- The greatest amount of warming in recent decades has occurred in the fall, with statewide temperatures increasing by 3.1°F from 1980-2022.
- Southwestern and South-central Colorado have experienced the largest magnitude of warming.
- The observed warming trend in Colorado is strongly linked to the overall human influence on climate and recent global warming. The observed warming over the last 20 years is comparable to what was projected by earlier climate models run in the 2000s.
- Further and significant warming is expected in all parts of Colorado, in all seasons, over the next several decades.
- By 2050 (the 2035-2064 period average), Colorado statewide annual temperatures are projected to warm by +2.5°F to +5.5°F compared to a 1971-2000 baseline, and +1.0°F to +4.0°F compared to today, under a medium-low emissions scenario (RCP4.5).
- By 2070 (the 2055-2084 period average), Colorado statewide annual temperatures are projected to warm by +3.0°F to +6.5°F compared to the late 20th century, and +1.5°F to +5.0°F compared to today, under RCP4.5.
- By 2050, the average year is likely to be as warm as the very warmest years on record through 2022. By 2070, the average year is likely to be warmer than the very warmest years through 2022.
- Summer and fall are projected to warm slightly more than winter and spring.

Climate variable/event	Recent trend	Projected future change	Confidence in change
Average Temperature	Warmer	Warmer	Very High ●
Annual Precipitation	Lower	Uncertain	Low 🟡

Table 2.1 Summary of the observed and projected changes in annual average temperature and annual precipitation for Colorado, as detailed in the following sections. "Confidence in change" reflects the judgment of the authors, based on both the assessments in higher-level climate reports (NCA, IPCC) as well as relevant literature and model output for Colorado.

Precipitation

- Colorado has observed persistent dry conditions in the 21st century. According to water year precipitation accumulations, October 1 – September 30, four of the five driest years have occurred since 2000.
- Drying trends have been observed over the majority of the state during the spring, summer, and fall seasons.
- Northwest Colorado summer precipitation has decreased 20% since the 1951-2000 period.
- Southwest Colorado spring precipitation has decreased 22% since the 1951-2000 period.
- The direction of future change in annual statewide precipitation for Colorado is much less clear than for temperature. The climate model projections for 2050 range from -7% to +7% compared to the late 20th century average, under a medium-low (RCP4.5) emissions scenario.
- The model projections for precipitation change by 2070 are very similar to those for 2050.
- Most climate models project an increase in winter (Dec-Feb) statewide precipitation; the model consensus is weaker for the other seasons. The models do suggest enhanced potential for large decreases (-10% to -25%) in summer precipitation.

Streamflow

- Since 2000, annual streamflow in all of Colorado major river basins has been 3% to 19% lower than the 1951-2000 average.
- Modeling studies have attributed up to half of the observed decrease in streamflow since 1980 in Colorado river basins to warming temperatures.
- Future warming will act to reduce annual streamflows. Most climate model projections of annual streamflows in the state's major river basins for 2050 show reductions of 5% to 30% compared to 1971-2000.
- Higher future streamflow would require large overall increases in precipitation to offset the effects of warming, an outcome that appears unlikely.
- Summer and fall streamflows are projected to decline significantly by 2050 as the seasonal runoff peak shifts earlier, by 1-4 weeks, due to warming.

Soil Moisture

- Modeled soil moisture based on meteorological observations suggests overall declines in high-elevation soil moisture from 1980-2022.
- Future warming will lead to declines in summer (June-August) soil moisture throughout the state. Spring (March-May) soil moisture will likely increase at higher elevations as snowmelt shifts earlier.
- Rapid depletion of soil moisture under warm conditions exacerbates warming. When summer sunshine hits a landscape with dry soil a greater fraction of solar energy directly heats the surface, leading to even warmer conditions.

Evapotranspiration

- The evaporative demand ("thirst") of the atmosphere—as measured by potential evapotranspiration (PET) and Reference ET—has increased across Colorado since 1980, mainly due to the warming trend. Statewide, growing-season PET increased by 5% from 1980-2022.
- Additional future warming will drive greater evaporative demand; all climate model projections show statewide annual PET increasing by 8-17% by 2050, compared to 1971-2000.





Climate variable/event	Recent trend	Projected future change	Confidence in change
Spring Snowpack	Lower	Lower	Medium 
Runoff timing	Earlier	Earlier	High 
Annual Streamflow	Lower	Lower	Medium 
Summer soil moisture	Lower	Lower	High 
Evaporative demand	Higher	Higher	Very High 

Table 3.1 Summary of the observed and projected changes in hydrology and water resources for Colorado, as detailed in the following sections. "Confidence in change" reflects the judgment of the authors, based on both the assessments in higher-level climate reports (NCA, IPCC), as well as relevant literature and model output for Colorado. In general, there is higher confidence in the changes in variables that are driven mainly by warming and less by the more uncertain change in annual precipitation.

Snowpack

- April 1 snow water equivalent (SWE, also known as snowpack) during the 21st century has been 3% to 23% lower than the 1951-2000 average across Colorado's major river basins.
- Future warming will lead to further reductions in Colorado's spring snowpack. Most climate model projections of April 1 SWE in the state's major river basins show reductions of -5% to -30% for 2050 compared to 1971-2000; the individual projections that show increasing snowpack assume large increases in fall-winter-spring precipitation.
- The seasonal peak of the snowpack is projected to shift earlier by a few days to several weeks by 2050, depending on the amount of warming and the precipitation change. This warming-driven shift could be accelerated by increases in dust-on-snow events.



5-30%
Reduction of
April 1 SWE by 2050

Climate variable/event	Recent trend	Projected future change	Confidence in change
Heat waves	More frequent/intense	More frequent/intense	Very High
Cold waves	Fewer	Fewer	Medium
Droughts	More frequent/intense	More frequent/intense	High
Wildfires	More and larger	More and larger	High
Extreme precipitation	More intense	More frequent/intense	Medium
Flooding	Mixed	Higher	Medium
Windstorms	Uncertain	Uncertain	Low
Severe thunderstorms	Uncertain	More frequent	Low
Hail	Uncertain	More large hail	Low
Tornadoes	Uncertain	Uncertain	Low
Winter storms	Uncertain	Larger storms	Low
Dust on snow events	Greater dust levels	Greater dust levels	Medium

Table 4.1: Summary of the observed and projected changes in climate extremes and hazards for Colorado, as detailed in the following sections.

Heat waves and cold waves

- Hot days and heat waves have become more common, and the number of cold nights and cold waves has decreased across Colorado in recent decades, but the changes have not been equal. There have been significant increases in extreme heat across most of the state, whereas the decrease in extreme cold has been more modest.
- Projected future changes are similarly asymmetric: Heat waves are projected to increase in frequency by as much as ten-fold by the middle of the 21st century, whereas the frequency of cold waves is projected to decrease by less than half.

Drought

- Warming temperatures have increased the severity of 21st century droughts in Colorado.
- Regardless of changes in precipitation, it is likely that warmer temperatures will contribute to more frequent and severe droughts. Warmer temperatures will also decrease the benefit of wetter years.
- Intense droughts have occurred multiple times in the 21st century, including in 2002, 2012, 2018, and 2020.

Wildfire

- Since 2000, Colorado has experienced a large increase in the number of large wildfires and in the annual area burned by all wildfires; on average, fires have burned at higher elevations and with higher intensity than in the late 20th century. While several factors have contributed to these trends, rising temperatures are a major driver.
- Future warming is expected to lead to further increases in the occurrence of large wildfires and in annual area burned by all fires, especially in forest ecosystems, according to multiple studies. A greater percentage of fires will occur in the fall, winter, and spring than at present.

Heavy and extreme rainfall

- There are some indications of recent increasing trends in heavy and extreme rainfall in Colorado, but these are not consistent across all indicators and time periods, unlike in other regions of the U.S.
- Atmospheric moisture has generally increased over Colorado, but not by as much as one would predict from the warming atmosphere alone.
- Future warming, by increasing the moisture-holding capacity of the atmosphere, will make heavy and extreme rainfall more likely unless counterbalanced by declining trends in other storm “ingredients”. Climate-model projections for Colorado show overall increases in the magnitudes of heavy and extreme rainfall events.

Floods

- Gaged streamflow records show no widespread, consistent trends in the magnitude of flood events in Colorado of different frequencies (e.g., 1-year, 20-year, 50-year, 100-year).
- The expectation that heavy and extreme rainfall events will increase in Colorado implies increases in future flood risk as well, but there are many factors influencing how rainfall is translated into runoff. Increased exposure to flooding through floodplain development may be more important than climate-driven changes in risk.

Thunderstorm hazards

- Because of the relatively short data record for thunderstorm hazards and the influences of changing observation systems, the sign and magnitude of any long-term changes is unclear.
- Some studies have suggested increases in the average size of hail in a warmer climate, with smaller hail becoming less frequent but larger hail more frequent. Overall, however, there remain large uncertainties regarding future changes, as data limitations and the infrequent and localized nature of these storms makes them challenging to study in the context of a changing climate.

Non-convective windstorms

- Colorado is prone to intense winds in the mountains and from downslope windstorms along the Front Range. These windstorms can cause considerable damage, and can exacerbate wildfires, such as in the 2021 Marshall Fire. Long-term changes in extreme winds have not been extensively studied, and potential future changes are highly uncertain.

Winter storms

- Despite warming temperatures in the winter, there are no detectable trends in winter severity across the Colorado Front Range and Eastern Plains. There are also minimal trends in large snowfall events.
- Several notable and high impact winter storm events have occurred over eastern Colorado in the last decade, including extreme cold, high winds, strong cold fronts, and large accumulations of snow.
- Future trends in winter storms remain highly uncertain, but the risk of high-impact winter events is likely to remain.

Dust-on-snow

- Dust-on-snow events have emerged as a concern since 2000 due to better understanding of its hydrologic effects, as well as an overall increase in the occurrence of dust-on-snow. Dust-on-snow causes earlier melt and runoff and may reduce annual runoff.
- It is likely that in a future warmer climate, drier conditions in the dust-source regions will allow for greater dust emission and thus deposition on snowpacks. Dust-on-snow and warming will both drive earlier snowmelt and runoff.

Chapter 1

Introduction

About this report

This is the third edition of Climate Change in Colorado. In 2008, the Western Water Assessment program at the University of Colorado Boulder, in collaboration with the Colorado Water Conservation Board (CWCB), produced the first edition, *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation* (Ray et al. 2008). The 2008 report synthesized the current science on the physical aspects of climate change relevant to evaluating future impacts on Colorado's water resources. It presented scientific analyses to support future studies and state efforts to develop a water adaptation plan. The 2008 Report was notable for being one of the first state-level climate change assessments; today, similar assessments have been conducted in at least 25 states.

Several years later, the CWCB partnered with the Western Water Assessment to undertake a thorough update and revision of the 2008 Report, the result of which was also called *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation* (Lukas et al. 2014). This update again covered the observed trends and future projections of hydroclimate variables—including temperature, precipitation, snowmelt, and runoff—that determine both water supply and demand for the state. The 2014 report also had a broader scope and more detail in many areas than the 2008 report, doubling its length compared to its predecessor.

The main findings about recent climate trends and projected future climate change for Colorado were consistent between the two reports: Colorado's climate has become much warmer and further warming is expected; precipitation has been highly variable, and its future direction was uncertain; significant future changes to the water cycle are likely due to the effects of warming alone, including decreases in snowpack and runoff.

The information in the 2008 and 2014 reports has been used as guidance for many statewide and local water planning and climate planning documents and processes, including the Colorado River Water Availability Study (CRWAS, CWCB 2012; CWCB 2019a), Colorado Water Plan (CWCB 2023), Colorado Climate Plan (State of Colorado 2018), and the Colorado Drought Mitigation and Response Plan (CWCB 2018). The 2008 and 2014 reports have each been cited in about 100 peer-reviewed studies, indicating that they have been highly regarded and relied upon in the scientific community as well.

For this third edition of *Climate Change in Colorado*, we cover a similar scope, though with overall less detail compared to the 2014 report. The core function of the report is still to describe recent trends in Colorado's climate and hydrology and interpret the model-based projections of future climate and hydrology. Compared to its predecessors, this report has greater coverage of climate extremes and hazards, including heat waves, droughts, wildfires, and extreme precipitation and floods. The overall societal impacts of climate change will be driven by both changes in these extreme events and by pervasive changes in the average climate.

While this report provides a scientific basis to prompt further studies of water resources impacts and support planning and adaptation efforts, the assessment of specific local sensitivities and vulnerabilities is beyond the scope of this report. Several other resources, including the Colorado Water Plan (CWCB 2023), the Analysis and Technical Update to the Colorado Water Plan (CWCB 2019b) and the Colorado River Water Availability Study (CRWAS), Phase II (CWCB 2019) provide more detailed assessments of climate change impacts on water resources at the basin scale and smaller. The Colorado Climate Change Vulnerability Study (Gordon and Djima 2015) focused on vulnerabilities due to climate change across multiple sectors, including water. A forthcoming compendium study to this report will further describe climate impacts and vulnerabilities based on hazards identified here.

About this report

Organization of the report

The Global Context for Colorado's Climate



Organization of the report

The key findings of this report are summarized at the beginning of each chapter and in the Executive Summary that precedes Chapter 1.

Chapter 2 provides analysis of the observed and projected changes in temperature and precipitation. Chapter 3 provides analysis of the observed and projected changes in Colorado's water, including snowpack, streamflow volume and timing, soil moisture, and evapotranspiration. Chapter 4 assesses the observed and projected changes in different climate hazards and extremes. Appendix A provides supplemental information on the observational climate dataset and the climate model projections used in the report.

The Global Context for Colorado's Climate

While Colorado's climate has characteristics specific to our state's particular geography, it plays out within a much broader arena: the global climate system. Since the 2014 report, the evidence that human influences have impacted the global climate system has only strengthened. The latest report from the Intergovernmental Panel on Climate Change (*IPCC 2021*) states that

It is unequivocal that human influence has warmed the atmosphere, ocean, and land. Wide-spread and rapid changes in the atmosphere, ocean, cryosphere [snow and ice] and biosphere have occurred. (Summary for Policymakers, p. 4)

The observed globally averaged warming of the Earth's surface (land and ocean) as of early 2023 has reached 1.4°F (0.8°C) since 1980, and a total of 2.0°F (1.1°C) relative to the 1850-1900 period. It is estimated that the total warming influence of human drivers is responsible for all the globally averaged warming relative to 1850-1900, while solar and volcanic drivers and natural climate variability have had little net effect over this period (*IPCC 2021*). The most important human drivers of warming are the increases in greenhouse gases, principally carbon dioxide (CO₂) and methane (CH₄), which have acted to trap additional heat in the lower atmosphere and at the Earth's surface compared to pre-industrial (<1750) conditions. As of 2022, the annually averaged level of CO₂ in the atmosphere was at 420 parts per million (ppm), higher than at any time in at least 2 million years (*IPCC 2021*). The anthropogenic (human-caused) increases in CO₂ (+50%) and methane (+150%) since 1750 greatly exceed the natural changes in those two gases that occurred over thousands of years between past glacial and interglacial periods (*IPCC 2021*).

The rapid global warming of the past several decades, a rate unprecedented in at least 2000 years, is associated with pervasive changes to the Earth system (*IPCC 2021*), including:

- Global retreat of glaciers, decreases in Arctic sea ice area and volume, mass loss from the Greenland and Antarctic ice sheets, and decline in Northern Hemisphere snow cover.
- An acceleration in the rate of global sea level rise since the 1970s due to both thermal expansion of ocean water and increasing melt from glaciers and ice sheets.

- Increases in global water vapor levels and global annual precipitation as evaporation has increased and the water cycle has intensified.
- Widespread increases in the frequency and/or severity of extremes and natural hazards such as heat waves, heavy precipitation, droughts, and tropical cyclones.
- Overall poleward and upslope shifts in the distributions of many plant and animal species as their habitable climate zones shift due to warming.

These global climate trends and changes have shaped the recent evolution of Colorado's climate and will continue to do so. Like nearly every other part of the globe, Colorado has warmed substantially over the past century, particularly since the 1980s, as described in Chapter 2. Figure 1.1 shows that the overall trajectory of Colorado's observed temperatures since 1900 has closely followed those of U.S. and global temperatures. Like other land areas, Colorado has warmed more than the global average—which mainly reflects the slower-warming oceans that cover 71% of the Earth's surface. This relative difference between Colorado's warming and the globally averaged warming is expected in future warming as well.

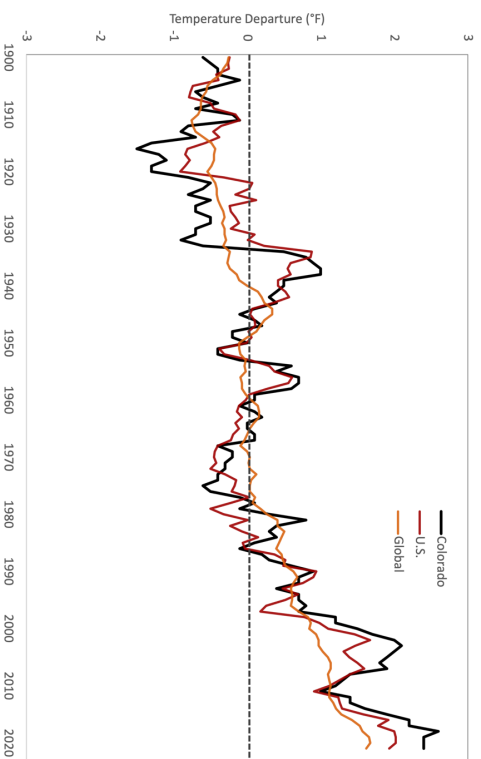


Figure 1.1: Observed 5-year running mean surface temperature departure from a 20th century baseline for Colorado (black), the U.S. (red), and the globe (orange). Data from NOAA National Centers for Environmental Information.

Chapter 2

Changes in Colorado's Climate

KEY MESSAGES

Temperature

- Statewide annual average temperatures warmed by 2.3°F from 1980 to 2022.
- Only one year in the 21st century has been cooler than the 1971-2000 average. 2012 remains the state's warmest year in the 128-year record, at 48.3°F (3.2°F warmer than the 1971-2000 average).
- The greatest amount of warming in recent decades has occurred in the fall, with statewide temperatures increasing by 3.1°F from 1980-2022.
- Southwestern and South-central Colorado have experienced the largest magnitude of warming.
- The observed warming trend in Colorado is strongly linked to the overall human influence on climate and recent global warming. The observed warming over the last 20 years is comparable to what was projected by earlier climate models run in the 2000s.
- Further and significant warming is expected in all parts of Colorado, in all seasons, over the next several decades.
 - By 2050 (the 2035-2064 period average), Colorado statewide annual temperatures are projected to warm by +2.5°F to +5.5°F compared to a 1971-2000 baseline, and +1.0°F to +4.0°F compared to today, under a medium-low emissions scenario (RCP4.5).
 - By 2070 (the 2055-2084 period average), Colorado statewide annual temperatures are projected to warm by +3.0°F to +6.5°F compared to the late 20th century, and +1.5°F to +5.0°F compared to today, under RCP4.5.
 - By 2050, the average year is likely to be as warm as the very warmest years on record through 2022. By 2070, the average year is likely to be warmer than the very warmest years through 2022.
- Summer and fall are projected to warm slightly more than winter and spring.

Climate variable/event	Recent trend	Projected future change	Confidence in change
Average Temperature	Warmer	Warmer	Very High ●
Annual Precipitation	Lower	Uncertain	Low ○

Table 2.1 Summary of the observed and projected changes in annual average temperature and annual precipitation for Colorado, as detailed in the following sections. "Confidence in change" reflects the judgment of the authors, based on both the assessments in higher-level climate reports (NCA, IPCC) as well as relevant literature and model output for Colorado.

Precipitation

- Colorado has observed persistent dry conditions in the 21st century. According to water year precipitation accumulations, October 1 – September 30, four of the five driest years have occurred since 2000.
- Drying trends have been observed over the majority of the state during the spring, summer, and fall seasons.
- Northwest Colorado summer precipitation has decreased 20% since the 1951-2000 period.
- Southwest Colorado spring precipitation has decreased 22% since the 1951-2000 period.
- The direction of future change in annual statewide precipitation for Colorado is much less clear than for temperature. The climate model projections for 2050 range from -7% to +7% compared to the late 20th century average, under a medium-low (RCP4.5) emissions scenario.
- The model projections for precipitation change by 2070 are very similar to those for 2050.
- Most climate models project an increase in winter (Dec-Feb) statewide precipitation; the model consensus is weaker for the other seasons. The models do suggest enhanced potential for large decreases (-10% to -25%) in summer precipitation.

2.1 Overview

This chapter assesses recent trends and likely future changes in the basic indicators of Colorado's climate—average temperature (monthly, seasonal, annual), and precipitation (monthly, seasonal, annual)—based on the best available scientific evidence.

Colorado's Average Climate

Colorado's climate reflects its mid-continental location, high elevations, and the complex topography of the mountains, plains, and plateaus. Topographic influences on weather and climate processes result in large variations in climate over short distances. Wind, humidity, temperature, and precipitation patterns are all modulated by sharp changes in elevation and the orientation of mountain ranges and valleys (Doerken *et al.* 2003).

The states interior location results in frequent sunshine, low humidity, and large variations in daily temperature ranges and annual temperature variability. The distance from large sources of moisture (i.e., Pacific Ocean and Gulf of Mexico) results in lighter precipitation for the lower elevations. High mountain ranges benefit from Pacific moisture moving eastward during the winter months.

Average Temperature

For most parts of the state, on average, January tends to be the coldest month of the year, and July is the warmest (Figure 2.1). Topography plays a role in temperatures – in general, temperatures decrease with elevation. Average high elevation temperatures (over 10,000 feet above sea level [asl]) range from single digits in the winter months to 60s and 70s (°F) in the summer. For lower elevation areas and the plains (elevations around 5,000 ft asl or less), average temperatures dip to the teens in the winter and frequently top the 90s (°F) in the summer. Middle elevations offer warm temperatures in the summer, but rarely into the 90s, with frequent single digit temperatures in the winter. Extremes across the state range from negative temperatures (with winter temperatures observed below -40°F in the high mountain valleys) to triple digits (over 110°F occurring in the lower river valleys of the eastern plains of Colorado).

Average Precipitation

Topography also plays an important role in influencing precipitation processes and patterns. Precipitation typically increases with elevation in all seasons, but especially in winter when nearly all moisture falls as snow. The seasonal cycle of precipitation is highly dependent on location (Figure 2.1). The Eastern Plains are generally wetter during the spring and summer months, with a May peak in northeast Colorado and a July peak in southeast Colorado. The higher mountain areas tend to be wetter during the winter and early spring months, and southwest Colorado's wettest months coincide with the occurrence of the North American Monsoon in August and September. Annual precipitation totals are less than 10 inches in the San Luis Valley, while the high mountain ranges typically receive over 40 inches of liquid precipitation in one year (with amounts observed between 60 and 80 inches in wet years).

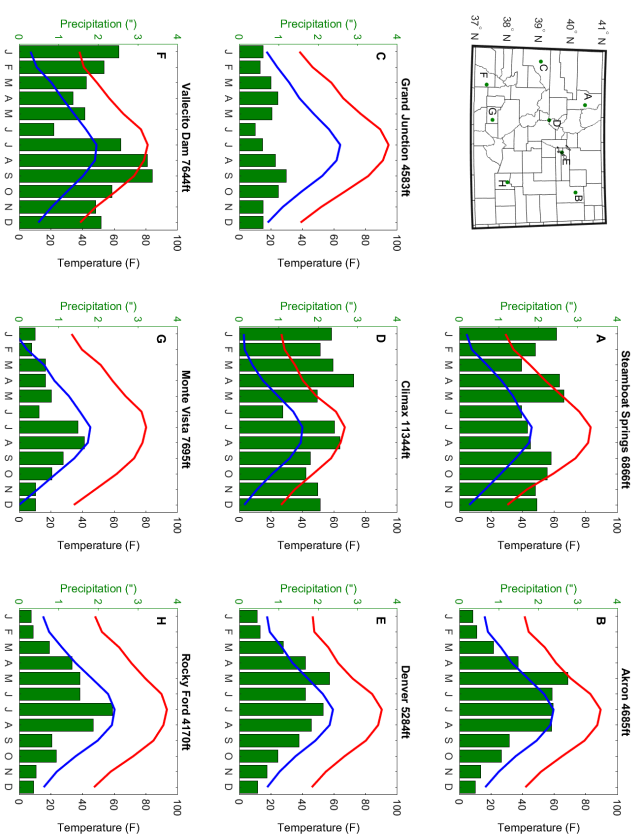


Figure 2.1: 1991-2020 normal monthly precipitation (green bars), daily average maximum (red line) and daily average minimum (blue line) temperatures for eight National Weather Service Cooperative Observer Program (COOP) stations around the state. Precipitation in inches and temperature in degrees Fahrenheit. Locations of the eight stations are labeled on the top left map.

Data

For recent trends and variability in temperature and precipitation, we have relied on NOAA nClimGrid, a gridded dataset based on weather observations from hundreds of sites across Colorado, and corrected for biases from changes in instrumentation, changes in the daily time of observation, moves in station location and other inhomogeneities. An earlier version of nClimGrid was used in the 2014 report. See Appendix A for more information on this dataset and a comparison with a similar dataset.

For likely future changes in temperature and precipitation, as with the previous two reports, we relied on the simulations (projections) from global climate models (GCMs). The 2014 report featured results from the then-latest global archive of GCM projections, known as CMIP5 (Coupled Model Inter-comparison Project, Phase 5; see Appendix A for more information about the CMIPs). The 2014 report also compared those results from the previous archive (CMIP3).

In this report, we show results from CMIP5 as well as the most recent archive of GCM projections (CMIP6) that was released in 2020-21. The projections from CMIP6 have not yet been used to generate basin-scale projections of hydrology and water resources (such as in Chapter 3); thus, we have chosen to emphasize CMIP5 projections throughout Chapters 2, 3, and 4 to maintain consistency among the analyses. We also examine the differences between the CMIP5 and CMIP6 projections for Colorado.

Sidebar: Colorado climate divisions

NOAA's official set of climate divisions for the U.S. (*Guttman and Quayle 1996*) splits Colorado into five divisions that correspond to the large river basins in the state (the Arkansas, Platte, Rio Grande, Colorado, and Republican). However, there are limitations of these divisions for climate analysis and monitoring. For example, all of western Colorado is included in a single climate division, even though the climates (and climate variability) of northwest and southwest Colorado have major differences. *Wolter and Allured (2007)* developed a method for alternate divisions based on seasonal variability at long-term stations, and an adaptation of these divisions was used in the 2014 Climate Change in Colorado report. For this report update, we applied the Wolter and Allured method of hierarchical cluster analysis to monthly gridded data from 1950-2021 to establish a set of 11 alternate climate divisions that are used throughout this report (Figure 2.2). These divisions have the advantage of providing information that is more granular than the existing climate divisions, and more representative of available data than county-level calculations (Schumacher et al. 2024).

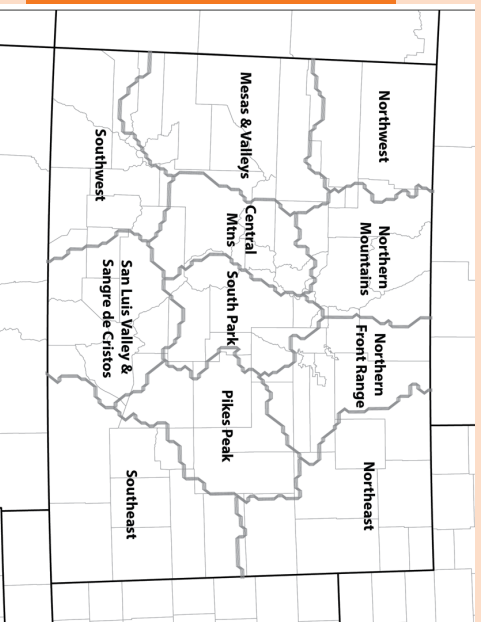


Figure 2.2: The eleven alternate climate divisions with names assigned by the authors based on how they are often referred to in relation to climatology or local convention.

2.2 Temperature

The most fundamental and pervasive effect of anthropogenic (human-caused) climate change is an overall warming of the climate system. This global warming has manifested in nearly all regions of the world in the past several decades.

Observed temperature changes

Colorado statewide temperatures have warmed since systematic instrumental observation records began in the late 19th century (Fig. 2.3). When compared to the 1971-2000 average, only one year in the 21st century had below-average annual temperature. Seven of the top 10 hottest years on record have occurred since 2010. Recent mean temperatures (2001-2022) have averaged 1.4°F warmer than the 1971-2000 average (45.1°F).

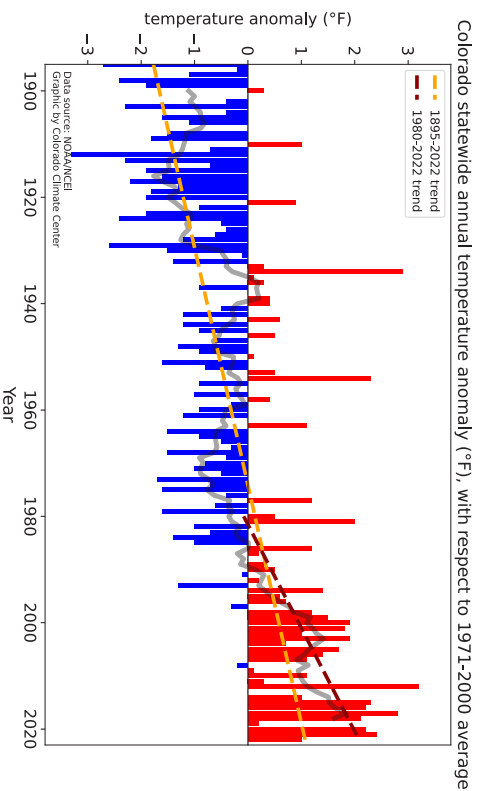


Figure 2.3: Colorado statewide temperature anomaly (°F) with respect to the 1971-2000 average of 45.1°F. The 1895-2022 trend (yellow dashed), and 1980-2022 (red dashed) lines are included.

We analyzed temperature changes by season, both long-term (from 1895-2022) and more recent trends (1980-2022). From 1895-2022, the winter season (Dec-Jan-Feb) shows the greatest warming (Table 2.2). However, since 1980, winter warming has diminished, largely due to recent cooling observed in February. Fall season (Sep-Oct-Nov) temperatures have warmed more than any other season for 1980-2022 (Table 2.2). All seasons have exhibited increasing trends in both short- and long-term periods, with seasonal changes ranging between +1°F to +3°F for the 1980-2022 period.

Statewide	1895-2022 change	1980-2022 change
Winter	+3.3°F	+1.0°F
Spring	+2.6°F	+1.7°F
Summer	+2.7°F	+2.5°F
Fall	+2.1°F	+3.1°F
Annual	+2.9°F	+2.3°F

Table 2.2. Changes in statewide average annual and seasonal temperature as calculated by the linear trend, 1895-2022 (middle column) and 1980-2022 (right column)

We also analyzed seasonal and annual temperature changes for each of the 11 alternate climate divisions (see sidebar for description of climate divisions). Figure 2.4 shows the seasonal changes in temperature for each division for the recent period of 1980 to 2022. Most notably, the greatest warming has occurred in the fall (Fig. 2.4d) for each climate division. Summer warming has also been significant (Fig. 2.4c), with larger changes in the western climate divisions. The south and the west have observed more warming in the spring (Fig. 2.4b). The Northern Front Range (including the majority of the state's population) has experienced little to no warming in spring, while the Central Mountains and South Park area experienced little to no warming during the winter (Fig. 2.4a). Annually, the greatest warming has been observed over the Southwest and San Luis Valley climate regions.

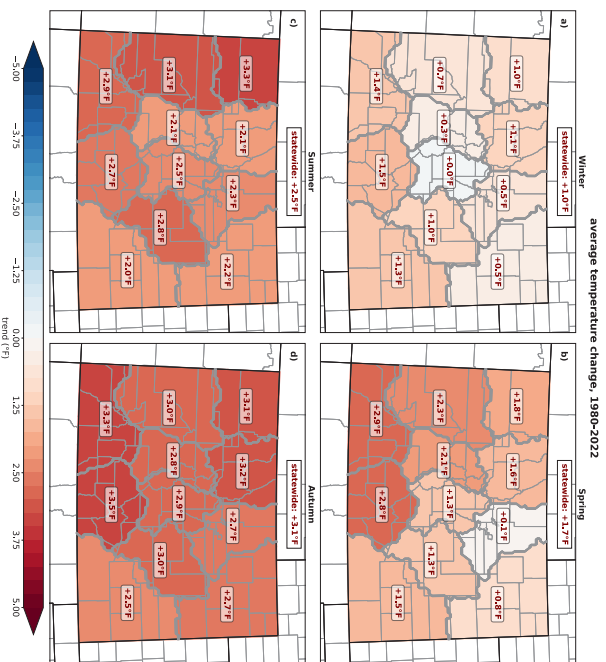


Figure 2.4. Changes in observed climate division temperature, 1980-2022, for (a) winter, December-January-February, (b) spring, March-April-May, (c) summer, June-July-August, and (d) fall, September-October-November.

Attribution of the observed trends

The pervasive observed warming trends that have been observed regionally, nationally, and globally. At the global scale, human influence has been the main driver of observed warming in the past several decades (USGCRP 2017, IPCC 2021). The warming trend in the southwest U.S., including Colorado, has likewise been primarily attributed to human influence (Leher et al. 2018). Figure 2.5 shows that the trajectory of observed annual average temperature for Colorado (gray) since 1950 is comparable to the trajectory of median modeled temperatures from the CMIP3 (yellow) and CMIP5 (orange) climate model ensembles. These model runs assume greenhouse gas emissions and atmospheric concentrations similar to what has actually occurred through 2022. The similarity between the observed and modeled statewide warming trends is consistent with the evidence at broader spatial scales that indicates human influence has played a substantial role in Colorado's recent warming trend.

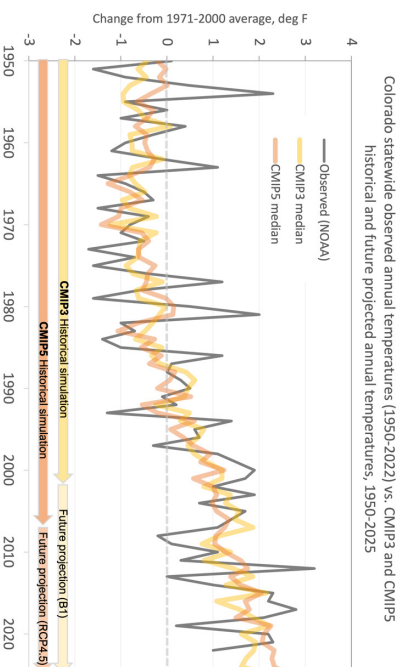


Figure 2.5. Observed statewide annual average temperatures 1950-2022 (same data as in Figure 2.3), compared with the median historical simulation plus the median future projection from the CMIP3 and CMIP5 climate model ensembles, respectively. (Data: Observations: NOAA NCEI nclimGrid, <https://www.ncei.noaa.gov/cag/>; CMIP3 and CMIP5 projections: GDO-BCP <https://gdo-dcp.ucdln.org/>)

Future temperature projections

There is very high confidence that the climate of Colorado will continue to warm in all seasons through the mid-21st century, given our understanding of the physical mechanisms for warming, the observed warming trend, and climate model projections. While the magnitude of warming is uncertain, by 2050, Colorado's average annual temperatures will likely match or exceed the very warmest years of the past, bringing large changes in the frequency and severity of heat waves, as we will discuss in Section 4.1. Note that in the analyses below, we focus on the medium-low emissions scenario RCP4.5, used for the CMIP5 climate model runs, and its counterpart SSP2-4.5, used for the CMIP6 model runs. The section "Emissions Scenarios" in Appendix A explains why we focused on these scenarios and provides more information about these and other emissions scenarios.

Under RCP4.5, Colorado statewide annual temperatures are projected by the CMIP5 climate models to warm by +2.5°F to +5°F compared to the late 20th century (1971-2000) average (Figure 2.6). We continue to use this 1971-2000 baseline to maintain consistency with the analysis of climate projections in the 2008 and 2014 reports, and in other state reports such as the Colorado Water Plan. Colorado has already warmed by about 1.5°F beyond this baseline, as detailed below.

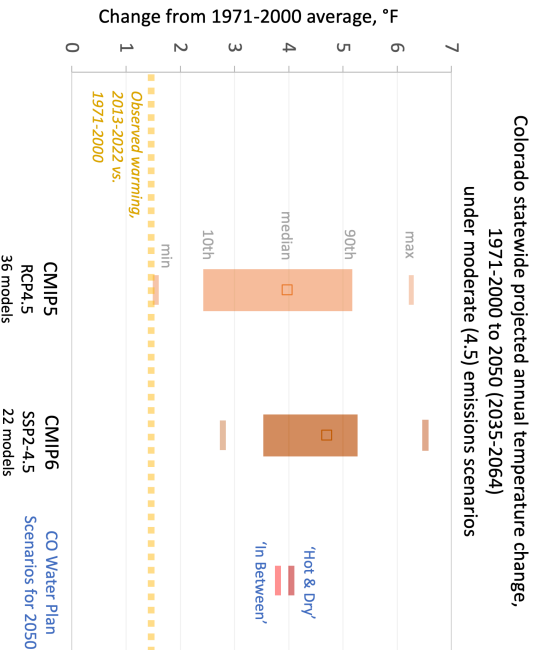


Figure 2.6: Projected future temperature change for Colorado statewide for a 2050-centered period (2035-2064) relative to 1971-2000 from the CMIP5 and CMIP6 climate models under medium-low emissions scenarios. The solid orange bars show the middle 80% of the model projections (10th-90th percentiles), the two orange dashes show the minimum and maximum projections, the open squares show the median projections. (Data: Observations: NOAA NCEI nclimGrid, <https://www.nclimdata.noaa.gov/cad/>; CMIP5 data: GDD-DGP, <https://ddp-dgp.ucsl.org/>; CMIP6 data: KMI Climate Explorer, <https://climateexplorer.kmi.co/water-plan/scenarios-cwcb> (2019); <https://cwcb.colorado.gov/colorado-water-plan/technical-update-to-the-plan>)

Under a comparable emissions scenario (SSP2-4.5), the CMIP6 models show a range of warming that is shifted upward, especially at the low end, compared to CMIP5, showing +3.5°F to +5°F warming for Colorado, as taken from the 10th to 90th percentiles of the projected values. The two red bars on the right side of Figure 2.6 show that the climate change scenarios for 2050 used in the Colorado Water Plan (*CWCB 2015*, *CWCB 2023*) are within the range of both CMIP5 and CMIP6 under 4.5 emissions scenarios. It is not surprising that the CMIP6 models show overall warmer futures for Colorado than CMIP5, since the global temperature response of the CMIP6 models given additional increments of greenhouse gases (i.e., climate sensitivity) is overall higher than for the CMIP5 models (see Appendix A for more detail on the CMIP6 “hot” model issue.)

It is important to remember that Colorado has already warmed, through 2022, a substantial fraction of the projected warming relative to the 1971-2000 baseline: about +1.5°F, depending on the calculation method (Fig. 2.6). Thus, the projected statewide warming for 2050 shown by the CMIP5 models is +1.0°F to +3.5°F relative to “today”, and in the CMIP6 models, +2.0°F to +3.5°F relative to today. The fact that Colorado has already experienced +1.5°F of warming relative to 1971-2000 suggests that the lowest-warming projections in the CMIP5 ensemble, below the 10th percentile, are now very unlikely outcomes.

Most of the projections under a medium-low (4.5) emissions scenario, whether from CMIP5 or CMIP6, show a mid-century climate that is, on average, at least 3°F warmer than the 1971-2000 baseline. If this does occur, an “average” year in 2050 will be warmer than the very warmest individual years observed through 2022 (Figure 2.7).

For a later future period centered on 2070 (2055-2084), the CMIP5 models under medium-low (RCP4.5) emissions scenario projects Colorado statewide temperatures to have warmed +3.0°F to +6.5°F of warming relative to 1971-2000, and +1.5°F to +5.0°F of warming relative to today. For the same 2070-centered period, the CMIP6 models under a comparable emissions scenario (SSP2-4.5) show warming of +4.0°F to +7.0°F relative to 1971-2000, and so +2.5°F to +5.5°F of warming relative to today. As seen in Figure 2.7, the difference between the CMIP5 and CMIP6 median warming under the 4.5 scenarios increases to about 1.0°F by 2070.

With continued warming over the next few decades, the future temperatures at every location in Colorado will become more like those currently experienced in places that are to the south, or lower in elevation. With 2°F of further warming, the seasonal temperature regime for Denver would become more like the current temperatures in Pueblo. With 4°F of further warming, Denver's temperature regime would be similar to Lamar today. With 6°F of further warming, Denver's temperatures would be slightly warmer than the current temperatures in the warmest parts of the lower Arkansas Valley (Las Animas and La Junta), and similar to Albuquerque, New Mexico. Note that this comparison only speaks to temperatures, not precipitation; Denver is very unlikely to experience a large decline in precipitation that would make the overall climate like Albuquerque, even with 6°F of warming.

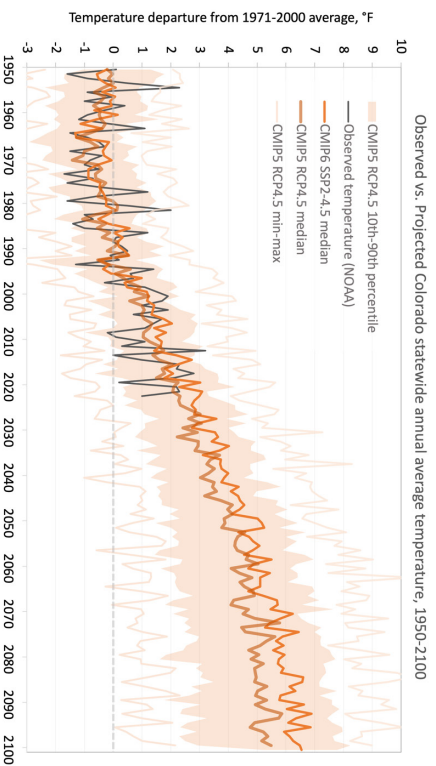


Figure 2.7: Projected change in Colorado statewide average annual temperatures to 2100, relative to a 1971-2000 baseline, from CMIP5 models (median and range) and CMIP6 models (median only) under medium-low emissions scenarios (RCP4.5, SSP2-4.5), compared to observed temperatures through 2022. (Data: Observations: NOAA NCEI ClimateGrid, https://www.cdeel.noaa.gov/lead/CMIP5_data_GDO-DOP/; <https://gdo-dcp.ucdlnl.org/>; CMIP6 data: KNMI Climate Explorer, <https://climate.knmi.nl/>)

Under a given emissions scenario (e.g., RCP4.5), the differences in warming across the various projections have two sources. The primary one is that the various climate models have different inherent sensitivity to each increment of greenhouse gases, because of how physical feedbacks are represented in each model. The second and lesser source is the “noise” of model-simulated natural (internal) variability. The 30-year averaging period (e.g., 2035-2064) used here is designed to reduce this noise, but some projections will happen to simulate a relatively warmer or cooler, few decades in the middle of the longer-term warming trend, and we cannot easily distinguish the noise from the background signal (the warming trend). The effect of this noise is more problematic for the precipitation projections than for temperature projections, as will be discussed in section 2.3.

Figure 2.8 shows the statewide seasonal temperature changes projected by CMIP5 models under RCP4.5, using the same data as shown in Figures 2.6 and 2.7. Overall, summer and fall show slightly greater future warming than winter and spring, though the differences between the seasons are relatively small compared to the magnitude of the overall projected warming. The CMIP6 models exhibit the same pattern (not shown); summer and fall are expected to warm slightly more than winter and spring.

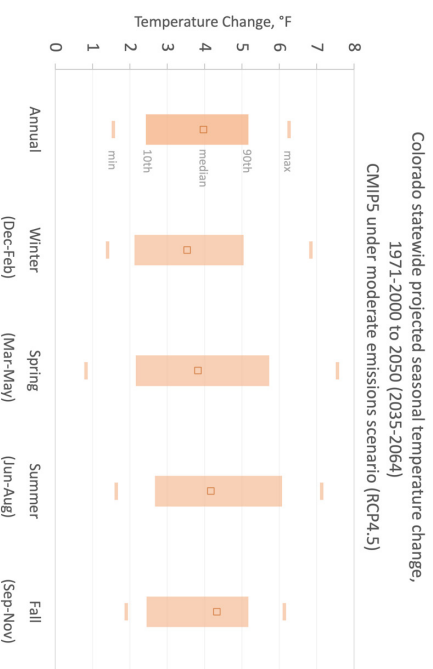


Figure 2.8: Projected future change in seasonal temperatures for Colorado statewide for a 2050-centered period (2035-2064) relative to 1971-2000, from CMIP5 (36 models/projections) under a medium-low emissions scenario (RCP4.5). The solid orange bars show the middle 80% of the model projections (10th-90th percentiles); the two orange dashes show the minimum and maximum projections; the open squares show the median projections. (Data: CMIP5: GDO-DOP, <https://gdo-dcp.ucdlnl.org/>).

Downscaled (regional) projections of temperature

The “raw” output from climate models provides useful estimates of future climate changes at the global scale down to statewide scales. But the spatial resolution of the data, generally 100-km (60-mi) to 300-km (180-mi) grid boxes in the midlatitudes, is too coarse to adequately represent the complex terrain of Colorado and its effects on climate, or for the data to be used as inputs for watershed hydrology modeling or other impact modeling. Thus, global climate model output is typically downscaled through statistical methods, or via higher-resolution regional climate models (RCMs), in order to better represent localized changes to weather and climate, and to facilitate further modeling. The process of downscaling also includes a bias-correction step which adjusts for systematic biases or offsets between the model-projected climate at regional scales and the observed historical climate, over the period of overlap between the two (e.g., 1950-2005).

For a closer look at how the projected future climate change may vary in different areas in Colorado, we analyzed the CMIP5-LOCA (Localized Constructed Analogs) statistically downscaled climate projection dataset developed by Pierce et al. (2014). These projections were not available at the time of the 2014 Report, but they have since been used in many climate assessments and studies, including USGCRP (2017, 2018), Lukas et al. (2020), and Reclamation (2021). Taking the 11 alternative climate divisions described earlier in this chapter, we obtained CMIP5-LOCA data for a 0.75° x 0.75° (40 mi./64 km x 52 mi./83 km) quadrangle within each division.

Figure 2.9 shows the projected change in annual average temperature under RCP4.5 between the historical baseline (1971-2000) and the 2050-centered future period (2035-2064) for the 11 alternative climate divisions. All of them are expected to see substantial future warming into this mid-century period. Slightly greater future warming is generally seen in the divisions in Western Colorado and the northern Front Range, with slightly less warming seen in South Park and the San Luis Valley divisions. Keep in mind that these differences in the projected changes in average temperature between the divisions, which are at most 0.7°F, are much smaller than the overall warming across all divisions (median: 4.1°F), or the uncertainty in the warming across the ensemble of 32 projections (generally ± 2°F). The key point is that all parts of the state are expected to warm at rates that are similar to the statewide average.

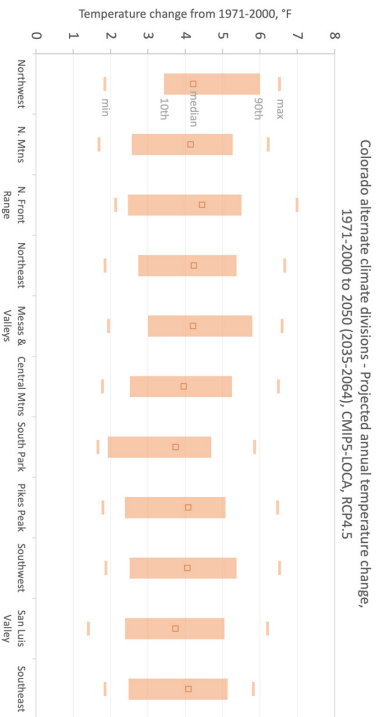


Figure 2.9: Projected future change in annual average temperature in 11 alternative Colorado climate divisions for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA climate projections under a medium-low emissions scenario (RCP4.5). The solid orange bars show the middle 80% of the model projections (10th to 90th percentiles); the two orange dashes show the minimum and maximum projections; the open squares show the median projections. (Data: CMIP5-LOCA, GDO-DCP; <https://gdo-dcp.wallick.org/>)

2.3 Precipitation

In Colorado, statewide precipitation exhibits high variability at both year-to-year and longer-term decadal timescales (Figure 2.10). With respect to the 1971-2000 average, annual precipitation has varied from more than 6 inches below average to nearly 6 inches above average. The smoothed time series (Fig. 2.10, gray line) shows frequent extended dry periods with wet periods in between.

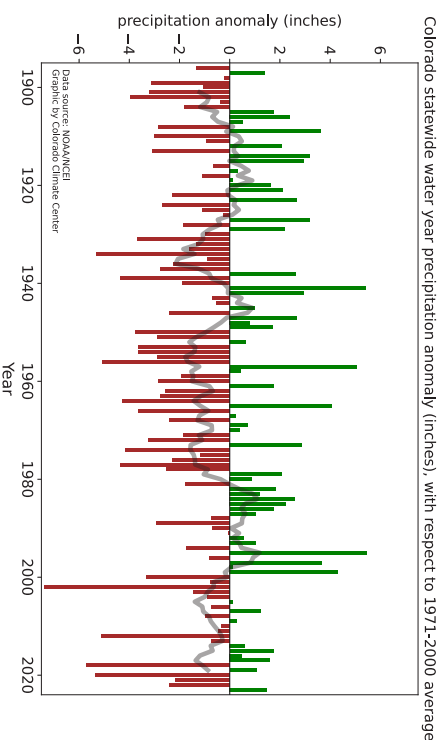


Figure 2.10: Colorado statewide water year precipitation anomaly (inches) with respect to the 1971-2000 average of 18.51 inches. Smoothed 10-year running mean (gray line) included.

Observed precipitation changes

Since the relatively wetter periods of the 1980s and 1990s, Colorado has experienced more persistent dry conditions since 2000. The differences in precipitation and temperature variability necessitate different approaches in analyzing their changes. Rather than calculating a linear trend, we calculate the difference in precipitation between the period 2001-2022 and the period 1951-2000. Statewide, precipitation was 4% lower in 2001-2022 compared to the 1951-2000 average (Table 2.3). These decreases have largely been concentrated in spring, summer, and autumn.

Statewide	Change from 1950-2000 to 2001-2022
Winter	+3%
Spring	-7%
Summer	-6%
Autumn	-5%
Annual	-4%

Table 2.3: Recent changes in statewide annual and seasonal precipitation, as calculated by the difference between the 1950-2000 average and the 2001-2022 average.

Dry conditions since 2000 have been particularly notable in western Colorado, with the Southwest division having precipitation decreases of 22%, 11%, and 12% in spring, summer, and fall, respectively (Fig. 2.11b, 2.11c, 2.11d). In contrast, winter precipitation increased over this period, but the increase was largely observed in lower-elevation regions of Colorado, where winter is typically the driest part of the year, thus the seasonal change had less impact on annual precipitation (Fig. 2.11a). The higher elevations saw relatively small changes in winter precipitation over this period.

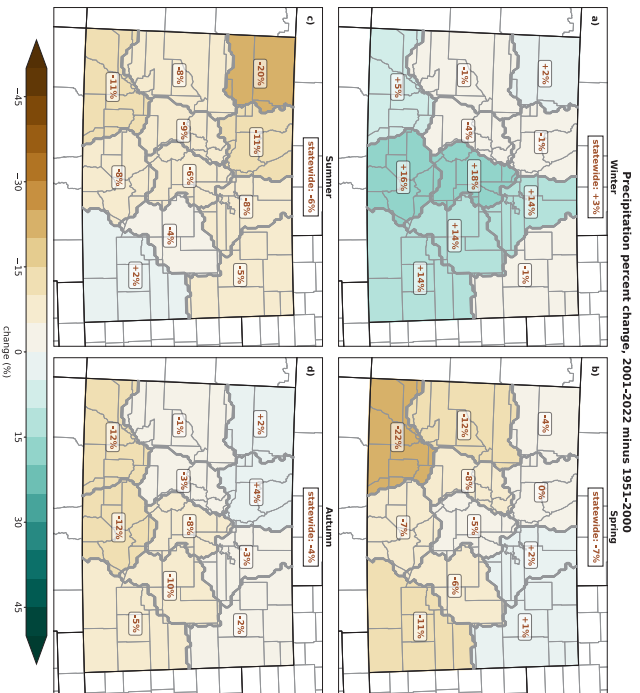


Figure 2.11: Percent change in precipitation between the periods 1951-2000 and 2001-2022, for (a) winter, December-January-February, (b) spring, March-April-May, (c) summer, June-July-August, and (d) fall, September-October-November (d).

Colorado’s precipitation variability is partially modulated by the El Niño-Southern Oscillation (ENSO). ENSO is an episodic interaction that occurs between the tropical Pacific Ocean and the atmosphere, which results in the occurrence of three different phases (recurring every 2 to 7 years): El Niño (warmer ocean temperatures in the tropical Pacific), La Niña (cooler ocean temperatures), and neutral (when there is neither an El Niño or La Niña). Variability in ENSO strongly influences global weather patterns. Coastal areas of the U.S. tend to have the strong correlations with ENSO variability. The general pattern

in the western U.S. is that wetter conditions are favored in the Southwest during an El Niño and wetter conditions are favored in the Northwest during a La Niña. With Colorado on the eastern edge of these areas (far from the ocean), and bisecting the two regions latitudinally, the state’s relationship with ENSO is more complex.

La Niña winters tend to be wetter for our northern and central mountains (Fig. 2.12, DJF panel). Aside from that signal, La Niña is generally associated with drier conditions around the state. El Niño favors wetter conditions along the Front Range and west slope in the spring, in northeast Colorado in the summer, and over large portions of the state in the fall (Fig. 2.12). While the relationship between Colorado precipitation and ENSO does exist, ENSO only accounts for a small percentage of precipitation variability. While ENSO forecasts can be used as a guide for more or less favorable precipitation patterns around the state, its year-to-year predictive potential is limited.

El Niño conditions occurred more frequently in the 1980s and 1990s, while La Niña conditions have been much more common since the turn of the century. Colorado’s climate connection with ENSO, and its relative frequencies over the last 40-50 years, may have partially contributed to the persistent dry conditions observed over most of the state since 1980.

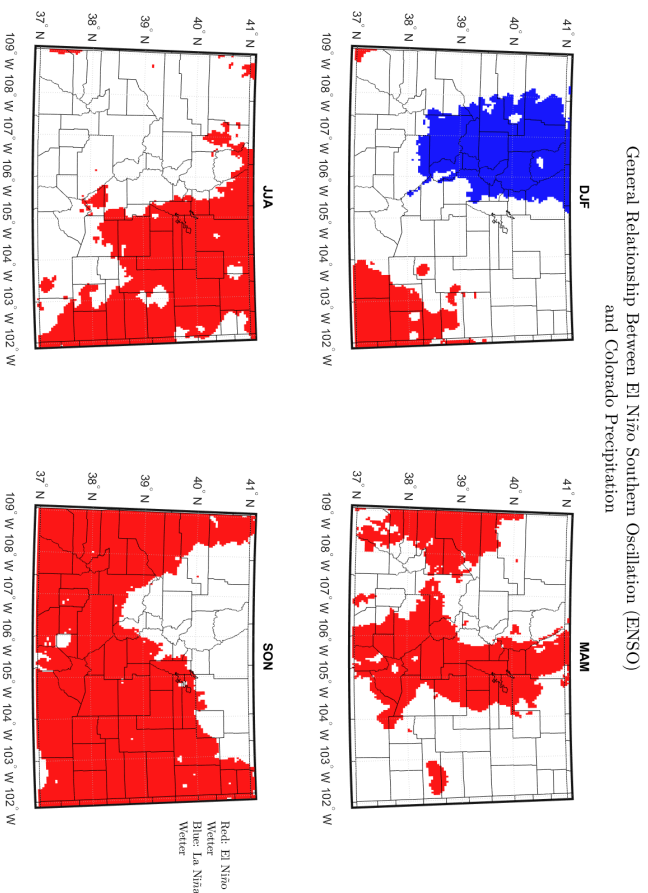


Figure 2.12: General relationship between El Niño Southern Oscillation and Colorado seasonal precipitation. Areas of correlation are shaded red when El Niño tends to be wetter and blue if La Niña tends to be wetter.

Future precipitation projections

The future direction of precipitation change in Colorado is much less certain than for temperature change. The climate models lack consensus about whether Colorado will on average see less, more, or about the same annual precipitation in the future, reflecting potentially offsetting physical mechanisms, as well as the greater complexity of the physical processes controlling precipitation compared to temperature. The climate models—CMIP3, CMIP5, and CMIP6—consistently project is the northernmost U.S. states and Canada will see overall higher annual precipitation in the future, and that the far Southwest and Mexico will see lower annual precipitation in the future. Colorado is in a transition zone between these regions of greater model consensus; this has opposing implications for the northern (more likely wetter) and southern (more likely drier) portions of Colorado, as will be explored in the next section, on downscaled projections of future precipitation.

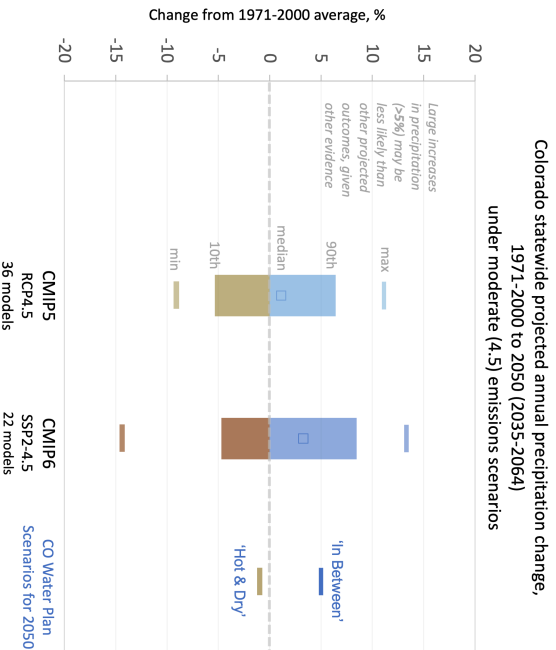


Figure 2.13. Projected future change in average annual precipitation for Colorado statewide for a 2050-centered period (2035-2064) relative to 1971-2000, from the CMIP5 and CMIP6 climate models under medium-low emissions scenarios. The solid blue and brown bars show the middle 80% of the model projections (10th-90th percentiles), the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: Observations: NOAA NCEI [cagl/](https://www.ncdc.noaa.gov/cagl/); CMIP5 data: GDO-DCH <https://gdo-dch.dcp.uh.edu/>; CMIP6 data: KNMI Climate Explorer <https://climate.knmi.nl/>; CO Water Plan Scenarios: CWCB (2019); <https://cwcb.colorado.gov/colorado-water-plan/technical-update-to-the-plan>)

Figure 2.13 illustrates the projected changes in statewide annual precipitation for Colorado from CMIP5 and CMIP6 models straddle the no-change line under a medium-low emissions scenario, with some projections showing wetter conditions for 2050 (2035-2064) and some showing drier conditions for 2050. The two blue bars on the right side of Figure 2.13 show that the climate change scenarios for precipitation in 2050 used in the Colorado Water Plan (CWCB 2015, CWCB 2023) are within the range

of both CMIP5 and CMIP6 under 4.5 emissions scenarios, although the “Hot & Dry” scenario is not as dry as many of the projected precipitation outcomes. Note that even the 90th percentile (+6%) and 10th percentile (-5%) changes shown by the models are much smaller than the observed year-to-year variability in statewide precipitation (+30% to -40%), although these changes are similar to the largest observed deviations in running 30-year averages in precipitation.

Most CMIP5 projections also show increases in year-to-year and decadal variability in annual precipitation for Colorado and the interior West over the next several decades (Lukas *et al.* 2014; Pendergrass *et al.* 2017). This suggests more frequent occurrences of both very dry and very wet years, and multi-year periods, than seen in the historical record. It also suggests more frequent oscillations from one extreme to the other, such as from 2018 to 2019.

With each model generation since CMIP3, there has been a slight shift towards wetter outcomes. However, the range of projected changes (i.e., model uncertainty) has not shrunk from CMIP5 to CMIP6. For a 2070-centered period, the CMIP5 models show the range of precipitation outcomes shifted slightly wetter than for 2050.

Figure 2.14 shows the seasonal precipitation changes projected by CMIP5 models under RCP4.5 for a 2050-centered period, using the same dataset shown in Figures 2.13. The slight overall model signal towards increased annual precipitation (far left) is strongly accentuated for winter (Dec-Feb) precipitation and to a lesser degree for spring (Mar-May) precipitation. Summer (Jun-Aug) precipitation shows the largest range and uncertainty across the models, with the greatest tendency towards large decreases among the seasons. The projections for fall (Sep-Nov) precipitation are very similar to annual, with a slight tendency towards increased precipitation. Seasonal precipitation projections from the CMIP6 models (not shown) are very similar to CMIP5.

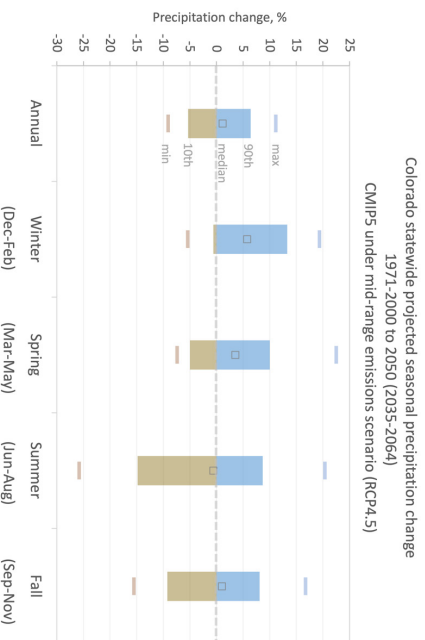


Figure 2.14. Projected future change in seasonal precipitation for Colorado statewide for a 2050-centered period (2035-2064) relative to 1971-2000, from CMIP5 (36 models/projections) under a medium-low emissions scenario (RCP4.5). The solid blue and brown bars show the middle 80% of the model projections (10th-90th percentiles), the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: CMIP5: GDO-DCH <https://gdo-dch.dcp.uh.edu/>)

The climate models disagree about the direction of change in future precipitation for Colorado in part because they disagree about how much the average storm track in the fall, winter, and spring over the western U.S. will shift northward. This northward shift has been observed already and is expected to continue, as a consequence of warming-induced expansion of the dry subtropical high-pressure zone that dominates the climate in the region south of Colorado (McAfee et al. 2011; Harvey et al. 2020). At the same time, individual storms that affect Colorado will tend to be wetter, as a warmer atmosphere holds more moisture (Seager et al. 2010); the implications of this relationship for extreme precipitation will be explored in Chapter 4.

A second key factor leading to model disagreement regarding precipitation change is how ENSO will change in a much warmer climate. Some CMIP5 and CMIP6 models show more frequent and intense El Niño events (on average associated with wetter conditions for Colorado), while others show more frequent and intense La Niña events (associated with drier conditions). None of the CMIP5 and CMIP6 model simulations capture the recent observed sea-surface temperature (SST) trends in the tropical Pacific, which show a systematic shift towards a more La Niña-like SST gradient from east to west. It is not clear if this shift is associated with anthropogenic influences on the climate system (Seager et al. 2019; Heede et al. 2020; Lee et al. 2022) or natural (internal) variability (Zhang et al. 2021). If this observed trend towards a more La Niña-like tropical Pacific is in fact anthropogenically forced, then drier precipitation outcomes for Colorado would be more likely to occur over the next several decades.

As described earlier in Chapter 2, observed annual precipitation for Colorado from 2000 through 2022 was about 4% lower than the second half of the 20th century (1951-2000). While several studies suggest that this recent period of reduced precipitation across the southwest U.S. is likely due to natural variability (Barnett et al. 2008; Hoerling et al. 2010; Lehner et al. 2018), other analyses suggest that there is a long-term anthropogenic trend towards lower precipitation in the southwest U.S., including Colorado—though this effect is small enough to be overwhelmed by natural variability on decadal timescales (Gao et al. 2011; Hoerling et al. 2019).

If any anthropogenic decrease in Colorado's average annual precipitation does occur over the rest of the 21st century, as a large minority of the projections indicate, that would substantially worsen the impacts of warming temperatures on future hydrology. Conversely, only a relatively large increase in statewide annual precipitation (>5%) would ameliorate the impacts of future warming. That outcome, while not off the table, cannot be counted on.

Again, note that the climate models simulate the natural (internal) variability in precipitation as well as the anthropogenic (forced) change signal. Each projection from one climate model simulates a unique sequence of variability (e.g., ENSO events), not synchronized with other models. Even when using a 30-year averaging period (e.g., 2035-2064) for calculation of future change, some long-term variability is picked up in the future “change” for a given model projection. This is consistent with how the real future climate will evolve: there will still be variability in precipitation (whose characteristics may change), which will potentially be superimposed on a forced trend in precipitation.

Downscaled (regional) projections of precipitation

For a closer look at how the projected future precipitation changes may vary in different regions of Colorado, we analyzed the CMIP5-LOCA downscaled climate projection dataset, as described under Temperature (section 2.2, above).

Figure 2.15 shows the projected change in annual precipitation, under RCP4.5, between the historical baseline (1971-2000) and the 2050-centered future period (2035-2064) for the 11 alternative Colorado climate divisions. In each division, the downscaled model projections do not agree on the direction of future precipitation change, with the range of projections extending from large increases to large decreases, as with the statewide projections (Figure 2.15). But in general, the ranges of projections for the northern divisions (Northwest, N. Mtns, N. Front Range, Northeast) are shifted towards wetter outcomes than for the southern divisions (Southwest, San Luis Valley, Southeast). Whatever the overall future change in annual precipitation for Colorado as a whole—more, less, or about the same—the southern divisions are likely to have a drier outcome than the rest of the state, especially the northern divisions.

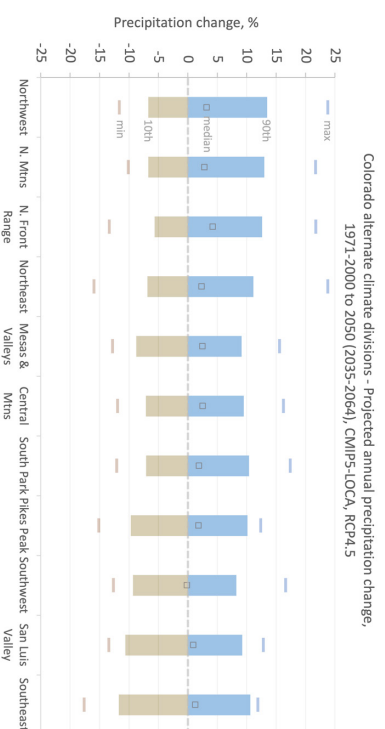


Figure 2.15: Projected future change in annual precipitation in 11 alternative Colorado climate divisions for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA climate projections under a medium-low emissions scenario (RCP4.5). The solid blue and brown bars show the middle 80% of the model projections (10th-90th percentiles); the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: GDO-DCP <https://ddc-dcp.ucdln.org/>)

Chapter 3

Changes in Colorado's Water

KEY MESSAGES

Climate variable/event	Recent trend	Projected future change	Confidence in change
Spring Snowpack	Lower	Lower	Medium 🟡
Runoff timing	Earlier	Earlier	High 🟢
Annual Streamflow	Lower	Lower	Medium 🟡
Summer soil moisture	Lower	Lower	High 🟢
Evaporative demand	Higher	Higher	Very High 🟢

Table 3.1 Summary of the observed and projected changes in hydrology and water resources for Colorado, as detailed in the following sections. "Confidence in change" reflects the judgment of the authors, based on both the assessments in higher-level climate reports (NCA, IPCC), as well as relevant literature and model output for Colorado. In general, there is higher confidence in the changes in variables that are driven mainly by warming and less by the more uncertain change in annual precipitation.

Snowpack

- April 1 SWE (snow water equivalent) during the 21st century has been 3% to 23% lower than the 1951-2000 average across Colorado's major river basins.
- Future warming will lead to further reductions in Colorado's spring snowpack. Most climate model projections of April 1 SWE in the states' major river basins show reductions of -5% to -30% for 2050 compared to 1971-2000; the individual projections that show increasing snowpack assume large increases in fall-winter-spring precipitation.
- The seasonal peak of the snowpack is projected to shift earlier by a few days to several weeks by 2050, depending on the amount of warming and the precipitation change. This warming-driven shift could be accelerated by increases in dust-on-snow events.

Streamflow

- Since 2000, annual streamflow in all of Colorado major river basins has been 3% to 19% lower than the 1951-2000 average.
- Modeling studies have attributed up to half of the observed decrease in streamflow since 1980 in Colorado river basins to warming temperatures.
- Future warming will act to reduce annual streamflows. Most climate model projections of annual streamflows in the states' major river basins for 2050 show reductions of 5% to 30% compared to 1971-2000.
- Higher future streamflow would require large overall increases in precipitation to offset the effects of warming, an outcome that appears unlikely.
- Summer and fall streamflows are projected to decline significantly by 2050 as the seasonal runoff peak shifts earlier, by 1-4 weeks, due to warming.

Soil moisture

- Modeled soil moisture based on meteorological observations suggests overall declines in high-elevation soil moisture from 1980-2022.
- Future warming will lead to declines in summer (June-August) soil moisture throughout the state. Spring (March-May) soil moisture will likely increase at higher elevations as snowmelt shifts earlier.
- Rapid depletion of soil moisture under warm conditions exacerbates warming. When summer sunshine hits a landscape with dry soil a greater fraction of solar energy directly heats the surface, leading to even warmer conditions.

Evapotranspiration

- The evaporative demand ("thirst") of the atmosphere—as measured by potential evapotranspiration (PET) and Reference ET—has increased across Colorado since 1980, mainly due to the warming trend. Statewide, growing-season PET increased by 5% from 1980-2022.
- Additional future warming will drive greater evaporative demand; all climate model projections show statewide annual PET increasing by 8-17% by 2050, compared to 1971-2000.

3.1 Overview

Colorado is known as a ‘headwaters’ state because four major river systems have most of their mountain headwaters within its borders: the Colorado River, the Rio Grande, the Arkansas River, and the Platte River. All of these major rivers, and all of their tributaries with headwaters above 8,000 feet, have a snowmelt-dominated hydrology: most of their annual streamflow (~60-80%) originates as meltwater from the seasonal snowpack (Li *et al.* 2017). Streams whose watersheds are entirely at lower elevations, whether on the eastern plains or in the western plateau region, have flows driven more by rainfall in the warmer months, with less contribution from snowfall and snowmelt.

Most of the water use in Colorado (83%) depends on surface water supply from streams and rivers, often stored in reservoirs (CWCB 2023). The remaining 17% of water supply comes from groundwater wells that tap either alluvial aquifers that are strongly connected to a river or stream, or deeper aquifers that are replenished over much longer time periods.

In this chapter, we describe recent trends and likely future changes in four related dimensions of Colorado’s water resources: snowpack, streamflow, soil moisture, and evapotranspiration. To summarize observed trends, we rely on both recent research studies and new analyses using observations from key datasets. For likely future changes, we rely on recent studies and new analyses using the ensemble of CMIP5-LOCA-VIC hydrologic projections (Vano *et al.* 2020). See Appendix A for more information about these hydrologic projections.

3.2 Snowpack

Overview

Colorado’s snowpack serves as a huge seasonal reservoir that stores about 1.5 million acre-feet of water on average at the spring peak and then makes that water available later in the year when water demands for agricultural uses and outdoor watering are higher. Precipitation that falls and is stored as snow is also more likely to end up as runoff than precipitation that falls as rain (Li *et al.* 2017). Colorado’s seasonal snowpack begins accumulating in late fall and typically peaks in April or May. Once rising spring temperatures warm all of the snowpack to 32°F (0°C), the sun’s energy can more effectively drive snowmelt. The snowmelt leads to an abrupt peak in streamflow, typically in May or June. On most streams and rivers in Colorado fed by mountain snowmelt, about 70-80% of the annual runoff comes in the four months from April to July.

Snow water equivalent (SWE) refers to the amount of liquid water that would result if the snowpack were melted down. SWE is a better measure for hydrologic monitoring than total snowfall or snow depth, since the latter measures don’t account for the highly variable density of snow. The amount of SWE around the seasonal peak (usually April 1 to May 15) is a very useful predictor of the spring and summer runoff. The peak SWE in Colorado’s mountains is typically 10” to 50”, depending on location, elevation, and year. Note that the snow and rain that falls after peak SWE (in April, May, and June) can dramatically shift the runoff outcomes in years with anomalous spring precipitation, such as 2020 (low) and 2015 (high). In Colorado, SWE is measured hourly at 114 automated SNOTEL (SNOWpack TELemetry) sites, and monthly at 81 snow courses, all maintained by the Natural Resources Conservation Service (NRCS) Colorado Snow Survey and its cooperators. Nearly all of these SNOTEL and snow course sites are between 8,500’ and 11,500’.

Similar to weather station data, snow data are subject to non-climatic influences (especially changes in vegetation over time, such as beetle-kill or wildfire) that affect snow deposition at the site (Lurlander and Brice 2006; Pugh and Small 2012; Kampf *et al.* 2022; Giovanco and Niemann 2022). Thus, monitoring and trend analysis based on multiple sites is more representative of basin-wide conditions compared to single site monitoring and analysis.

Observed snowpack changes

Several recent studies have documented widespread declining trends in April 1 SWE across the West over the past 40 to 70 years (Fyfe *et al.* 2017; Mote *et al.* 2018; Zeng *et al.* 2018; Siler *et al.* 2019; Musselman *et al.* 2021). These studies showed that SWE has decreased in most sites in Colorado’s major river basins, though the percentage declines in SWE in Colorado were generally smaller than in most other regions of the West due to Colorado’s relatively high elevations and colder winter climate. These studies also found that warming temperatures were an important cause of the observed SWE declines, while below-normal fall and spring precipitation in the past few decades has also played a role.

An analysis of Colorado’s snowpack updated from the 2014 report is consistent with these recent West-wide studies. Figure 3.1 shows basin-wide SWE from SNOTEL sites and snow courses starting in the 1940s to 1960s for eight of Colorado’s river basins. Note that the year-to-year variability, especially drought years, is highly correlated among the basins. The 21st century (2001-2022) average April 1 SWE for all eight basins is lower, by 3% to 23%, than the 1951-2000 average (Figure 3.1). The largest decreases occurred in the southwestern portion of the state, specifically in the San Juan and Rio Grande basins. Figure 3.1 shows that years with very large snowpacks (>140% of median)—important for refilling reservoirs—have been less frequent since the 1980s. Though as 2019 demonstrates, these big snowpacks can still occur.

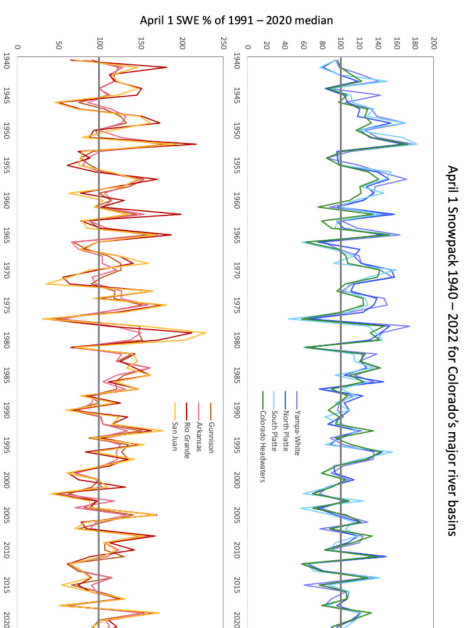


Figure 3.1: Observed April 1 snow water equivalent for northern basins (top) and southern basins (bottom) compared to 1991-2020 median.

Future snowpack projections

Many previous studies have used climate projections (Chapter 2) in combination with hydrologic models to simulate future changes in the hydrology of river basins in Colorado and elsewhere in the interior West. They show that April 1 SWE is likely to decline across Colorado's river basins due to the systemic impacts of warming temperatures, despite the projected increases in winter and spring precipitation (Battaglin et al. 2011; Lukas et al. 2014; Lute et al. 2015; Alder and Hostetler 2015; Lukas et al. 2020b; Reclamation 2021).

For this report, we analyzed the CMIIP5-LOCA-VIC hydrologic projections as noted in Section 3.1. Figure 3.2 shows the projected change in April 1 SWE, under RCP4.5, between the historical baseline (1971-2000) and the 2050-centered period (2035-2064) for the watersheds above key gages within seven major Colorado river basins. In all of the basins, most projections indicate decreased April 1 SWE in the 2050-centered period.

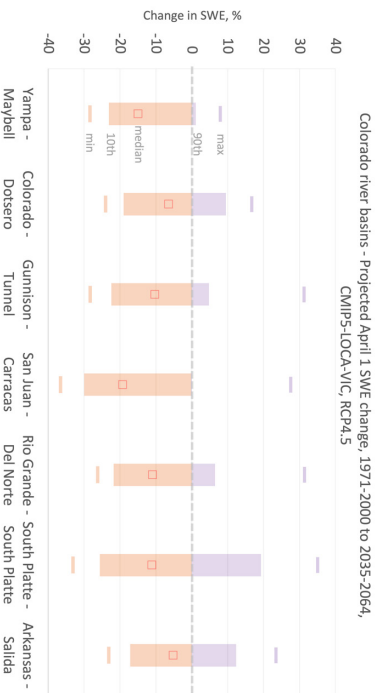


Figure 3.2: Projected future change in April 1st snow water equivalent (SWE) in watersheds above key gages in seven Colorado river basins for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIIP5-LOCA-VIC hydrology projections under a medium-low emissions scenario (RCP4.5). The solid purple and red bars show the middle 80% of the projections (10th-90th percentiles); the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: GDO-DCP, <https://gdo-dcp.ucllnl.org/>)

While April 1 SWE is a very commonly used indicator of snowpack and a good predictor of April-July streamflow, it is also a single snapshot in time. Figure 3.3 shows the projected monthly SWE, under RCP4.5, for the 2050-centered period (2035-2064) compared with the historical baseline (1971-2000) for the watershed above the Colorado at Dotsero gage. From November to April, most of the projections for 2050 show lower first-of-month SWE than the historical baseline, reflecting reductions in snow accumulation due mainly to warmer temperatures. For May 1, nearly all projections for 2050 show lower SWE than the historical baseline; the decreases in SWE are greater for April 1. This indicates that snowmelt is starting earlier in the future period. For June 1, all 32 projections show lower SWE than the historical baseline, including projections that showed increased SWE on April 1.

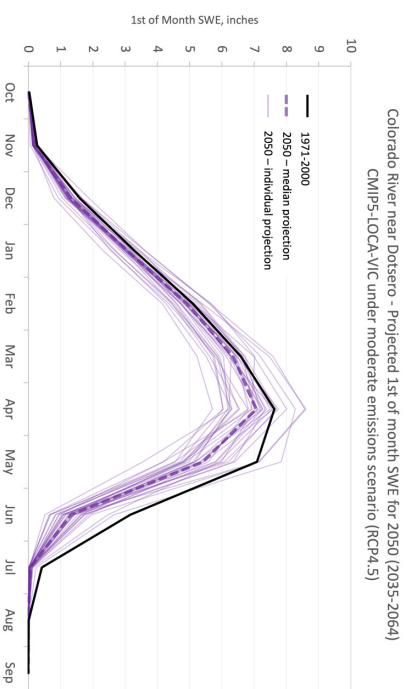


Figure 3.3: Projected future 1st-of-month snow water equivalent (SWE) for the basin above the Colorado River at Dotsero gage for a 2050-centered period (2035-2064) from an ensemble of 32 CMIIP5-LOCA-VIC hydrology projections (purple) under a medium-low emissions scenario (RCP4.5), and the simulated mean monthly SWE for the 1971-2000 period (black). The plotted monthly values are for the 1st of the month. (Data: GDO-DCP, <https://gdo-dcp.ucllnl.org/>)

Examination of the daily data underlying Figure 3.3 shows that the seasonal peak SWE during the 1971-2000 historical period occurred, on average, on April 9. For the 2050-centered period, 27 of the 32 projections indicate seasonal peak SWE occurring earlier than April 9, by as much as 38 days. The median projection suggests peak SWE will occur 11 days earlier, on March 29.

3.3 Streamflow

Overview

The high mountains of Colorado form the headwaters of major rivers and their tributaries that provide water supply for Colorado and over two dozen downstream states and Mexico, including the Colorado, Rio Grande, Arkansas, and North and South Platte rivers. Water from the Colorado River alone is relied upon by over 40 million people. Accurate forecasts of the volume and timing of streamflow are crucial on a daily- to-annual basis for reservoir managers, irrigators, municipal water providers, and flood-warming systems. Similarly, understanding historical variability in streamflow and any potential future changes in streamflow is critical to long-term water planning.

As discussed in the previous section, seasonal (e.g., April-July) and annual streamflows in most of the state's streams and rivers are driven by snowmelt, so the year-to-year variability in surface water supply in Colorado is strongly related to the variability in the snowpack (e.g., April 1 SWE). Accordingly, seasonal and annual streamflow can be skillfully (though not perfectly) predicted 1-5 months ahead of peak runoff, primarily using SWE and precipitation data. However, precipitation that falls before the start of the snowpack season and after the seasonal SWE peak contributes to runoff as well. The larg-

est source of uncertainty in streamflow forecasts made between January and May is how the subsequent weather will evolve (Goble and Schumacher 2023).

The large magnitude of interannual streamflow variability is an ongoing challenge for water managers. As seen in figure 3.4, water year streamflows in Colorado's river basins vary by up to six-fold from year to year—more than the relative variability in precipitation and snowpack. This is because the fraction of precipitation and snowpack lost to evapotranspiration (see later in this chapter) is greater than average in dry years and less than average in wet years, magnifying the difference in runoff outcomes between dry and wet years. For example, a basin snowpack that is 90% of normal will tend to produce streamflows that are only around 80% of normal (Vano et al. 2012).

Observed streamflow changes

Since 2000, the average annual naturalized streamflows in all of Colorado's major river basins have been lower than the 1951-2000 period (Figure 3.4). Naturalized streamflows are gaged streamflows that have been corrected for upstream diversions, depletions, and reservoir operations, making them more appropriate for monitoring long-term change. The largest relative reductions in flow have been seen in the Arkansas (-1.9%), South Platte (-1.8%), San Juan (-1.5%), and Gunnison (-1.3%), with smaller reductions in the Yampa (-3%), Colorado headwaters (-5%), and Rio Grande headwaters (-8%). A growing body of evidence indicates that the recent lower streamflows in Colorado have been driven not just by below-normal precipitation, but also by anthropogenic warming (Udall and Overpeck 2017; McCabe et al. 2017; Xiao et al. 2018; Hoerling et al. 2019; Albano et al. 2022; Milly and Dunne 2020). While most of these studies have focused on the Upper Colorado River Basin (i.e., Yampa, Colorado, Gunnison, San Juan) the general findings are applicable to Colorado's other river basins. The rough consensus that emerges from these studies is that 20-50% of the observed reduction in streamflows since 2000 has been due to higher temperatures. As discussed in Chapter 2, anthropogenic atmospheric changes may also have some role in the reduced precipitation since 2000, alongside natural variability.

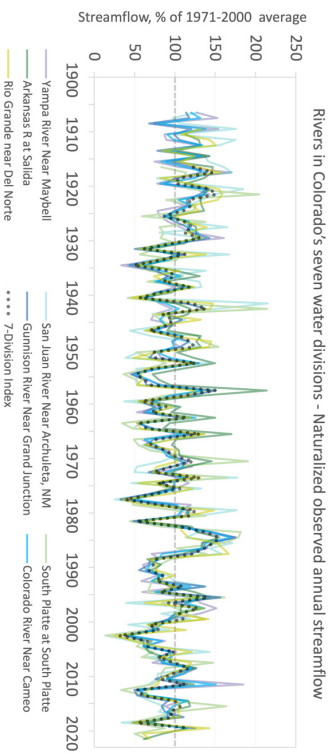


Figure 3.4. Observed naturalized annual (water-year) streamflows for key gages in seven river basins, one from each of Colorado's water division, from the early 1900s through 2019 or 2021, depending on the gage. The gage records have been corrected for upstream diversions and depletions to reflect the natural hydrology of the watershed (data sources: Yampa, Gunnison, San Juan, Colorado, Reclamation, South Platte; Denver Water, Rio Grande; COWR, Arkansas; J. Lukas based on Hydrosphere/Aurora Water)

Future streamflow projections

As Colorado's climate continues to warm over the next several decades (Chapter 2), the warmer temperatures will have increasing systemic impacts on the hydrologic cycle. Given the same amount of precipitation, annual runoff will be lower in a warmer climate—an effect that is already occurring as described above. It is uncertain how much Colorado's climate will warm (Chapter 2), and it is not precisely known how sensitive the streamflow in Colorado's river basins is to each increment of warming. However, the science is clear: further warming alone will push the water cycle towards reductions in streamflow and water supply.

Due to the pervasive impacts of warming, most of the plausible climate and hydrologic futures for Colorado's river basins show decreasing annual runoff. Increases in runoff will occur only if there is a large future increase in precipitation. This general finding has been seen across many studies, using different sets of climate models, different downscaling methods, and different hydrologic models (Nash and Gleick 1991; Christensen et al. 2004; Christensen and Lettenmaier 2007; Reclamation 2011; CWCB 2012; Woodbury et al. 2012; Lukas et al. 2014; Alder and Hostetler 2015; Harding 2015; Lukas et al. 2020b; Reclamation 2021). In studies that have projected future changes in streamflow for multiple basins across Colorado, besides the Colorado River and headwaters, the overall tendency towards lower future flows is not as strong in the northwestern basins (Yampa and White), while it is strongest in the southern basins (San Juan, Rio Grande) (CWCB 2012; Lukas et al. 2014; Harding 2015).

Figure 3.5 shows the projected annual streamflow change under RCP4.5 between the historical baseline (1971-2000) and the 2050-centered period (2035-2064) for gages within seven major Colorado river basins, based on the set of the hydrologic projections (CMIP5-LOCA-VIC) described above under future snowpack projections. In every basin, a large majority (65-80%) of the 32 projections indicate decreased streamflow in the 2050-centered period, even though most of the underlying climate model projections show at least slightly higher annual precipitation in the future period (Chapter 2). This difference between the precipitation outcomes and the streamflow outcomes reflects the impact of warming in reducing streamflow for a given amount of precipitation.

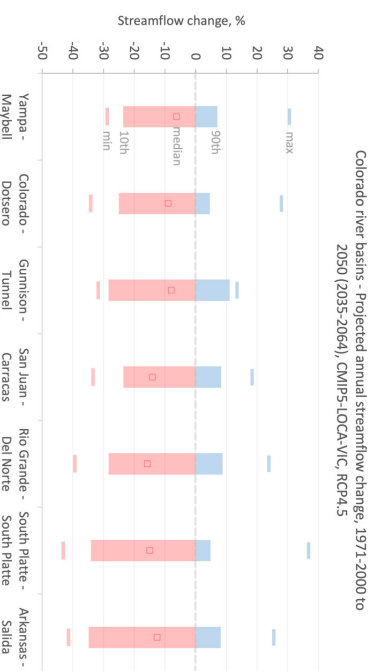


Figure 3.5. Projected future annual streamflow change for key gages in seven Colorado river basins for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA-VIC hydrologic projections under a medium-low emissions scenario (RCP4.5). The solid blue and red bars show the middle 90% of the projections (10th-90th percentiles); the two dashes show the minimum (red) and maximum (blue) projections; the open squares show the median projections. (Data: GDO-DCP; <https://gdo-dcp.uchlnl.org/>)

The relative impacts of warming and precipitation change on projected streamflow can be seen in Figure 3.6, which shows the 32 CMIP5-LOCA-VIC projections of streamflow change for the Colorado River near Dotsero as a function of that projection's temperature increase and precipitation change. From the underlying relationships between streamflow change, temperature change, and precipitation change using this chart, we can estimate that an ensemble-average warming ($\sim 4^{\circ}\text{F}$) for 2050, relative to 1971-2000, coupled with no precipitation change would result in a streamflow decline of $\sim 13\%$. Since about 1.5°F of warming has already occurred beyond the 1971-2000 average, this implies that a $\sim 5\%$ streamflow decline has already occurred with another $\sim 8\%$ decline taking place by 2050, under the 4°F overall warming scenario. These estimates are consistent with previous studies suggesting that each 1°F increment of warming results in a streamflow reduction of 3-5% in Colorado river basins (Woodbury et al. 2012; Vano and Lettenmaier 2014; Milly and Dunne 2020). The minority of the projected climate futures that show increased streamflow in the 2050 period (Figure 3.6; blue bubbles) are all predicated on an increase in annual precipitation of at least 5% enough to overcome the impacts of warming. Previous studies have found that a precipitation change of 1% results in a streamflow change of 2-3% (Vano and Lettenmaier 2014), consistent with what is seen here.

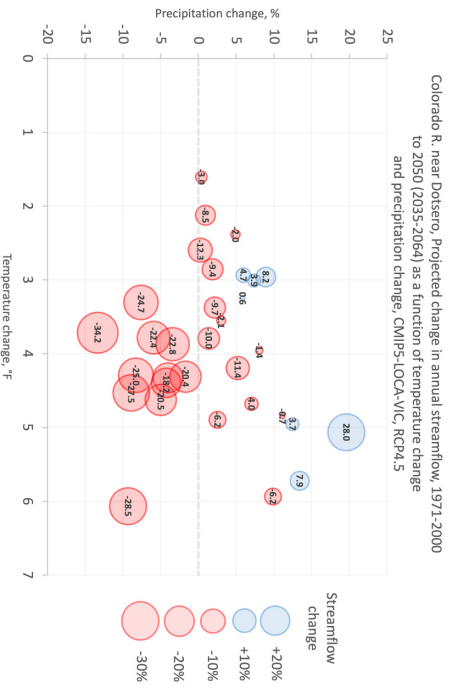


Figure 3.6: Projected change (%) in annual streamflow (values inside the circles) for the Colorado R. near Dotsero gage, as a function of the projected temperature increase (x-axis) and precipitation change (y-axis), for a 2050-centered period (2035-2064) relative to 1971-2000, from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections under a medium-low emissions scenario (RCp4.5). (Data: GDO-DCP <https://gdo-dcp.ucllnl.org/>)

The same analysis of CMIP5-LOCA-VIC projected streamflow, temperature, and precipitation for the South Platte River at South Platte (not shown) exhibits a similar pattern as for the Colorado River, though with greater sensitivity to warming. For the South Platte, an ensemble-average warming ($\sim 4^{\circ}\text{F}$) for 2050 relative to 1971-2000, coupled with no change in precipitation, is associated with a streamflow decline of $\sim 18\%$. If 1.5°F of that warming has already occurred, that implies a warming-driven streamflow reduction of $\sim 7\%$ to date, with $\sim 11\%$ yet to come by 2050 under the $+4^{\circ}\text{F}$ scenario. The magnitudes of

these estimates are consistent with previous studies that have examined climate change impacts for the South Platte (Woodbury et al. 2012; Harding 2015).

As noted earlier in section 2.2, most CMIP5 projections show increased interannual variability in future precipitation for Colorado, implying that streamflow variability would also increase. The projections for the Upper Colorado River Basin (Lees Ferry) as analyzed for Lukas et al. (2020), also from the CMIP5-LOCA-VIC dataset, show increases in the coefficient of variation (CV) of annual streamflows from the late 20th century (1950-1999) to the mid-21st century (2025-2074) in about 70% of the projections.

Future changes in the annual volume of streamflow due to warming will also be accompanied by changes in the timing of streamflow, consistent with the shifts in timing that have already been observed in the past few decades. For streamflow timing, projections based on climate models show near-annularity regarding the direction of change towards even earlier snowmelt, runoff, and peak streamflow.

Figure 3.7 shows the CMIP5-LOCA-VIC projections of monthly streamflow for the Colorado River near Dotsero for the 2050-centered period compared to the 1971-2000 baseline. There are systematic shifts in the streamflow for almost all months: For March, April, and May, monthly streamflow increases across the model projections as snowmelt and runoff is initiated earlier, and the hydrograph shifts from a sharp peak in June to a more of a 'plateau' across May and June, with a May peak in some cases. Flows in June decrease in most projections, and then as the declining limb of the hydrograph shifts and steepens, flows in July, August, and September decrease sharply in all projections. Late fall and winter baseflows (Oct-Feb) are also lower in nearly all projections.

Note that this modeled shift in the hydrograph does not consider the effects of dust-on-snow deposition (Chapter 4), which also acts to shift snowmelt and runoff earlier in the spring. Especially in the southwestern basins of Colorado, which have experienced greater dust-on-snow impacts, a future increasing trend in dust-on-snow events and dust deposition could have a larger effect on shifting the runoff timing than climate change alone and would compound the warming-related shift (Deems et al. 2013; Painter et al. 2018).

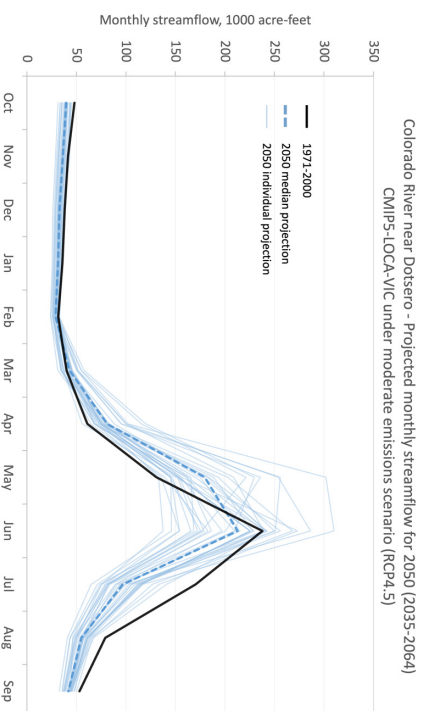


Figure 3.7: Projected future monthly streamflows for the Colorado River at Dotsero for a 2050-centered period (2035-2064) from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections (thin blue) under a medium-low emissions scenario (RCp4.5), and the simulated mean streamflow for the 1971-2000 period (black). (Data: GDO-DCP <https://gdo-dcp.ucllnl.org/>)

3.4 Soil Moisture

Overview

Soil moisture is an important component of Colorado's hydrologic cycle. Balanced soil water content is essential for the health of agricultural and natural ecosystems. Persistent low soil moisture levels will reduce agricultural yields, stress native vegetation, and reduce both the amount and predictability of Colorado's water supply (*Livneh and Badger 2020; Sazib et al. 2020; Goble et al. 2021*). Extreme wet soil moisture anomalies, which are much less common in Colorado, are associated with increased flooding and pest and disease issues (*Lavelle et al. 2010; Chuang et al. 2012*).

Soil moisture has an important feedback effect on weather. Part of the sun's incoming energy evaporates water from bare soil and leads plants to transpire water from their leaves while carrying out photosynthesis. When soil moisture is unavailable, this fraction of the sun's energy instead will directly heat the Earth's surface. Low soil moisture also limits atmospheric water vapor near the ground, an important ingredient for generating thunderstorms. Particularly during summer, dry soils will act to sustain hot, dry atmospheric conditions until a large-scale weather system breaks the pattern (*McKinnon et al. 2021*).

Much of Colorado is classified as a semi-arid climate, which means some soil moisture limitations are to be expected in a normal year. Surface soil moisture gets recharged only after rain events and then used by plants for transpiration. Plants with access to only shallow soil moisture (less than 36") must be able to survive for days-to-weeks during the growing season without water. Trees and deep-rooted plants can make use of deeper soil moisture supplied primarily from snowmelt.

In Colorado our understanding of soil moisture averages, seasonal variation, interannual variation, and trends at large spatial scales comes mainly from modeling. Land surface models (e.g. Noah, VIC), which use observed weather data as inputs, are often relied upon to enhance our understanding of Colorado soil moisture. The combination of the Snowpack Telemetry Network (SNOTEL) and Colorado Agricultural Meteorological Network (COAGMET) offer a limited (< 20 years) observational record at high (8000+ feet) and low elevations. Additionally, it is difficult to interpolate between observations because soil moisture is dependent on soil type, which can change over short distances.

Root-zone soil moisture in Colorado typically peaks in the spring both at high and low elevations. High-elevation soil moisture increases sharply as the snowpack melts. Lower elevation soil moisture, particularly on the eastern plains, remains low through the dry season in winter but increases in response to cool, soaking rains in the spring. During the summer season, soil moisture decreases overall due to evapotranspiration but spikes in response to convective rain events. Soil moisture is typically lowest at the end of the growing season (early fall).

Observed soil moisture changes

Soil moisture models typically do a poor job detecting long-term trends in soil moisture. *Fan et al. (2004)* showed that on a global scale, soil moisture models capture the seasonal cycle and spatial variability of soil moisture better than trends. Even so, *Andreadis and Lettenmaier (2006)* found significant decreases in soil moisture in southern Colorado from the mid-20th century to the early 21st century. *Tobin et al. (2020)* showed significant decreases in soil moisture for eastern Colorado in summer and fall.

Like precipitation, snowpack, and streamflow, soil moisture varies considerably from year to year based on weather patterns. Based on the Western Land Data Assimilation System (WLDAS) model analyses for elevations above 8000' in Colorado, soil moisture in the uppermost 2 m (80") has declined from 1980-2022 (Figure 3.8). Water year 2021 saw near record-low fall soil moisture conditions following a poor snowpack year and a hot and dry summer, including a record-warm August for western Colorado (*NOAA National Centers for Environmental Information 2023*).

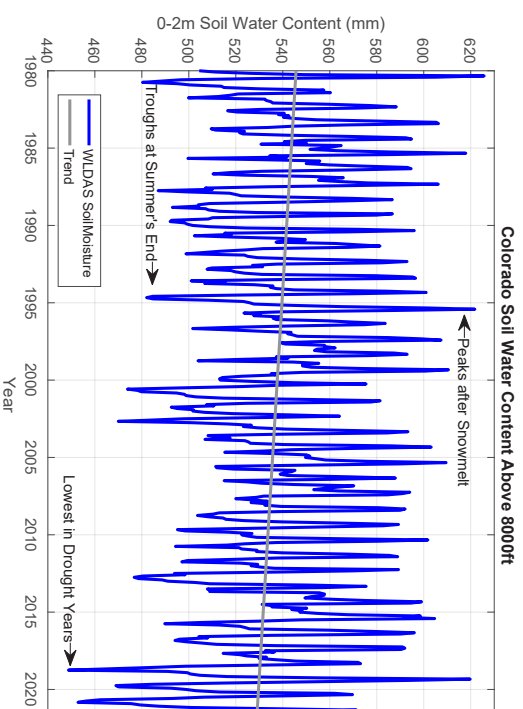


Figure 3.8: Colorado volumetric water content in top 2m soils above 8000ft, for 1980-2022. WLDAS model reanalysis soil moisture in blue, with trend line in gray.

Future soil moisture projections

As the climate continues to warm, the evaporative demand of the atmosphere increases (see section 3.5), which will tend to drive more moisture from soils through both direct evaporation and transpiration from plants, i.e., evapotranspiration. In high-elevation areas where most soil moisture derives from snowmelt, warming temperatures will act to reduce the snowpack through sublimation even before that snow water has a chance to enter the soils.

Previous studies projecting future (~mid-21st century) soil moisture for Colorado's key runoff-producing basins have consistently shown widespread declines in summer (June-August) soil moisture (typically, down to 2 m/80") regardless of the ensemble of climate models and hydrologic models used (*Ray et al. 2008; Reclamation 2012a; Ayers et al. 2016*). These analyses also showed increases in spring (March-May) soil moisture as snowmelt shifts earlier (see section 3.4) and leads to a saturated soil column earlier in the year relative to historical conditions.

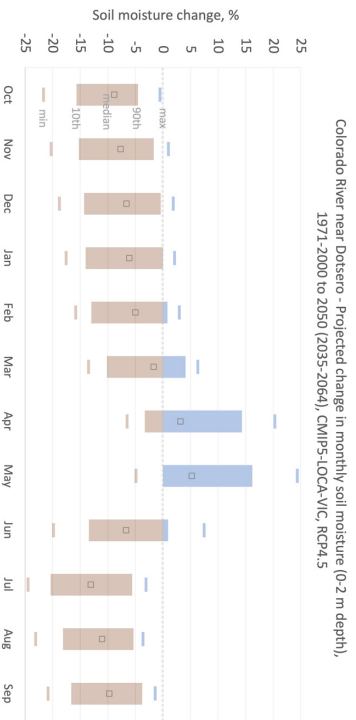


Figure 3.9: Projected future changes in monthly soil moisture (0–2 m depth) for the watershed above the Colorado River near Dotsero for a 2050-centered period (2035–2064) from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections under a medium-low emissions scenario (RCP4.5). The solid blue and brown bars show the middle 80% of the model projections (10th–90th percentiles); the two dashes show the minimum and maximum projections; the open squares show the median projections. (Data: GDD-DGP. <https://ddc-dcp.ucdavis.org/>)

Figure 3.9 shows the CMIP5-LOCA-VIC projections of change in monthly total soil moisture (0–2 m/0–79" depth) for the watershed above the Colorado River near Dotsero for the 2050-centered period, compared to the 1971–2000 baseline. The pattern in monthly and seasonal changes is consistent with the previous studies. Most of the individual projections show increases in spring (April–May) soil moisture, due to earlier snowmelt, but nearly all projections show decreases in the summer, fall, and winter months, driven by warming temperatures. Since soil moisture—along with the snowpack—acts as the interface between the atmosphere and streamflow, it is not surprising that these projected changes in soil moisture appear very similar to the projections of change in monthly streamflow (Fig 3.7 above).

3.5 Evapotranspiration

Overview

Evapotranspiration (ET) encompasses evaporation from soils and open water, transpiration from plants and crops, and sublimation from the snowpack. On a statewide basis, about 80% of the precipitation that falls on Colorado returns to the atmosphere through ET before reaching a stream or aquifer. The relatively cool and wet high mountain areas experience smaller Fractional ET losses, but typically amount to 30–50% of annual precipitation (Sanford and Selnick 2013).

ET technically refers to the actual loss of water from the land surface—thus, the alternative abbreviation AET (actual evapotranspiration) is used for clarity. The magnitude or rate of AET is constrained by the water that is available to evaporate or transpire (Figure 3.10). After soils and vegetation are fully dried out, no more AET can occur. So cumulative AET over an extended period (e.g., 12 months) will

not exceed cumulative precipitation—or in the case of irrigated cropland, precipitation plus the depth of irrigation water.

Evaporative demand (E_0) and its equivalent, Potential Evapotranspiration (PET), are measures of the atmosphere's "thirst" for surface moisture, and thus the potential loss of water from the land's surface. E_0 and PET can exceed and often do exceed AET over any given period. The conceptually similar Reference ET (ET_0) is an estimate of the upper bound of ET losses given a particular crop that is fully irrigated. Reference ET is the measure of evaporative demand that is usually reported by agricultural weather station networks such as COAGMET.

Evaporative demand increases with warmer temperatures, greater solar radiation, lower humidity, and higher winds. Of these, temperature is usually the most important in explaining the level of evaporative demand. PET, E_0 , and Reference ET are best estimated using a "fully physical" equation such as Penman-Monteith that inputs all four variables: temperature, solar radiation, humidity, and winds; methods using only temperature (Thornthwaite, Hargreaves, Blaney-Criddle) have larger errors in real-time monitoring (Sentelhas et al. 2010) and are also problematic for modeling future conditions (Reclamation 2012b).

The tight coupling between temperature and evaporative demand reflects a basic physical relationship, as well as an important feedback mechanism. First, warmer air can hold more moisture than cooler air, as governed by the Clausius-Clapeyron equation. This means that under warmer temperatures—if nothing else changes—evaporative demand increases. This general increase in evaporative demand (PET) with higher temperatures is clearly seen in the seasonal cycle shown in Figure 3.12. Second, when the soils and vegetation dry out seasonally or periodically (i.e., drought)—which often involves increased evaporative demand—a feedback mechanism occurs: More of the sun's energy heats the surface and the atmosphere above it, rather than going towards evaporating moisture. This drives faster warming and lower humidity of the air, thus increasing evaporative demand more rapidly (Figure 3.10, right panel).



Figure 3.10: Schematic showing how under high soil moisture and water availability, Actual Evapotranspiration (AET) can have the same magnitude as evaporative demand. With time, if the soils dry out, evaporative demand will often increase (as air temperature rises and humidity decreases in response to the now-dry land surface) but AET decreases, limited by the lower amount of water available at the surface to evaporate and transpire. (Modified from Lukas et al. 2017, The EDDI User Guide).

AET is much more challenging to measure than evaporative demand. AET can be estimated using a land-surface (hydrology) model with meteorological inputs, or by assimilating satellite observations of land-surface temperature (which reflects evaporation losses) into an energy-balance model. In-situ measurements of AET can be made using Eddy Covariance (EC) methods, in which several instruments at different heights on a tower measure the vertical transfer of energy and moisture between the surface and the atmosphere.

Observed evapotranspiration changes

Since rising temperatures, all else equal, will lead to higher evaporative demand (E_0 , PET, Reference ET), it is reasonable to expect that trends in evaporative demand would reflect the strong warming trend in Colorado over the last several decades. And in fact, upward trends in evaporative demand for Colorado have been found in several studies, using different observational datasets (Ficklin et al. 2015; McCabe and Wolock 2015; Vicente-Serrano et al. 2020; Albano et al. 2022).

Most recently, a comparison of recent U.S. trends in Reference ET (1980-2020), using five gridded observational datasets, found that the average of the datasets show increasing Reference ET trends across all of Colorado, with the largest increases seen in southeastern Colorado, moderate increases in the northeastern and far southwestern parts of the state, and the smallest increases in the northwest part of the state (Albano et al. 2022). Examination of the four meteorological components of evaporative demand shows that decreased humidity and increases in solar radiation only contributed a small amount to the observed increase in evaporative demand.

Figure 3.11 shows Colorado statewide PET for the growing season (April-September) since 1980, from the gridMET gridded observational dataset, one of the five used in the Albano et al. (2022) study, and whose results are closest to the average across all five datasets. While there is large variability from year to year, the upward trend is clear: statewide PET has increased about 5% over the 1980-2022 period.

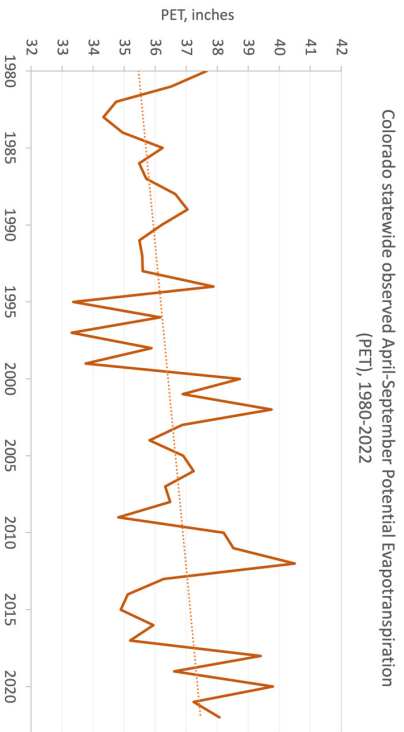


Figure 3.11: Observed Colorado statewide Potential Evapotranspiration (PET) over the April-September growing season, 1980-2022. Dashed line shows the linear trend over that period. (Data: gridMET via Climate Toolbox, <https://climatologytoolbox.org/tool/historical-climate-tracker/>)

Future evapotranspiration projections

Given the continued and substantial warming projected for Colorado over the next several decades, further increases in evaporative demand in Colorado are extremely likely. Figure 3.12 shows the projected changes monthly PET under RCP4.5 between the historical baseline (1971-2000) and the 2050-centered period (2035-2064) for the watershed of the Colorado River above Dotsero, using the same projection dataset (CMIP5-LOCA-VIC) in the preceding sections.

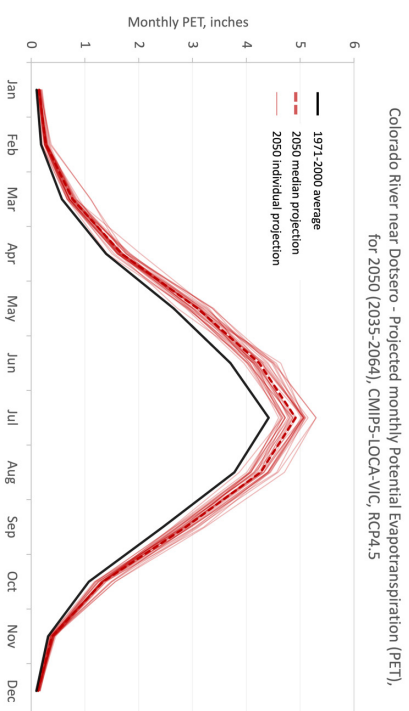


Figure 3.12: Projected future monthly Potential Evapotranspiration (PET) for the watershed above the Colorado River at Dotsero for a 2050-centered period (2035-2064) from an ensemble of 32 CMIP5-LOCA-VIC hydrology projections (thin red) and the median (thick red dashed) under a medium/low emissions scenario (RCP4.5), and the simulated mean streamflow for the 1971-2000 period (black). (Data: GPO-DCP <https://gdo-dcp.udel.edu/>)

Note the extreme seasonality in PET; about 90% of annual PET occurs from April through September. In each month of the year, all 32 projections show increased PET; total April-September PET increases 10% to 20% by 2050 compared to the 1971-2000 baseline. Comparing the PET change with the temperature change in the same 32 model runs, it is clear that temperature is the primary driver of increased PET. Each 1°F of warming leads to about a 4% increase in PET, with a 4°F warming associated with a 15% increase in PET. A similar downscaled projection dataset (CMIP5-MAACA), also paired with the VIC hydrologic model, suggests that increases in PET of roughly similar magnitude (~4%) for each 1°F of warming will occur across all elevations both east and west of the Continental Divide.

Chapter 4 | Climate Extremes and Hazards

KEY MESSAGES

Climate variable/event	Recent trend	Projected future change	Confidence in change
Heat waves	More frequent/intense	More frequent/intense	Very High ●
Cold waves	Fewer	Fewer	Medium ○
Droughts	More frequent/intense	More frequent/intense	High ●
Wildfires	More and larger	More and larger	High ●
Extreme precipitation	More intense	More frequent/intense	Medium ○
Flooding	Mixed	Higher	Medium ○
Windstorms	Uncertain	Uncertain	Low ●
Severe thunderstorms	Uncertain	More frequent	Low ●
Hail	Uncertain	More large hail	Low ●
Tornadoes	Uncertain	Uncertain	Low ●
Winter storms	Uncertain	Larger storms	Low ●
Dust on snow events	Greater dust levels	Greater dust levels	Medium ○

Table 4.1. Summary of the observed and projected changes in climate extremes and hazards for Colorado, as detailed in the following sections.

Heat waves and cold waves

- Hot days and heat waves have become more common, and the number cold nights and cold waves has decreased across Colorado in recent decades, but the changes have not been equal. There have been significant increases in extreme heat across most of the state, whereas the decrease in extreme cold has been more modest.
- Projected future changes are similarly asymmetric: Heat waves are projected to increase in frequency by as much as ten-fold by the middle of the 21st century, whereas the frequency of cold waves is projected to decrease by less than half.

Drought

- Warming temperatures have increased the severity of 21st century droughts in Colorado.
- Regardless of changes in precipitation, it is likely that warmer temperatures will contribute to more frequent and severe droughts. Warmer temperatures will also decrease the benefit of wetter years.
- Intense droughts have occurred multiple times in the 21st century, including in 2002, 2012, 2018, and 2020.

Wildfire

- Since 2000, Colorado has experienced a large increase in the number of large wildfires and in the annual area burned by all wildfires; on average, fires have burned at higher elevations and with higher intensity than in the late 20th century. While several factors have contributed to these trends, rising temperatures are a major driver.
- Future warming is expected to lead to further increases in the occurrence of large wildfires and in annual area burned by all fires, especially in forest ecosystems, according to multiple studies. A greater percentage of fires will occur in the fall, winter, and spring than at present.

KEY MESSAGES CONTINUED:

Heavy and extreme rainfall, Floods, Thunderstorm hazards, Non-convective windstorms, Winter storms, Dust-on-snow



Climate Extremes and Hazards | Chapter 4

KEY MESSAGES

Heavy and extreme rainfall

- There are some indications of recent increasing trends in heavy and extreme rainfall in Colorado, but these are not consistent across all indicators and time periods, unlike in other regions of the U.S.
- Atmospheric moisture has generally increased over Colorado, but not by as much as one would predict from the warming atmosphere alone.
- Future warming, by increasing the moisture-holding capacity of the atmosphere, will make heavy and extreme rainfall more likely unless counterbalanced by declining trends in other storm “ingredients”. Climate-model projections for Colorado show overall increases in the magnitudes of heavy and extreme rainfall events.

Floods

- Gaged streamflow records show no widespread, consistent trends in the magnitude of flood events in Colorado of different frequencies (e.g., 1-year, 20-year, 50-year, 100-year).
- The expectation that heavy and extreme rainfall events will increase in Colorado implies increases in future flood risk as well, but there are many factors influencing how rainfall is translated into runoff. Increased exposure to flooding through floodplain development may be more important than climate-driven changes in risk.

Thunderstorm hazards

- Because of the relatively short data record for thunderstorm hazards and the influences of changing observation systems, the sign and magnitude of any long-term changes is unclear.
- Some studies have suggested increases in the average size of hail in a warmer climate, with smaller hail becoming less frequent but larger hail more frequent. Overall, however, there remain large uncertainties regarding future changes, as data limitations and the infrequent and localized nature of these storms makes them challenging to study in the context of a changing climate.

Non-convective windstorms

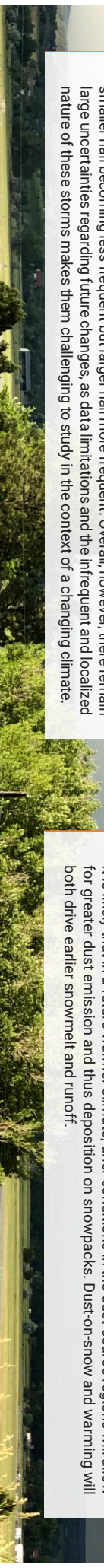
- Colorado is prone to intense winds in the mountains and from downslope windstorms along the Front Range. These windstorms can cause considerable damage, and can exacerbate wildfires, such as in the 2021 Marshall Fire. Long-term changes in extreme winds have not been extensively studied, and potential future changes are highly uncertain.

Winter storms

- Despite warming temperatures in the winter, there are no detectable trends in winter severity across the Colorado Front Range and Eastern Plains. There are also minimal trends in large snowfall events.
- Several notable and high impact winter storm events have occurred over eastern Colorado in the last decade, including extreme cold, high winds, strong cold fronts, and large accumulations of snow.
- Future trends in winter storms remain highly uncertain, but the risk of high-impact winter events is likely to remain.

Dust-on-snow

- Dust-on-snow events have emerged as a concern since 2000 due to better understanding of its hydrologic effects, as well as an overall increase in the occurrence of dust-on-snow. Dust-on-snow causes earlier melt and runoff and may reduce annual runoff.
- It is likely that in a future warmer climate, drier conditions in the dust-source regions will allow for greater dust emission and thus deposition on snowpacks. Dust-on-snow and warming will both drive earlier snowmelt and runoff.



4.1 Overview

This chapter assesses recent trends and likely future changes in climate extremes and climate-driven hazards in Colorado. While it is true that anthropogenic climate change is increasing the overall risk of impacts across the various extreme weather and climate events and natural hazards, both globally and in Colorado, this generalization does not necessarily apply to each type of extreme or hazard. Each type has different climatic drivers, and there may also be non-climatic factors that act to increase (or decrease) their risk and impacts, such as with floods and wildfires.

In general, extremes and natural hazards that have strong physical linkages to warming temperatures are the ones most likely to have already increased and to increase further in the future. At the top of this list are heat waves; droughts and wildfires are also worsened in a warmer climate. All three have shown clear recent upward trends in Colorado. Extreme precipitation also has a direct physical linkage with temperature and is expected to become more frequent and severe with warming, yet this has not been clearly seen in our region. Severe thunderstorms and their related hazards—tornadoes, hail, and winds—have more complex linkages with warming. Due to observational challenges, it is difficult to assess recent trends and future projections for thunderstorm hazards.

In the sections below, for each type of climate extreme or hazard, we describe its drivers, examine recent variability and trends to the extent that observed datasets can support that assessment, highlight recent high-impact events, and then summarize the likelihood of future changes and the evidence for that assessment. This chapter emphasizes the observed and potential future changes of these extremes and hazards, with limited references to the impacts from these events. The update to the Colorado Vulnerability Study will provide greater detail on Colorado's vulnerabilities, documented impacts, and risk of future impacts to these types of events.

4.2 Heat Waves and Cold Waves

Overview

As the climate warms, periods of extreme heat are expected to become more frequent, while periods of extreme cold become less frequent (USGCRP 2017). Two different approaches can be employed to investigate changes in temperature extremes. One is to consider the exceedance of absolute temperature thresholds (e.g., exceeding 95°F or dropping below 0°F). The advantage of this method is that these thresholds are familiar to people, and they generally correspond to some kind of impact (e.g., heat stress to humans and animals increases at higher temperatures). The disadvantage is that, in a state as diverse as Colorado, some areas surpass these thresholds many times per year, whereas other areas may never experience those temperatures. Another method is to consider temperatures that are rare for that location (e.g., a temperature that occurs on average only once per year, or that exceeds a percentile, etc.). Furthermore, when considering heat waves and cold waves, many different definitions have been proposed in the literature (e.g., Perkins and Alexander 2013). Regardless of the specific methods used, available data show that heat waves are generally becoming more frequent, and cold waves less frequent, in Colorado. However, the details of the results vary, as shown below.

Observed heat and cold wave changes

Changes in exceedance of high and low absolute temperature thresholds

Comparing the most recent two decades (2001-2020) to the 1971-2000 period shows that in eastern Colorado and the valleys in western Colorado, the number of hot days (95°F or higher) has increased. Some areas experienced over 10 more hot days per year during the period from 2001-2020 than during the period from 1971-2000 (Fig. 4.1a). Other thresholds such as 90°F show similar spatial patterns, although many areas in Colorado, especially at high elevations, rarely or never reach 90°F.

Very cold nights are becoming less frequent across Colorado but generally at a slower pace than hot days are increasing. Fig. 4.1b shows that the San Luis Valley has experienced the greatest reduction in sub-zero temperatures, by a few days per year. Most other parts of the state have relatively small reductions of 1-2 nights per year, whereas a few pockets in Gunnison, Fremont, and Rio Blanco Counties have seen small increases in the frequency of sub-zero temperatures. In some areas of southeastern Colorado, temperatures below zero are very rare.

Calculations at individual stations (not shown) are generally consistent with the findings from the gridded dataset used in Fig. 4.1. However, this gridded dataset only has daily data available back to 1951, and long-term stations in southeastern Colorado show that the dust bowl era in the 1930s had more frequent occurrence of extreme heat than even the first two decades of the 2000s. Nonetheless, recent trends in this part of the state are toward more frequent hot days.

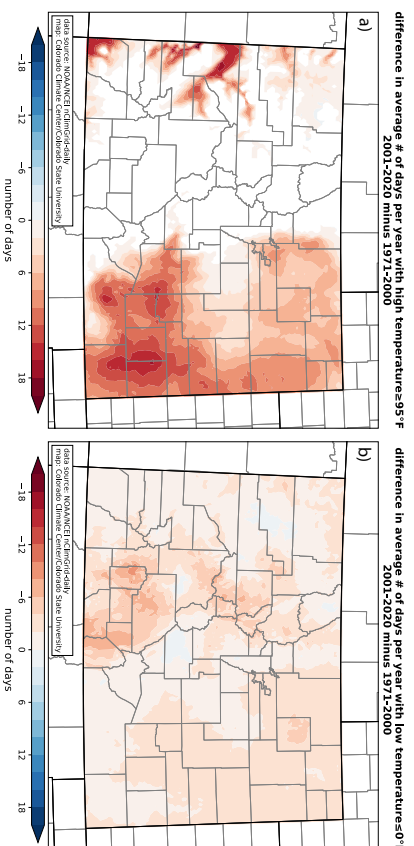


Figure 4.1: Differences in the number of days per year with (a) daily maximum temperature $\geq 95^{\circ}\text{F}$ and (b) daily minimum temperature $\leq 0^{\circ}\text{F}$, comparing the period 2001-2020 to 1971-2000.

Changes in occurrence of heat waves and cold waves

In contrast to the absolute temperature thresholds presented above, heat waves and cold waves are generally defined relative to the historical temperature ranges for an area. Some studies consider heat/cold waves as consecutive days exceeding a threshold (Perkins and Alexander 2013; Keellings and Moradkhani 2020; Domeisen et al. 2023), whereas others consider the average temperature over a period of days (Peterson et al. 2013). Here, we will use a definition for heat and cold waves that is similar to Peterson et al. (2013). Specifically, a heat wave or cold wave is defined using a 4-day averaged daily mean temperature (daily mean is the average of the high and low for the day). The 4-day average temperature that was exceeded on average once per year during 1971-2000 was defined as a heat or cold wave (in other words, the average hottest or coldest 4-day period per year during 1971-2000). This calculation is done for each alternate climate division, and then the number of heat/cold waves in each year and decade over the full dataset (1951-2022) were calculated. Other definitions of heat/cold waves, including different lengths and requiring consecutive days exceeding a threshold, showed qualitatively similar results. The benefits of this calculation are 1) it includes both maximum and minimum temperature in the analysis, 2) the four-day average indicates a sustained period of hot or cold (thus a “wave”), and 3) the extreme threshold is uniquely defined for each climate division.

Heat waves have increased in frequency from the 1950s to present in all climate divisions (Fig. 4.2), though the upward trend is statistically significant in only 8 of the 11 divisions. In particular, the decades of the 2000s and 2010s had substantially more heat waves than the preceding decades in nearly all divisions. The increases are especially large in the Northwest and Mesas & Valleys divisions, where very few heat waves occurred in the 1950s and 60s, and then 2-3 per year occurred on average in the 2000s and 2010s. The increase in heat waves has been less prominent in the Northeast and Southeast divisions (Fig. 4.2), despite the total number of hot days increasing (Fig. 4.1a).

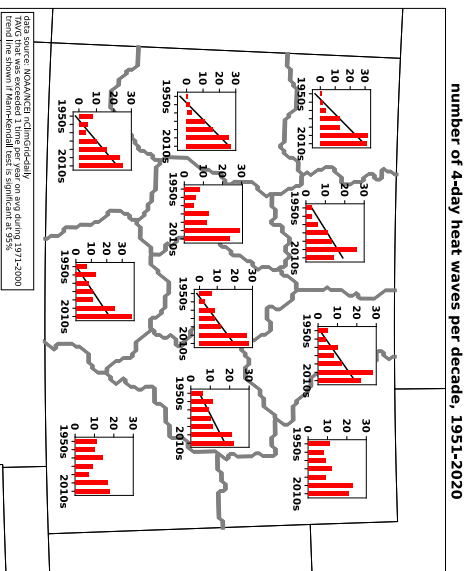


Figure 4.2: Time series of the number of 4-day heat waves per decade from 1951-2020 for each climate division. (See Fig. 2.2 for the names of the divisions.) Heat waves are defined as a 4-day period in which the daily mean temperature (the sum of the daily maximum and minimum temperatures divided by two), averaged over the four days, exceeds the 4-day average temperature that was exceeded on average once per year during 1971-2000.

Data for 2021-22 (not included in the decadal analysis above) revealed a large number of heat waves in all parts of the state; in some divisions, there were more heat waves in the first two years of the 2020s than in some entire decades in the 20th century.

Cold waves have generally declined in frequency across Colorado from 1951-2020, but the decline is much less pronounced than the increase in heat waves (Fig. 4.3). The decrease in 4-day cold waves was not found to be statistically significant in any of the climate divisions. In most divisions, the 1970s and 80s had a large number of cold waves; then, they declined in the 1990s and 2000s before increasing slightly in the 2010s.

number of 4-day cold waves per decade, 1951-2020

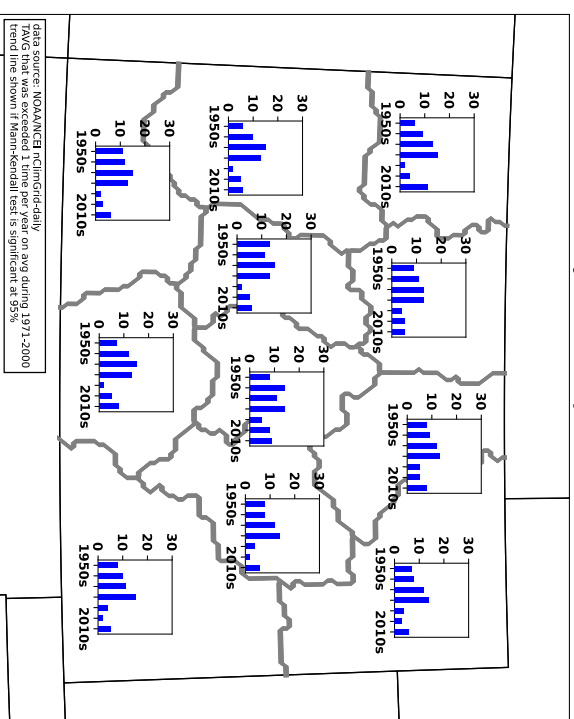


Figure 4.3: As in Fig. 4.2, but for 4-day cold waves.

Future heat and cold wave projections

Research has consistently indicated that heat waves are likely to increase in frequency and intensity in a warmer climate (Domeisen et al. 2023). In one study relevant to Colorado, Cowan et al. (2020) examined what would happen if the anomalous conditions associated with the Dust Bowl-era heat waves occurred in the present-day climate. They found that those 1930s heat waves that had a probability of around 1 in 100 years, would have a probability closer to 1 in 40 years today (and a higher probability in an even warmer climate). They also illuminate the impact of dry springs, noting that summer heat waves are generally more frequent and intense following a dry spring as compared to a wet spring.

The 32 CMIP5-LOCA model projections for medium-low emissions scenario RCP4.5 (described in Chapter 2.2) were analyzed using the same definitions of heat waves and cold waves that were used for observed conditions. Specifically, the 4-day average temperature (hot or cold) that was exceeded on average once per year during 1971-2000 was identified in each individual model run, and then occurrences of those temperatures in daily CMIP5-LOCA output from 1951-2090 were tabulated.

Heat waves are projected to increase at a rapid pace in all parts of Colorado as the climate warms. In most regions, the median number of projected heat waves is expected to increase from 1 per year during 1971-2000 (by definition; not shown), to approximately 10 per year by the 2060s (Fig. 4.4). Some projections show a smaller increase in the number of heat waves, others a much larger one. All model projections show a statistically significant increase in heat waves from the 1950s to the 2080s in all regions; at least 90% of the model projections show a significant increase in heat waves from the 2000s to the 2080s in all regions except the Southeast (where there is 87.5% agreement among models for a significant increase). To put these results in other terms: what would have been the hottest 4-day period of each year during 1971-2000 is projected to occur approximately 10 times—spanning 40 days per year—by the 2060s.

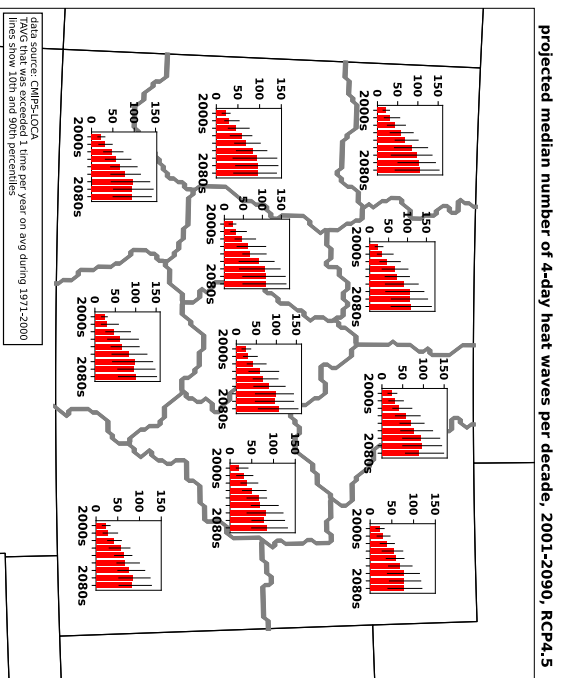


Figure 4.4. Time series of the number of 4-day heat waves per decade from 2001-2090 in CMIP5-LOCA projections for each climate division. (See Fig. 2.2 for the names of the divisions.) The red bars indicate the median projection for each decade, and the lines indicate the 10th and 90th percentile of the 32 projections. Heat waves are defined as a 4-day period in which the daily mean temperature (the sum of the daily maximum and minimum temperatures divided by two), averaged over the four days, exceeds the 4-day average temperature that was modeled on average once per year during 1971-2000 in each individual model projection.

Although extreme cold is also generally expected to decrease in frequency as the climate warms (e.g., *USGCRP 2017*), in Colorado, both observations (Fig. 4.3) and future projections (Fig. 4.5) indicate that cold waves will not decrease nearly as much as heat waves increase. Whereas model projections indicate that heat waves will increase in frequency by as much as ten-fold, similarly defined cold waves are projected to decrease in frequency by half, or even less, depending on the region (Fig. 4.5). There is also much less agreement on the robustness of the trend: fewer than half of CMIP5-LOCA projections show a statistically significant decrease in 4-day cold waves across the 21st century. In most regions, the frequency of cold waves decreases from roughly once per year in the early 21st century, to roughly once per two years by late century.

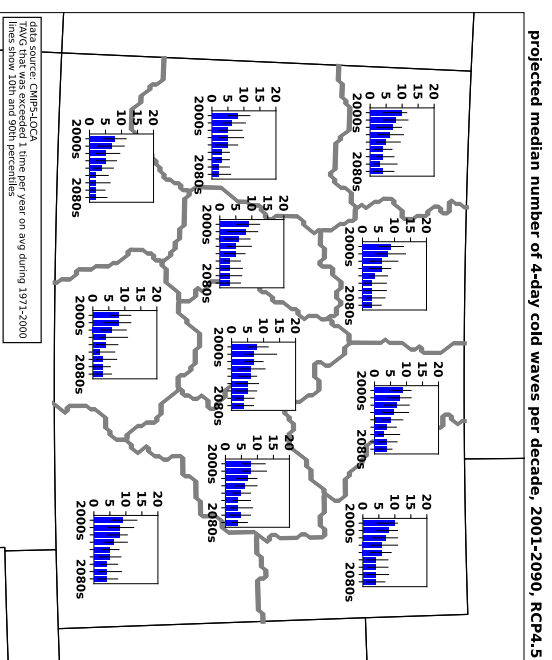


Figure 4.5: As in Fig. 4.4, but for cold waves.

The strong asymmetry in the projections of heat waves and cold waves in a warmer climate is likely to have impacts on the agricultural sector in Colorado. As one example, western Colorado has had several instances in the early 21st century of extremely hot summers punctuated by strong cold waves in the fall and spring that have led to the loss of fruit crops (*NOAA 2020a*). Challenges such as these may become more acute in the future, as periods of extreme heat become much more frequent, but the risk of extreme cold remains.

4.3 Drought

Overview

Most simply defined, drought is insufficient water to meet demands. Drought is most commonly assessed as a deficit of precipitation, snowpack, soil moisture, and/or streamflow across timescales from months to years. Temperature has played a critical role in increasing the severity of recent droughts in Colorado and the Southwest U.S.

Conventional monitoring of droughts has focused on defining extreme deficits in each of the water variables. Historically, the Palmer Drought Severity Index was widely used and included both temperature and precipitation. However, it was insufficient for certain regions of the country and fixed on one time scale (correlating well with 9-month analyses). For precipitation, the Standardized Precipitation Index (SPI) introduced methods to assess the severity of drought on varying timescales (McKee et al. 1993). Because of its versatility to work well both spatially and temporally, it became a primary tool for monitoring drought, but it did not consider the temperature aspect of drought.

Warmer temperatures during drought result in higher evaporative demand. Evaporative demand describes the atmosphere's "thirst" for moisture (see Chapter 3.5). Drought severity can be exacerbated by high evaporative demand; in conjunction with moisture deficits, the atmosphere is trying to take more water away from the surface (through evaporation and transpiration). To better capture this phenomenon, new indicators and indices have been introduced into regular drought monitoring, including the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010), the Evaporative Demand Drought Index (EDDI) (McEvoy et al. 2016), and vapor pressure deficit (VPD) (Lomman et al. 2023).

Observed drought changes

The Standardized Precipitation Evapotranspiration Index has expanded the utility of the SPI by adding a temperature component to the index. The distinction between SPI and SPEI over longer time periods illustrates the differences between precipitation-driven droughts that occurred historically and the droughts driven by the combination of low precipitation and warmer temperatures since 2000.

Looking at a time series of 24-month SPI since 1895 (Fig. 4.6), there are 8 significant dry periods, including the drought at the turn of the 20th century, the Dust Bowl in the 1930s, major droughts in the 1950s, 1960s, and 1970s, and three periods since 2000. The SPEI time series suggests nearly continuous drought since 2000 (Fig. 4.7). This illustrates that because of higher temperatures, not only are times of drought more severe, there may be less benefit and recovery during wetter times. This phenomenon, increasingly prevalent in the 21st century, has been termed "hot drought" (Udall and Overpeck 2017).

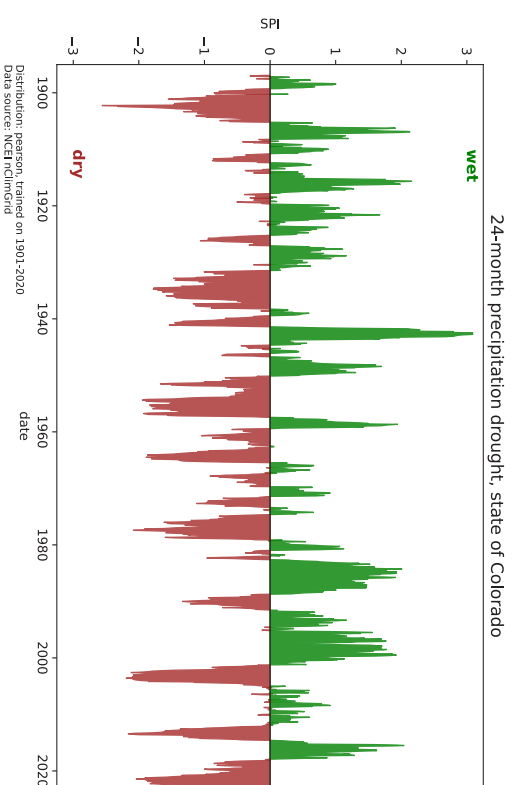


Figure 4.6: 24-month Standardized Precipitation Index for Colorado. Data were fit to a Pearson distribution using NOAA nClimGrid data from 1901-2020.

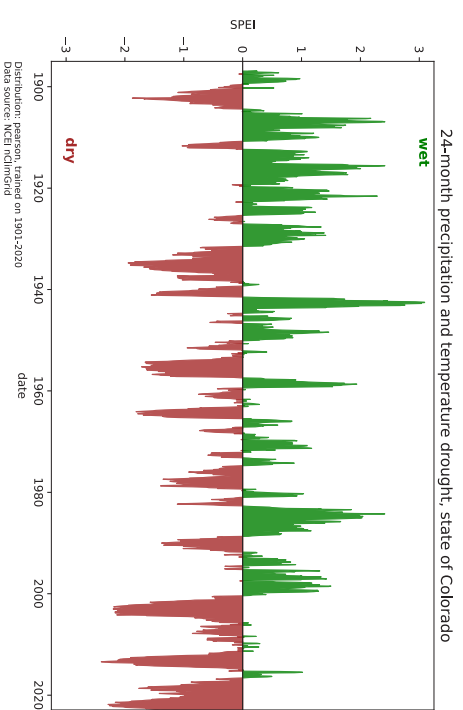


Figure 4.7: As in Fig. 4.6 but for Standardized Precipitation-Evapotranspiration Index. Potential evapotranspiration was calculated using the Thornthwaite method.

Each of the significant drought periods of the 21st century – centered around 2002, 2012, and 2020 – exhibited the indicators that we typically expect with droughts: low peak snowpack and early runoff, decreased streamflows, dry soils accompanying very hot summers, and high evaporative demand. Subsequent studies of these drought periods find that certain events would not have been as severe if the climate were not warming. In addition to *Udall and Overpeck (2017)*, *Williams et al. (2020)* and *Williams et al. (2022a)* found that the 21st century megadrought over the Southwest would not have been a megadrought in terms of duration or severity without climate change. A NOAA Drought Task Force assessed conditions in the Southwest during the 2020-2021 drought period (*Mankin et al. 2021*). They found that precipitation deficits over those two years, although exceptionally low, had the same likelihood of occurring in past decades (1950-2000). They also evaluated VPD, which *Lowman et al. (2023)* simply describes as “high atmospheric aridity.” VPD tends to be elevated during drought, ultimately impacting plants’ growth and photosynthetic activity. Observed VPD during the 2020-2021 drought had virtually no chance of occurrence in the 20th century but is more likely to occur in future climate scenarios. *Mankin et al. (2021)* concluded that increased VPD in 2020-2021 made the drought worse. Regardless of changes in precipitation, rising temperatures are making droughts more severe and frequent.

Future drought projections

Williams et al. (2020, 2022) found that anthropogenic climate change in the CMIP6 (CMIP5) climate models contributed 42% (46%) to soil moisture deficits in the Southwest U.S. for the 2000-2021 time period. Precipitation simulations are a large source of uncertainty in the models, but there is strong agreement that warmer temperatures (where confidence in future scenarios is much higher) result in a net drying effect across the Southwest (including Colorado). This drying effect, shown in soil moisture anomalies, reduction in snowpack, and increased evaporative demand, increases the likelihood of widespread and severe droughts over the region (*Williams et al. 2022b*).

Future projections of VPD (*Mankin et al. 2021*) highlight the relationship between atmospheric demand and temperatures. Future VPD increases can be attributed to increasing temperatures. The high VPD observed from 2011-2020 over the Southwest (and specifically during the 2020-2021 drought) is likely to occur more frequently in future projections (2030-2050).

Despite uncertainty in future precipitation projections, droughts are projected to increase in frequency and severity for Colorado (and the Southwest in general) because of warmer temperatures.

Sidebar: Flash Drought

New studies have also emerged on the topic of flash droughts (*Orkin et al. 2018*). Flash droughts indicate a rapid intensification of drought during the growing season, with primary impacts on agriculture. The Eastern Plains of Colorado are vulnerable to flash droughts, observed in the summers of 2012 and 2020. Typical onset and intensification of drought stemming from precipitation and soil moisture deficits differ from flash droughts, which are primarily initiated in the atmosphere with hot temperatures, low humidity, higher winds, and high VPD. This rapid increase in evaporative demand quickly outpaces evolution from precipitation deficits, thus becoming more “flashy” in behavior.

4.4 Wildfire

Overview

The occurrence and behavior of wildfires in the western U.S. are strongly influenced by weather and climate, and they are especially linked to drought conditions (*Littell et al. 2009*; *Hostetler et al. 2018*). Below-normal winter and spring precipitation and early meltout of the snowpack are linked with dry fuels and greater fire activity in subsequent months. Shorter periods of far-below-normal precipitation can lead to dry fuels and increased fire activity at any time of the year. High temperatures—whether as part of a drought or a long-term trend—hasten the drying of fuels, making fire ignition, fire spread, and intense fire behavior more likely. Fires are also much more likely to spread and exhibit intense behavior on days with high winds and low humidity. Note that in some vegetation types, such as grasslands and shrublands, wet growing seasons that lead to temporarily high fuel loads may be required for fire to spread during subsequent drier periods.

Wildfire occurrence and behavior are also driven by several non-climatic factors, such as the legacies of historical forest and land management (e.g., fire suppression) and resulting changes in fuel loads. Additionally, increasing human activity and development of houses and other structures within fire-dependent forest, shrublands, and grasslands leads to more ignitions year-round.

Observed wildfire changes

Over the past 20 to 40 years, the Western U.S. has experienced several linked trends in wildfires: large increases in annual area burned, number of very large fires (>10,000 acres), fraction of fire area burned at high severity, and length of the fire season (*Demison et al. 2014*; *Abatzoglou and Williams 2016*; *Westerling 2016*; *Parks and Abatzoglou 2020*; *Higuera et al. 2021*; *Parks et al. 2023*). While these trends are also affected by non-climatic factors (*Balch et al. 2017*; *Radeloff et al. 2018*) and by multidecadal variability in precipitation, a critical common thread is the role of increasing temperatures. Two recent studies found that anthropogenic climate change, via warmer temperatures and resulting increases in fuel dryness across the region, could account for half or more of the recent increase in annual area burned (*Abatzoglou and Williams 2016*; *Zhuang et al. 2021*). However, *Holden et al. (2018)* found that, while acknowledging the role of warming temperatures, a declining trend in summer precipitation was the primary driver.

These West-wide increasing trends in wildfire are very clearly expressed in Colorado. Figure 4.8 shows the number of very large Colorado wildfires (over 10,000 acres), and the total area burned in those fires, from 1984 through 2020. From 1984-1999, there were 8 wildfires larger than 10,000 acres, and records suggest that only two additional fires that size occurred from 1950 to 1983. Since 2000, there have been 60 wildfires larger than 10,000 acres, including six fires larger than 100,000 acres: all but one of the latter occurred after 2017. The annual area burned by wildfires in the forested areas of Colorado, and adjacent areas of New Mexico and Wyoming, increased by over 300% from the 1984-2000 period to the 2001-2017 period. The average elevation at which these wildfires occurred shifted upwards by over 1000' between 1984 and 2017, which is consistent with how warming is shifting temperature regimes upslope (*Alizadeh et al. 2021*).

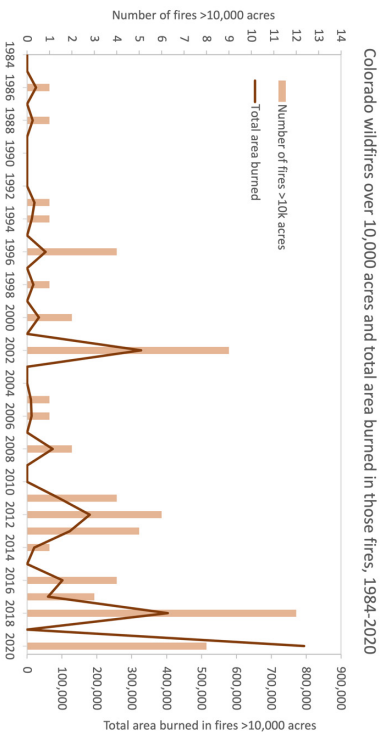


Figure 4.8: Number of Colorado wildfires that burned over 10,000 acres, 1984-2020, and total area burned in those fires, 1984-2020 year. (Data: Monitoring Trends in Burn Severity (MTBS). <https://www.mtbs.gov/direct/download>)

Future wildfire projections

Many studies have combined climate model projections with observed fire-climate relationships to estimate the impacts of future climate change on wildfires in Colorado and the Rocky Mountain West. These studies have uniformly indicated substantially worsened wildfire risk for Colorado by the mid-21st century compared to the late 20th-century, as additional warming further increases fuel dryness and enhances fire ignition and spread (Liu et al. 2015; Brey et al. 2021; Moritz et al. 2012; Pechony and Shindell 2010; Spracklen et al. 2009; Litschert et al. 2012; Yue et al. 2013; Abatzoglou and Williams 2016; West et al. 2016; Kitzberger et al. 2017; Littell et al. 2018; Abatzoglou et al. 2021; Brown et al. 2021).

Most of these studies quantified potential changes in annual area burned, collectively indicating a 100-500% increase under a warming of 2.5°F to 5°F (equivalent to RCP4.5 projections for mid-century). Under the same level of warming, Stavros et al. (2014) projected a 400% increase in the occurrence of very large wildfires (>50,000 acres). In short, studies consistently project a continuation of the recent increasing statewide trends in wildfire, given the near-certain continuation of the recent warming trend. However, some grassland and shrubland ecosystems in which fire is fuel-limited could see reduced fire occurrence as warming leads to overall lower fuel accumulation and continuity (Littell et al. 2018).

While post-fire changes to vegetation type, structure, and fuels could eventually limit how much new fire can occur on the landscape in each year or decade (Westerling et al. 2011), such feedback mechanisms will not prevent large, climate-driven increases in average annual burned area from occurring over the next several decades (Abatzoglou et al. 2021).

4.5 Heavy and Extreme Rainfall

Overview

Heavy and extreme precipitation events occur when three main storm “ingredients” are at unusually high levels, including atmospheric moisture, the transport of moisture into the storm (convergence), and upward motion (lift) within the storm. During the warm season (April-September), most heavy and extreme precipitation events in Colorado occur in convective storms, such as supercell thunderstorms and larger mesoscale convective systems (MCS). They can also occur in larger-scale systems with front-driven lift and orographic (terrain-driven) lift, such as during the Front Range floods in September 2013 (Gochis et al. 2015). The precipitation in warm-season storms usually falls as rain or hail, leading to flooding risk. During the cold season (October-March), heavy and extreme precipitation is associated with strong mid-latitude cyclonic storms with both frontal and orographic lift. While precipitation in cold-season storms generally falls as snow at all elevations (see Winter Storms, section 4.9), heavy rainfall and flooding risk can occur at lower elevations (~6000’ and below), especially in the “shoulder” months (October and March).

There are substantial differences between the eastern and western slopes of Colorado in the frequency, magnitude, and seasonality of heavy and extreme precipitation events, along with the prevalent storm types associated with these events. In particular, eastern Colorado is much more prone to strong convective storms; thus, rainfall events of a given frequency (e.g., 1-year) are generally much larger than in western Colorado (Mahoney et al. 2013).

Of the main storm ingredients, only atmospheric moisture has a direct physical link to temperature, through the Clausius-Clapeyron (C-C) equation. The application of the C-C equation to water vapor says that for every 1°C rise in temperature, the moisture-holding capacity (saturation vapor pressure) of the atmosphere increases by 6.5%–or 3.5% for every 1°F rise (Brune 2023). Not every storm in a warmer climate will necessarily drop more precipitation than previously, but in general, with other factors held the same, storms will have access to more moisture in a warmer climate. Atmospheric instability, which influences the lifting of air parcels in convective storms, also tends to be greater under warmer temperatures, although the relationship is not as direct or as strong as with moisture (Mahoney et al. 2018). Definitions can vary; here we use “heavy” to refer to events expected to occur in a given location once per year or less frequently, and “extreme” to refer to events expected to occur every 20 years or less frequently. Thus, depending on the location in Colorado, a “heavy” event is at least 1”-2” of precipitation over 24 hours, while an “extreme” event is at least 2”-4” of precipitation over 24 hours.

Observed extreme rainfall changes

In the southwestern U.S., including Colorado, there have been some indications of increasing trends in heavy and extreme precipitation over the past several decades (Westerling et al. 2011; Kunkel et al. 2020). For other metrics and time periods that were analyzed, increasing trends have not been observed (Bonnin et al. 2011; Hoerling et al. 2010; Lehmann et al. 2015). By comparison, in the Eastern and Midwest regions of the U.S., increasing trends are stronger and more consistent across different metrics of heavy and extreme precipitation and across different time periods.

The total from heavy and extreme precipitation events as a fraction of annual precipitation has increased since the 1950s in the six-state Southwest region (CO, UT, NM, AZ, CA, NV). Over the same region, the magnitude of every-20-year, 24-hour event has increased (*USGCRP 2017*). Across a range of event durations (1-day to 30-day), *Kunkel et al. (2020)* found that for the four-state Southwest (CO, UT, NM, AZ), the amount of precipitation falling in heavy (1-, 2-, 5-, and 10-year) and borderline extreme (20-year) events had generally increased from 1949-2016 and from 1979-2016. These increases were larger and more consistent in the warm season than the cold season.

Atmospheric moisture (precipitable water, PW) over Colorado and the surrounding states is observed to have increased from 1979 to 2016 by 0-8%, overall less than C-C scaling would suggest (*Kunkel et al. 2020*). It is possible that over the southwestern U.S., multi-decadal natural variability in the climate has suppressed the general effect of warming temperatures and increased regional precipitable water on heavy and extreme precipitation (*Hoerling et al. 2016*). Specifically, the prevalence of La Niña conditions since 2000 may have led to fewer such events in our region.

Future extreme rainfall projections

Given the near-certain continuation of warming for the rest of the 21st century, the C-C equation points to continued increases in atmospheric moisture globally (by 3.5% per 1 degree F) and a strong potential for increases in heavy and extreme precipitation. A very basic assumption is that the amount of precipitation in those events would increase, on average, according to C-C scaling. Under this assumption, 4°F of additional warming would lead to heavy and extreme precipitation events that are about 15% larger than without any warming. Whether that C-C-based “juicing” ultimately leads to that level of overall increase in extreme precipitation for Colorado depends on whether the future frequency of the different types of weather patterns that produce extreme precipitation, and other storm “ingredients” such as moisture convergence and lift, also change. Some observational studies have found evidence of “super-C-C scaling,” i.e., that convergence and/or lift have changed or interacted with warming so that the overall effect is to increase precipitation amounts beyond the C-C relationship, especially for short-duration (< 3-hour) events (*Fowler et al. 2021*).

The ability of climate models to simulate these other storm ingredients is limited by the relatively coarse spatial resolution of the models, especially for convective storms. A review of the different mechanisms by which climate change could affect extreme precipitation in Colorado and New Mexico concluded that the C-C-driven increase in atmospheric moisture with warming temperatures is likely to take precedence over the other effects (*Mahoney et al. 2018*).

Studies based on climate model projections (CMIP5 and CMIP6) for Colorado and the Southwest have consistently indicated overall future increases in the magnitudes of heavy and extreme precipitation events for our region, generally following the C-C scaling (*Khariin et al. 2013*; *Wuebbles et al. 2014*; *Janssen et al. 2016*; *Lynker 2019*; *Swain et al. 2020*; *Rupp et al. 2022*; *Pierce et al. 2023*). Again, even when downscaling, these studies based on global climate models poorly represent the shorter-duration convective storms that are important sources of extreme rainfall events in Colorado. The only recent study specific to Colorado, conducted on behalf of CWCB, projected the future change in the 24-hour, 100-year precipitation event for 28 grid boxes (1° by 1°) covering Colorado (*Lynker 2019*). This analysis found that under RCP4.5, most of the grid boxes over the state would see 2% to 12% increases in 24-hour, 100-year events by 2050. Additionally, under RCP8.5 with higher warming, most grid boxes would see increases of 8% to 20% by 2050. The upper ends of these changes are approximately equivalent to C-C scaling. This study did not show any consistent discrepancies between different parts of Colorado with respect to future changes in extreme precipitation.

4.6 Floods

Overview

Flood events are very obviously linked to heavy and extreme precipitation, but they are also influenced by many factors, including characteristics of the watershed (geology, slope angles, vegetation, soil texture and depth, extent of impervious (e.g., paved) surfaces, urban drainage system). They are also influenced by the stream channel itself, which is often modified extensively by human activity (dams, diversions, channelization). Other factors that vary more over time, such as the level of soil moisture or the presence and depth of snowpack, can also play an important role. As a result, the intensity of a flood event may not match the intensity of the underlying precipitation event; a 100-year rainfall can produce a 10-year flood, a 100-year flood, or a 1000-year flood, depending on these other factors.

In Colorado, floods occur almost entirely during the warmer half of the year (April-September), driven by either short-duration (< 6 hours) convective storms or longer-duration, broader-scale storm systems. Especially on the Western Slope, flooding also occurs from the melting of unusually large snowpacks. Such snowpacks typically arise from multiple heavy or extreme precipitation (i.e., snowfall) events during the cold season.

Watersheds that have recently burned in a wildfire, especially if the burn severity was high, are at much greater risk of flooding than unburned watersheds. Fire-induced changes to vegetation and soil properties mean that surface runoff and flooding can initiate at much lower precipitation intensities and total amounts, as little as 0.25” in one hour.



Historical flood marker near the lagoon on the Colorado State University Fort Collins campus.

Observed flood changes

There is limited evidence suggesting increases in flooding in Colorado in recent decades. A recent global analysis of trends in flooding examined over 10,000 gaged streamflow records, including about 40 in Colorado (Stater et al. 2021). Most of those gages in Colorado showed declining trends since 1970 in the size of the 20-year, 50-year, and 100-year flood events; however, many of these gages reflect extensive human modification of the streamflow regime. Increasing trends in floods were seen at about one-third of the gages, mainly on the Front Range and in northwestern Colorado. Two earlier studies that looked at U.S. trends in the 1-year flood event (i.e., annual peak daily discharge), but only in near-natural gaged streamflow records, found no increasing trends at any of the eight gages in Colorado they examined (Villarini et al. 2009; Hirsch and Ryberg 2012). Note that analyses of gaged stream and river flows may not capture changes in flash flooding involving overland flow outside of channels or in smaller basins without gages, such as in the 2013 Front Range floods.

Future flood projections

As described earlier, climate model projections indicate the likelihood of increased frequency and severity of extreme precipitation events for Colorado in the next several decades. Considered in isolation, these projected increases in extreme precipitation would lead to increased frequency and severity of flooding (Swain et al. 2020). However, the many factors that affect how rainfall is translated into runoff complicate the picture. In particular, the projected declines in summer soil moisture could be a countervailing factor. One study has found that semi-arid and semi-humid regions show smaller future increases in flooding than humid regions; in their model analysis, Colorado generally sees future declines in the intensity of the 30-year flood, despite increasing intensity of extreme precipitation (Tabari 2020).

Similar modeling by Brunner et al. (2021) for river basins in Europe found a threshold effect in the future translation of precipitation into flooding. This same effect may play out in Colorado: The drying of soil moisture and snowpack losses resulting from warming temperatures could counterbalance the increased magnitudes of the less-extreme precipitation events (< 10-year), leading to little or no change in less-extreme flood events. For more extreme precipitation events (> 50-year), the increased precipitation magnitudes with climate change could overwhelm the effect of soil drying and translate into increases in the largest flood events. In the September 2013 Front Range flood event, whose intensity was likely exacerbated by warming (Trenberth et al. 2015; Pall et al. 2017), very extreme precipitation (50-year to ~1000-year) overcame dry antecedent soils to cause extreme flooding (Gochis et al. 2015).

4.7 Thunderstorm Hazards: Tornadoes, Hail, and Winds

Colorado regularly experiences severe convective weather, defined by the National Weather Service as a tornado, hail at least 1" in diameter, or thunderstorm wind gusts of at least 58 mph. Although severe storms can occur anywhere in the state, the vast majority of the impacts are along the Front Range and eastern Plains (Fig. 4.9). Nearly all thunderstorm hazards occur between March and October, with a peak in early June. Severe thunderstorms are very rare outside of these months. Notable recent severe thunderstorms in Colorado include the EF-3 tornado in Berthoud in 2015 (NOAA 2015), the wind

damage from a derecho and a macroburst, two days apart in eastern Colorado in June 2020 (Childs et al. 2020), and the state-record hailstone with diameter of 5.25" in Yuma County in August 2023 (NOAA 2023a). Tornadoes in Colorado are frequent, but the vast majority are relatively weak. Although strong and damaging tornadoes (rated 2-3 on the Enhanced Fujita scale) occur occasionally in Colorado, violent tornadoes (rated EF-4 or EF-5) have not been observed in Colorado. Eastern Colorado, along with the adjacent states in the Great Plains, is one of the global "hot spots" for large hail (Raupaach et al. 2021).

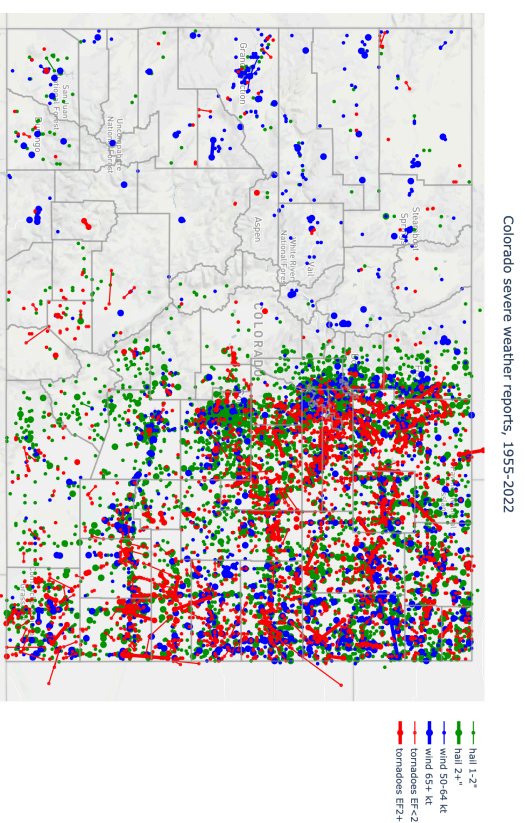


Figure 4.9: Map of severe weather reports from 1955-2022, based on data from the NOAA Storm Prediction Center. See https://climate.colostate.edu/severe_wx_climatology.html for an interactive version.

Long-term trends in hazardous convective weather are very challenging to identify because the data largely come from reports from storm spotters and the public. As the population of Colorado has grown, awareness of severe weather has increased, and the ability to easily submit reports has expanded. There are upward trends in severe weather reports that result from these non-meteorological factors. Childs and Schumacher (2019) closely examined the observed trends in tornadoes and severe hail and connected them to both meteorological and non-meteorological causes. They found that from 1997-2019, when severe weather reports have been more systematically collected, there was a slight downward trend in tornadoes in Colorado but an increasing trend in severe hail. They also found an upward trend in the ratio of "significant" severe hail (at least 2" in diameter) reports to those of "1" in diameter. Using a different method, Tang et al. (2019) showed that from 1979-2017, most of the continental U.S. experienced an increase in the number of days with the potential to produce large hail, but

in eastern Colorado, there was actually a significant decrease in the number of days. The decrease in eastern Colorado was noted to be “puzzling” and worthy of further investigation. Overall, because of the relatively short data record for these hazards and the influences of changing observation systems, the sign and magnitude of long-term changes remains uncertain (Raupach *et al.* 2021).

The influences of climate change on hazardous convective weather in the future are also uncertain. Mahoney *et al.* (2012) used numerical model simulations to show that in a warmer climate, despite increased intensity of thunderstorms overall, the occurrence of hail will be greatly reduced owing to an increase in the height of the melting level. The review by Raupach *et al.* (2021), as well as Brimelow *et al.* (2017) and Tapp *et al.* (2019), similarly concluded that the average size of hailstones reaching the ground will increase in a warmer climate. In other words, hail frequency may decline, with what would have been small hail instead falling as rain, but when hailstorms do occur, they are more likely to produce large hail. Using various proxies for hail in downscaled climate simulations, Childs *et al.* (2020) found that in northeast Colorado, environments supporting severe hail will occur on 2.3 additional days per year in the future compared to the late 20th century, with smaller increases along the Front Range and southeastern Colorado. They also found that the changes in the impacts of severe hail (e.g., human exposure and damage) will be more sensitive to future changes in population than to changes in hailstorms themselves—something that is true of many weather and climate hazards. If Colorado’s population continues to grow rapidly and the climatology of hailstorms remains similar to the present day, then exposure could more than double. However, if hailstorms shift to occur more frequently over eastern Colorado where population is projected to remain steady or decline, then overall human impacts from hail could decline in the future but impacts to agriculture could increase.

Regarding tornadoes, the results from Childs *et al.* (2020) echo those for hail in Colorado: in the future, a modest increase in days favorable for tornadoes in northeast Colorado is likely, with future trends in impacts driven much more by population changes than changes in tornado occurrence. The influence of climate change on convective wind events in Colorado has not been systematically studied. The derecho of 6 June 2020 (NOAA 2020b) across the western U.S. produced the largest number of severe wind reports on a single day in Colorado history, but it is unclear whether this event can be attributed to climate change in any way. (See section on non-convective windstorms for discussion of other types of wind hazards.)

In summary, for all three hazards (hail, tornado, and winds), there remain large uncertainties regarding future changes, as data limitations and the infrequent and localized nature of these storms makes them challenging to study in the context of a changing climate.

4.8 Non-convective Windstorms

Colorado’s topography, and a location that often intercepts the midlatitude jet stream, makes it prone to extreme wind. In particular, the Front Range from Fort Collins to Pueblo is prone to downslope windstorms, where air flowing eastward over the mountains rapidly descends and results in extreme gusts (American Meteorological Society 2022). Several damaging windstorms in Boulder, such as 11 January 1972, which had gusts of nearly 100 mph (Lilly and Zipser 1972) and 17 January 1982, which had a gust measured at 137 mph at the NCAR Mesa Lab (Zipser and Bedard 1982), motivated extensive research on the causes of downslope winds. The devastating Marshall Fire in December 2021 was also fueled by a downslope windstorm with gusts up to 115 mph (NOAA 2022). (See section below on compound events.)

Other areas in Colorado’s high country are also prone to extreme winds. Longs Peak had a wind gust of 201 mph in 1981, which is unofficially considered the state record, but it was measured at a temporary weather station as part of a research project. Other mountain areas routinely experience wind gusts exceeding 100 mph. The eastern plains can also experience extreme non-thunderstorm winds, such as a 107-mph gust at Lamar that occurred in December 2021.

Unfortunately, long-term changes in wind are difficult to quantify because data records for wind, especially wind gusts, are generally much shorter and less complete than records for temperature and precipitation. Detailed wind measurements generally require automated instrumentation, which only came into widespread use in the 1990s. Worldwide, there was some evidence for a “global stilling” trend (i.e., a slowing of average wind speed) that began in the 1980s, but this trend was found to have reversed after 2010 (Zeng *et al.* 2019). Using data from the Colorado Agricultural Meteorological Network, Goble (2018) found that from 1996–2018 average wind speeds declined in all seasons and all parts of the state, except for the western slope in spring. However, this study did not address windstorms specifically and was based on a relatively short data record. Future changes in extreme winds are highly uncertain, but changes notwithstanding, the threat for extreme winds in Colorado will remain.

4.9 Winter Storms

While we’ve observed increasing trends in cold season temperatures (Chapter 2) and fewer cold waves (Chapter 4.1) in recent decades, it is more challenging to assess how winter storms have changed, or may change in the future. “Winter storms” encompasses a broad range of natural hazards such as heavy snowfall, ice accumulations, high winds, and cold temperatures. The physical mechanisms required for most winter storms are large-scale in nature – associated with the troughs along the polar jet stream, low pressure centers, and cold fronts. These large-scale events can leave a trail of impacts that extend across the entire country. For example, in February 2021, a major winter storm brought extreme cold, snow, and ice accumulations that impacted states from Oregon to Alabama (Boling *et al.* 2022). In Colorado, record-low temperatures were observed across many parts of the eastern plains, with the primary impact being power outages.

Due to the complexity of winter storms, identifying trends (both historic and projected) is difficult. Changes in large scale factors are one option. For example, Cohen *et al.* (2021) found that Arctic amplification – where the higher latitudes are warming at a faster rate than the tropics, thus weakening the jet stream and resulting in a wavier pattern – is evident in observations and connected with changes in mid-latitude winter weather patterns. In theory, the wavier pattern of the jet stream would have more ridges and troughs, potentially increasing the frequency of winter storms. These connections are not represented in climate models, and the dynamic mechanisms are still being debated (Moon *et al.* 2022). Additionally, Blackport and Screen (2020) found that Arctic amplification does not necessarily mean more waviness, and recent reported trends toward a wavier circulation had reversed.

Identifying trends at a local level can also be challenging. Each winter storm is the collation of several different variables. Some characteristics of winter storms – cold fronts, freezing rain, high winds – are difficult to measure and assess over time. Measurement protocols for snowfall have also been inconsistent over time (Doesken and Judson 1997). Variables estimated from well measured observations of temperature and precipitation (such as cold waves or snowfall accumulations) can provide some insight.

The Accumulated Winter Season Severity Index – AWSSI – uses temperature, snowfall, and snow depth observations to monitor winter severity accumulated throughout the season (Boustedt et al. 2015). While they find that warming temperatures result in overall decreasing trends in historic accumulations of AWSSI, we find no significant trends in winter severity at eastern Colorado stations (Fig 4.10). Large accumulating snow events can still occur frequently across the Front Range Urban Corridor and Eastern Plains. For example, the largest annual 2-day snow events since 1951 exhibit high variability with minimal detectable trends (Fig 4.10). The number of 2-day events that exceed 3 inches may be decreasing slightly, with Denver observing a decreased frequency in seasons with more than 10 events since 2000. However, Fort Collins continues to experience between 10 and 15 of these events each year.

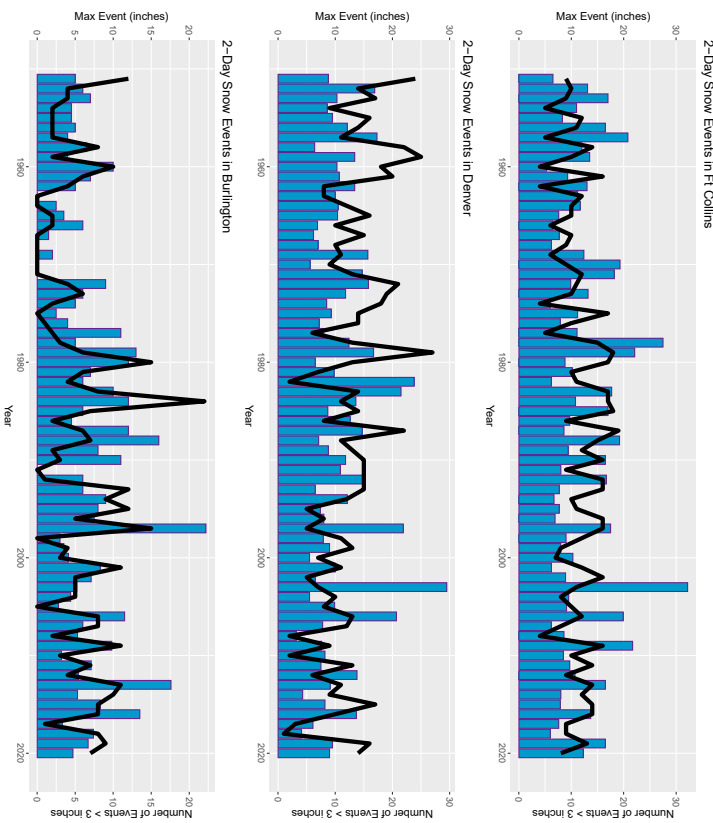


Figure 4.10. Maximum 2-day snow event per year in inches (blue bar) and total number of 2-day snow accumulations greater than 3 inches per year (black line) for Fort Collins (top), Denver Central Park (middle), and Burlington (bottom), 1951-2020.

Several recent notable winter storms have impacted Colorado's Front Range and Eastern Plains. A heavy snowstorm over southeastern Colorado in late April 2017 covered and killed hundreds of livestock. A bomb cyclone passed over southeastern Colorado in March 2019, bringing destructive winds (Colorado Springs airport reported a 96-mph wind gust), snow, and low visibility across eastern Colorado. In March 2021, 20-30" of widespread snow blanketed northern Colorado. In December 2022, a powerful cold front moved across the region; the temperature in Fort Collins fell 37°F in 20 minutes, to 6°F. These events indicate that Colorado's susceptibility to severe winter storms remains.

4.10 Dust-on-snow

Over the past 20 years, the phenomenon of dust-on-snow deposition in Colorado and the West has shifted from a periodic curiosity to a chronic concern for water managers and water users. This shift is due to both a much better understanding of the significant hydrologic effects of dust-on-snow, and an overall increase in the occurrence of dust-on-snow events. Dust-on-snow is also unusual in that the visual appearance is an accurate gauge of the eventual impact on snowpack and runoff; the darker the snow surface, the stronger the dust's radiative forcing (i.e., enhancing the sun's energy) on snowmelt.

Dust-deposition events in Colorado typically occur during large-scale storms that move in from the southwest, most frequently in the spring (Painter et al. 2018). Strong winds in these storms pick up fine soil particles in the Colorado Plateau from lands that have been disturbed by grazing, oil and gas drilling, dryland agriculture, and off-road vehicle use (Dunaway et al. 2019).

Dust deposition on snowpacks and its impacts, are usually greatest in the San Juans, closest to this primary source (Painter et al. 2012; Skiles et al. 2015). Yet, the dust may be transported hundreds of miles to all of Colorado's mountains, including the east slope of the Front Range. The dust layers from each event are often buried by subsequent snows, but then reemerge and coalesce at the snow surface as the snowpack compacts and melts down in late spring.

Lake-sediment cores from the San Juans show a several-fold increase in dust deposition starting in the mid-1800s through the 20th century (Neff et al. 2008). Dust mobility and deposition increased again around 2000, due to increasing aridity in the source areas and more widespread disturbance of the soils (Brahney et al. 2013).

Multiple studies have shown that dust loading in the snowpack alters the energy balance of snow-melt, enhances melt rates, and advances the timing of spring runoff by up to 3-6 weeks (Painter et al. 2007, 2012; Skiles et al. 2012; Painter et al. 2010; Deems et al. 2013). Modeling studies suggest that



An excavated snow pit near a weather station features individual dust events layered throughout, April 30, 2013 at Swamp Angel in the Senator Beck Basin.

dust-on-snow deposition over the 20th and early 21st centuries has reduced natural streamflows from the Upper Colorado River Basin by about 5% or 800,000 acre-feet, compared to pre-1800s low-dust conditions (*Painter et al. 2010*). This is mainly due to earlier meltout of snowpacks and increased evapotranspiration from soils and vegetation that are exposed and growing earlier in the season.

In a warmer future climate, overall drier soil conditions in the dust source region are very likely, which will tend to reduce vegetation cover and allow for greater dust emission, given the same level of disturbance (*Minson et al. 2017*). Further warming, like dust-on-snow, will tend to drive even earlier snowmelt and runoff. The only study to jointly model dust-on-snow and warming found that runoff timing remains strongly affected by dust under a variety of future warming scenarios (*Deems et al. 2013*). However, in a significantly warmer mid-century climate, going from “moderate” dust to “extreme” dust has no additional effect on runoff volume.

4.11 Compound Events

With the increase in the area burned annually by wildfires in the 21st century, attention to the issue of flash flooding and debris flows in burned areas has also increased. When the landscape is burned by wildfire, especially by a high-intensity fire, the soil often becomes hydrophobic, instead of being able to soak up rainwater (*NOAA 2023b*). As such, flash floods and debris flows can develop in recently burned areas with much less rainfall than would be needed in non-burned areas. For example, a rain rate of 0.25” in 15 minutes is used as a general guideline for the potential of flash flooding on a burn scar, whereas such rain rates would be very unlikely to produce flash flooding in non-burned areas (*COMET MetEd*).

While burn-scar flash flooding occurred after the large wildfire seasons in 2002, 2012, and 2018, the concerns became particularly acute after the record 2020 fire year. Several major floods and debris flows occurred in the summer of 2021. In the Poudre Canyon in northern Colorado, intense rain fell on the Cameron Peak burn scar on the evening July 21, and a devastating flash flood occurred, killing four people and destroying several homes (*Whitehead 2021*). Again in 2022, heavy rain on the Cameron Peak burn scar resulted in a deadly flash flood when a camper was washed away in Buckhorn Canyon (*Tabachnik 2022*).

Farther south, the Ghizzly Creek burn scar was the site of numerous debris flows following intense monsoon rains in July 2021. The largest of these occurred on July 31, when Interstate 70 in Glenwood Canyon was overtopped with debris and heavily damaged. The important western Colorado highway was closed for over two weeks for repairs (*Nicholson 2021*).

As discussed in section 4.4, area burned by wildfires has increased in the 21st century in Colorado and is expected to increase further in a warming climate. Although trends in extreme rainfall have not yet been robustly detected in Colorado, it is expected that the heaviest rain rates will generally increase as the climate continues to warm (see section 4.5 on extreme rainfall). Even if extreme precipitation remains unchanged, an increase in burned area increases the risk of burn-scar flooding during the intense thunderstorms that have regularly been observed historically. Then, if short-term rain rates also increase, the frequency and intensity of compound flood-after-fire hazards will increase significantly. *Touma et al. (2021)* projected large increases in future extreme rain events occurring within one year of intense wildfires in the western U.S. Although their results were for a high-emissions scenario, even more modest increases in each individual hazard (i.e., with less extreme future emissions) would lead to much higher future risk for these compound events.

4.12 Air Quality

Overview

There are several different air quality issues that impact Colorado. Each may exhibit varying trends around the state. While most air quality issues are anthropogenic (with the exception of smoke from naturally caused wildfires), they may or may not be influenced by climate change. The primary issues that may be impacted by climate change are discussed below.

Ground-level ozone

Traffic, industry, oil and natural gas production, and wildfire smoke can all contribute to ozone formation and abundance in the state. Currently, the Northern Front Range exceeds the ozone National Ambient Air Quality Standard (*Bien and Helmig 2018*), and despite decreasing ozone in other areas of the country, some Northern Front Range sites have exhibited increases in ozone between 2000 and 2015 (*Abelaira and Farmer 2017*). While it is essential to reduce precursor emissions, ozone’s temperature dependence (warmer temperatures increase ozone) means climate change will exacerbate the issue (*Crooks et al. 2022*).

Wildfire smoke

During the summer, the largest smoke-plume source regions are located in the Western U.S. and Rocky Mountains (*Brey et al. 2018*). More local wildfire smoke (which will have a more significant impact on Colorado from Rocky Mountain wildfires) tends to stay lower in altitude and have higher PM_{2.5} concentrations. As noted in the Wildfire section, wildfire activity (both acres burned and number of fires) is expected to increase with climate change. It is likely that air quality in Colorado (particularly in the summer) will subsequently continue to degrade.



Smoke and debris cover Northern Colorado from the Cameron Peak and East Troublesome wildfires, October 2020.

Observed temperature and precipitation trends

Gridded temperature and precipitation data

Since the 2014 Climate Change in Colorado report, several gridded datasets for temperature and precipitation have become available that are based on observations from long-term climate stations, but also apply homogenization methods that account for changes in observation time, station location, and so forth. Throughout this report, we use NOAA's nClimGrid dataset (Vose *et al.*, 2014), which includes monthly temperature and precipitation information on a 4-km latitude/longitude grid across the contiguous United States, and whose underlying station data and methods are similar to the NOAA nClimDiv dataset used in the 2014 report. The nClimGrid dataset is regularly used as an official source for climate monitoring by NOAA and by the Colorado Climate Center.

All climate datasets have uncertainties and limitations, and to explore these, we compared the nClimGrid monthly temperature data to a gridded climate dataset independently developed by the Berkeley Earth project (Rehde *et al.*, 2013). Figure A.1 shows that these two datasets provide remarkably similar estimates of the temperature change over Colorado during the period 1985-2022. Although differences exist month-to-month and year-to-year, the two temperature datasets have a correlation of $r = 0.984$. This provides confidence that the temperature changes presented in this report are robust and are not simply an artifact of the choice of dataset.

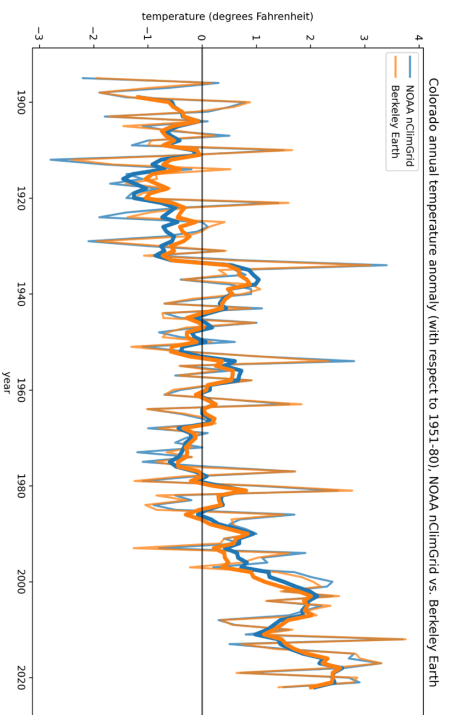


Figure A.1: Annual temperature anomalies (degrees Fahrenheit) for Colorado, with respect to a baseline of 1951-80, for the NOAA nClimGrid and Berkeley Earth datasets. The thick lines show a 5-year running mean.

Projected temperature, precipitation, and hydrology changes

Climate projections from global climate models (GCMs) - CMIP5 and CMIP6

Projections (i.e., simulations) by global climate models (GCMs) are the foundational data for assessing the direction and magnitude of physically plausible future climate changes at global, regional, and local scales. This report uses two sets of climate model data assembled by the Coupled Model Intercomparison Project (CMIP), incorporating the efforts of dozens of climate modeling groups around the world. CMIP is an organized “roundup” of several dozen of the latest generation of climate models conducted every 7 years or so to support policy-relevant climate assessments as well as climate research more broadly. (We acknowledge the World Climate Research Programme (WCRP), which supports and coordinates CMIP, the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support ESGF.)

The CMIP5 (Coupled Model Intercomparison Project, Phase 5) multi-model ensemble was previously used in the 2014 Climate Change in Colorado report and was used again in this report. CMIP5 data for Colorado regridded to a common 1-degree grid, but not downscaled (see section on downscaling below), were obtained through the LLNL GDO-DGP server (<https://gdo-dcp.ucidl.org/>) and used to evaluate statewide temperature and precipitation change (e.g., Figures 2.5, 2.6, 2.7, 2.12, 2.13). The CMIP5 ensemble used in this report encompasses 37 projections, one each from 37 models.

In 2020 and 2021, the data from CMIP6 (Coupled Model Intercomparison Project, Phase 6) were released, representing a new generation of climate models. Because of their relative newness, CMIP6 climate projections have only recently been added to public-facing climate portals. Only a handful of datasets of downscaled CMIP6 projections have been produced (as of July 2023), and no watershed-scale CMIP6-based hydrologic projections for the U.S. have yet been produced.

For this report, the CMIP6 multi-model ensemble was used to supplement and compare with the CMIP5 projections. CMIP6 data for Colorado regridded to a common 1-degree grid, but not downscaled, were obtained through the KNMI Climate Explorer (<https://climexp.knmi.nl>) and used to evaluate statewide temperature and precipitation change alongside CMIP5 (e.g., Figures 2.5, 2.6, 2.12). The CMIP6 ensemble used in this report initially encompasses 37 projections, one each from 37 models, but then was screened to a final ensemble of 22 projections, one each from 22 models, as detailed below.

GCMs have improved by many measures from one generation to the next, but since CMIP3, the improvements have diminished, indicating that climate modeling is maturing. While the CMIP6 models do show general improvements over CMIP5 in reproducing many features of the climate system and regional climate statistics, the assessed skill of the models by these benchmarks across the CMIP5 and CMIP6 ensembles show substantial overlap (e.g., Pierce *et al.*, 2021). In practical terms, CMIP6 does not make CMIP5 obsolete—in fact, an issue emerged with CMIP6 models for which the IPCC applied an adjustment that was not done for previous CMIP ensembles.

When researchers first examined projections across the CMIP6 models, a number of models showed higher rates of global and regional warming than the upper end of the CMIP5 models; that is, unexpect-

edly high climate sensitivity or climate response to a given increment of greenhouse-gas emissions. Since these models also appear to simulate excessive warming in recent decades (~1980-present), it is plausible that these “hot” models’ estimates of future warming are unrealistically high. Accordingly, the IPCC AR6 report (*IPCC 2021*) deemphasized the “hot” CMIP6 model projections, using additional modeling and analysis to develop an “assessed” range of future global temperatures that ended up very close to what had come directly from the CMIP5 model ensemble, given a similar emissions scenario.

Since then, a simpler method has been proposed for screening CMIP6 models to deemphasize the hot CMIP6 models in projecting future warming at regional scales (*Hausfather et al. 2022*). That method was used for this report to screen the CMIP6 ensemble from 37 models down to 22 models. If the same method were applied to the CMIP5 ensemble, none of the models would be screened out.

For Colorado, after the 12 “hot” CMIP6 models are screened out (along with 3 other models that are too “cold”, according to the screening criteria) CMIP6 still shows greater warming than CMIP5 for the same emissions increment, though the two ensembles mostly overlap (Figures 2.6 and 2.7). The reduced range across the CMIP6 temperature projections relative to CMIP5 primarily results from the screening of CMIP6 and the resulting smaller ensemble. In any case, there is much more difference among the models within each CMIP ensemble, than there is between the two CMIPs. The screening of CMIP6 models has virtually no impact on the projections of precipitation change as shown in Figure 2.13. Note that there is still considerable discussion within the climate science community regarding for what applications one should screen out or otherwise deemphasize the hot models in CMIP6 (*Rahimpour Asenjan et al. 2023*). For this report, on balance, we believed it was appropriate to screen out hot models, consistent with the latest global-scale climate assessment (*IPCC 2021*).

Emissions scenarios

A major uncertainty in how climate change will unfold in the coming decades stems from society, not the climate system: How annual global emissions of greenhouse gases, and thus their atmospheric concentrations, will change in the future. For the CMIPs and the IPCC reports, the climate modeling community has collectively adopted sets of assumptions, known as emissions scenarios, whose broad range is intended to capture this uncertainty (Figure A.2). For the most recent three CMIPs and IPCC report cycles, three sets of emissions scenarios have been used:

- CMIP3 – Special Report on Emissions Scenarios (SRES) scenarios
- CMIP5 – Representative Concentration Pathways (RCP)
- CMIP6 – Shared Socioeconomic Pathways (SSP)

For CMIP5 (RCP) and CMIP6 (SSP), each of the scenarios is tagged with a number (e.g., 2.6, 3.4, 4.5, 6.0, 7.0, 8.5) that represents the total radiative forcing in watts per square meter (W/m^2), the extra energy that will be trapped in the climate system under that scenario, beyond pre-industrial levels.

The 2014 Climate Change in Colorado report focused on outcomes under the medium-low RCP4.5 emissions scenario, while also reporting selected results under the high-end RCP8.5 scenario. Since 2010, the year-on-year increase in global fossil-fuel CO₂ emissions—and thus total anthropogenic CO₂ emissions—has slowed such that the trajectory of those emissions through 2022 is on track with the RCP4.5 scenario, and about 20% below what the RCP8.5 scenario assumes for 2022 (*Global Carbon Project 2022*). Fossil-fuel CO₂ emissions currently represent about 90% of all CO₂ emissions from human activities, and about 70% of all anthropogenic greenhouse gas emissions. The current emissions policies enacted by the major emitting countries indicate a path of global fossil-fuel and total anthropogenic CO₂ emissions through 2050 that is more consistent with the RCP4.5 trajectory, and well below the RCP8.5 trajectory (Figure A.2; *Hausfather and Peters 2020*). While current trends are encouraging, emitting countries may reverse policies or fail to meet targets. It is also possible that the total emissions of greenhouse gases through mid-century would end up being closer to RCP8.5 even if fossil-fuel emissions track RCP4.5, if unexpectedly large carbon-cycle feedbacks occur, e.g., releases of methane from permafrost (*Schwalm et al. 2020*).

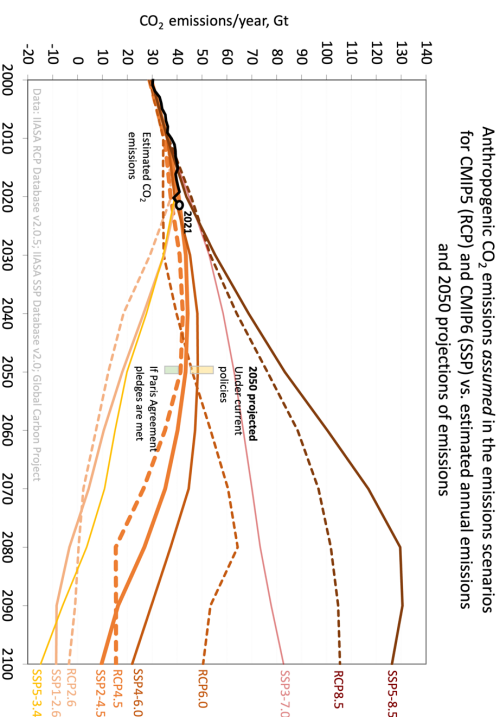


Figure A.2: Annual total anthropogenic CO₂ emissions—about 90% of which are from fossil fuel burning—assumed in the emissions scenarios used to drive climate model projections in the CMIP5 and CMIP6 ensembles. The black line shows estimated actual annual CO₂ emissions through 2021. This report focuses on projections driven by the RCP4.5 scenario (thick dashed orange) and similar SSP2-4.5 scenario (thick solid orange). (Data: IJASA RCP Database v2.0.5; IJASA SSP Database v2.0; Global Carbon Project)

As in the 2014 report, we again focus here on RCP4.5, and also SSP2-4.5, the comparable scenario used for the CMIP6 projections; both scenarios are approximately in line with the upper end of combined national pledges under the 2015 Paris Agreement (green box in Figure A.2; *IPCC 2021*). While this focus on 4.5 scenarios excludes an assessment of high-end warming outcomes seen only under RCP8.5 and its CMIP6 analog SSP5-8.5, Figures 2.6 and 2.7 showed that under the 4.5 emissions scenarios, there is still a wide range of projected warming outcomes by 2050, overlapping considerably with the range of projected warming under 8.5 scenarios. By 2070, the warming ranges under the 4.5 and 8.5 scenarios overlap less. Both of the full CMIP5 and CMIP6 datasets include projections run under scenarios that are between 4.5 and 8.5 in terms of warming outcomes (e.g., RCP6.0, SSP4-6.0, SSP3-7.0), and these should also be considered for use in future climate vulnerability assessments. The limited availability of downscaled projections under RCP6.0 meant that scenario was not used in this report.

Downscaled climate projections from GCMs

For use at spatial scales smaller than the state of Colorado, GCM output needs to be downscaled through statistical methods (statistical downscaling), or via higher-resolution regional climate models (RCMs; dynamical downscaling), in order to better represent localized changes to weather and climate and to facilitate hydrologic modeling. For this report, we used the CMIP5-LOCA (Localized Constructed Analogs) dataset developed by *Pierce et al. (2014)*. Projections from 32 CMIP5 models were statistically downscaling using the LOCA method, in which multiple daily weather patterns from the historical record are selected, adjusted, and blended in order to create fine-scale outputs that are consistent with the coarser-scale weather pattern shown for a given day in the raw GCM output. In this way, a long-term climate projection is built that is faithful to the way weather and climate vary (at least historically) across space and time at local scales.

The CMIP5-LOCA dataset was chosen among several options, including the CMIP5-BCSD (Bias-Correction Spatial Disaggregation) dataset that was used in the 2014 Report. The BCSD method has since been shown to have a statistical artifact that alters the GCM-projected precipitation change, causing “wetting” over the Interior West. Evaluations of downscaling methods have shown that LOCA imposes fewer alterations of the coarse-scale GCM change signals (*Alder and Hostetler 2019*) while increasing the level of local detail in a physically meaningful way based on past weather patterns.

The CMIP5-LOCA projections are a 1/16-degree (~6 km) grid, at a daily timestep. The full CMIP5-LOCA dataset includes 32 projections, one from each of 32 climate models, for each of two emissions scenarios, RCP4.5 and RCP8.5 (so 64 projections total). This report only analyzes the projections under RCP4.5, as discussed above.

Watershed-scale hydrology projections

To generate projections of future hydrology for basins in Colorado and elsewhere, researchers typically take the downscaled future temperature changes and precipitation changes projected by an ensemble of climate models and then run that set of plausible trajectories of future climate through a separate watershed-scale hydrologic model, such as VIC or Noah. That hydrologic model then simulates the changes in snowpack, streamflow, soil moisture, and other variables associated with each climate model’s projection of future climate: temperature change and precipitation change.

For this report, we used the set of CMIP5 global climate model (GCM) projections that were downscaled using the LOCA method and then run through the VIC (Variable Infiltration Capacity) hydrologic model. These hydrologic projections (CMIP5-LOCA-VIC) were created by NCAR researchers for a consortium led by the Bureau of Reclamation (*Vano et al. 2020*) and were previously analyzed for some basins in Colorado in *Lukas et al. (2020)* and *Reclamation (2021)*. These projections were obtained through the GDO-DCP server (<https://gdo-dcp.ucllnl.org/>)

The CMIP5-LOCA-VIC projections are on a 1/16-degree (~6 km) grid, the same resolution as the underlying CMIP5-LOCA projections, at a daily timestep.

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Anomaly

A deviation from the expected or normal value.

Bias correction

Adjustments to raw model output (e.g., from a climate model, or streamflow forecast model) using observations in a reference period.

Climate

Climate can be first defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The typical period for averaging these variables is 30 years. The most relevant variables are temperature, precipitation, humidity, atmospheric pressure and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate variability

Refers to variations in the mean state and other statistics (such as standard deviations, statistics of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).

Climatology

In forecasting and modeling, refers to the historical average climate used as a baseline (e.g., “compared to climatology”). Synonymous with climate normal.

Convection

The vertical transport of heat and moisture in the atmosphere, typically due to an air parcel rising if it is warmer than the surrounding atmosphere.

Downscaling

Method to take data at coarse scales, e.g., from a GCM, and translate those data to more local scales.

Dynamical

In modeling, refers to the use of a physical model, i.e., basic physical equations represent some or most of the relevant processes.

El Niño-Southern Oscillation (ENSO)

A coupled atmosphere-ocean phenomenon, with characteristic time scales of two to about seven years. During a warm-phase ENSO event (El Niño), the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature (SST) and precipitation patterns in the tropical Pacific. It has climatic effects on the western U.S. by influencing the position of the jet stream and storm tracks. The cold phase of ENSO, called La Niña, occurs when the trade winds strengthen, leading to colder-than-normal SSTs in the equatorial tropical Pacific.

Emissions scenarios

A plausible representation of the future emissions of substances that affect the radiative properties of the atmosphere (e.g., greenhouse gases, aerosols), based on a coherent set of assumptions about driving forces of emissions, such as demographic and socioeconomic development, technological change, and energy use. The values of the different greenhouse gases and aerosols associated with a given emission scenario are then used as inputs to a climate model to drive projections of climate under that emissions scenario. For the CMIP5 climate models, the four primary emissions scenarios are known as RCPs (Representative Concentration Pathways); for the CMIP6 climate models, there are seven SSPs (Shared Socioeconomic Pathways), four of which are roughly equivalent to those RCPs that share the same number at the end (2.6, 4.5, 6.0, 8.5).

Evapotranspiration

The aggregate of evaporation from the land surface and water bodies and transpiration of water from plant surfaces to the atmosphere. Generally, it includes sublimation from the snow surface as well.

Forcing – see radiative forcing**Global climate models (GCMs)**

Complex, computer-based, mathematical representations of the Earth’s climate system based on fundamental scientific principles. They are designed to capture the dynamics and interactions of the main components of the climate system: atmosphere, oceans, land surface and vegetation, sea ice, land ice. GCMs provide realistic simulations of the key physical phenomena at global down to continental scales, including planetary energy balance; large-scale atmospheric and oceanic circulation (like ENSO); broad-scale patterns of temperature and precipitation; and the statistical characteristics of the historical and current climate. Also known as Earth system models (ESMs).

Greenhouse effect

Greenhouse gases in the lower atmosphere effectively absorb and re-emit longwave (infrared) radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. The re-emitted radiation (i.e., heat) is emitted to all sides, including downward to the Earth's surface. Thus, greenhouse gases trap heat within the surface-atmosphere system, causing the Earth's surface and lower atmosphere to be about 57°F warmer than without the action of the greenhouse gases. This is called the (natural) greenhouse effect. An increase in the concentration of greenhouse gases leads to the greater absorption and re-emission of infrared radiation, and so more heat is trapped. This radiative forcing leads to an enhancement of the greenhouse effect and even warmer temperatures at the Earth's surface and in the lower atmosphere.

Greenhouse gases

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of longwave (infrared) radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapor (H₂O), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and ozone (O₃) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons (HFCs and PFCs) and other chlorine- and bromine-containing substances.

Gridded data

Data that is represented in a two-dimensional gridded matrix of graphical contours, interpolated or otherwise derived from a set of point observations.

Humidity

Typically expressed as relative humidity (RH). The amount of moisture in the atmosphere relative to the amount that would be present if the air were saturated. RH is expressed in percent (%) and is a function of both moisture content and air temperature. Absolute humidity is the amount of moisture in a volume of air (e.g., g/m²), without consideration of the air temperature.

Hydrograph

A graph of the volume of water flowing past a location per unit time (hours, days, or months)

IPCC

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by World Meteorological Organization (WMO) and United Nations Environmental Programme (UNEP) to provide an assessment of the state of knowledge on climate change based on peer-reviewed and published scientific/technical literature in regular time intervals. The IPCC Sixth Assessment Report (AR6) was released in 2021 and 2022.

Internal variability

Variability in climate that comes from chaotic and unpredictable fluctuations of the Earth's oceans and atmosphere. Synonymous with natural variability

Jet stream

A narrow band of very strong winds in the upper atmosphere that follows the boundary between warmer and colder air masses; low-pressure systems preferentially form along the jet stream and then their motion is guided by the jet stream (i.e., storm track)

Megadrought

A sustained and widespread drought that lasts at least 10-15 years.

Mid-latitude cyclonic storm

A common, large (~500-2000 km) storm system that has a low-pressure center, cyclonic (counterclockwise) flow, and a cold front. Over Colorado, mid-latitude cyclones almost always move from west to east and are effective at producing precipitation over broad areas, mainly between October and May.

Natural flow

Gaged flow that has been adjusted to remove the effects of upstream human activity such as storage or diversion. Equivalent to naturalized flow, virgin flow, and undepleted flow.

Orographic lift

A process in which air is forced to rise and subsequently cool due to physical barriers such as hills or mountains. This mechanism leads to increased condensation and precipitation over higher terrain.

Projection

A long-term (typically 10-100 years) forecast of future climate or hydrology that is contingent on specified other conditions occurring during the forecast period, typically a particular scenario of greenhouse gas emissions. The contingent condition is what differentiates a projection from a forecast, which has no conditions and is typically for a shorter term.

Percentile

A measure of where a particular observation or projection falls within a larger set of data; an observation in the 10th percentile is larger than only 10% all other observations in the dataset, and smaller than 90% of the observations. The median is the 50th percentile; there are equal numbers of observations larger and smaller than the median.

Radiative forcing

A factor causing a difference between the incoming and outgoing energy of the Earth's climate system, e.g., increases in greenhouse-gas concentrations. Synonymous with climate forcing.

Reanalysis

An analysis of historical climate or hydrologic conditions that assimilates observed data into a modeling environment to produce consistent fields of variables over the entire period of analysis.

Reference ET (evapotranspiration)

An estimate of the upper bound of evapotranspiration losses from irrigated croplands, and thereby the water need for irrigation. Equivalent to potential evapotranspiration (PET).

Resolution

Typically refers to the level of spatial detail in model output or other data; the ability to distinguish two points as separate and depict small features. Equivalent to grid cell size.

Runoff

Precipitation that flows toward streams on the surface of the ground or within the ground. Runoff as it is routed and measured within channels is streamflow.

Runoff efficiency

The fraction of annual precipitation in a basin or other area that becomes runoff, i.e., not lost through evapotranspiration.

Solar radiation

Incoming radiation from the sun, consisting of visible (i.e., sunlight), near-ultraviolet, and near-infrared spectra, with wavelengths between 0.2 and 3.0 micrometers. Also known as shortwave radiation, distinguishing it from longwave radiation, which is absorbed energy re-radiated from the Earth's surface at longer wavelengths.

Snow water equivalent (SWE)

The depth, often expressed in inches, of liquid water contained within the snowpack that would theoretically result if one were to melt the snowpack instantaneously.

SNOTEL

An instrumented site with both weather instruments and a snow pillow that provides a value of the water equivalent of snow that has accumulated on it (SWE); typically, the pillow contains antifreeze and has a pressure sensor that measures the weight pressing down on the pillow.

Streamflow

Water flow within a river channel, typically expressed in cubic feet per second for flow rate, or in acre-feet for flow volume. Synonymous with discharge.

Sublimation

When water (i.e., snow and ice) or another substance transitions from the solid phase to the vapor phase without going through the intermediate liquid phase; a major source of snowpack loss over the course of the season.

Transpiration

Water vapor discharged into the atmosphere from the leaf surfaces of plants.

Acronym List

AET	Actual Evapotranspiration		
AWSSI	Accumulated Winter Season Severity Index		
BCSD	Bias-Corrected Spatially Disaggregated [downscaling method]		
C-C	Clausius-Clapeyron [equation]		
CMIP3	Coupled Model Intercomparison Project – Phase 3		
CMIP5	Coupled Model Intercomparison Project – Phase 5 (there was no Phase 4)		
CMIP6	Coupled Model Intercomparison Project – Phase 6		
CWCB	Colorado Water Conservation Board		
DWR	[Colorado] Division of Water Resources		
EC	Eddy Covariance		
EDDI	Evaporative Demand Drought Index		
EF-[0...5]	Enhanced Fujita [scale for tornado severity]		
ENSO	El Niño-Southern Oscillation		
ET	Evapotranspiration		
GCM	Global climate model		
GDO-DCP	Green Data Oasis – Downscaled Climate Projections [web portal]		
gridMET	Gridded Surface Meteorological [climate dataset]		
GHG	Greenhouse Gas		
IIASA	International Institute for Applied Systems Analysis		
IPCC	Intergovernmental Panel on Climate Change		
KNMI	Royal Netherlands Meteorological Institute		
LLNL	Lawrence Livermore National Laboratory		
LOCA	Localized Constructed Analogs [downscaling method]		
MACA	Multivariate Adaptive Constructed Analogs [downscaling method]		
		MCS	Mesoscale Convective System
		NARCCAP	North American Regional Climate Change Assessment Project
		NCA	National Climate Assessment
		NCAR	National Center for Atmospheric Research
		NCEI	National Center for Environmental Information (at NOAA)
		nclimGrid	NOAA U.S. Climate Gridded Dataset
		NLDAS	North American Land Data Assimilation System
		NOAA	National Oceanic and Atmospheric Administration
		NRCS	Natural Resource Conservation Service
		NWS	National Weather Service
		PET	Potential Evapotranspiration
		PDSI	Palmer Drought Severity Index
		PW	Precipitable Water
		RCM	Regional Climate Model
		RCP	Representative Concentration Pathway
		SNOTEL	Snowpack Telemetry
		SPEI	Standardized Precipitation-Evapotranspiration Index
		SPI	Standardized Precipitation Index
		SRES	Special Report on Emissions Scenarios
		SSP	Shared Societal Pathway
		SWE	Snow Water Equivalent
		USGCRP	United States Global Change Research Program
		VIC	Variable Infiltration Capacity [hydrology model]
		VPD	Vapor Pressure Deficit

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About the Colorado Climate Center

The Colorado Climate Center is located at Colorado State University within the Department of Atmospheric Science. With the support of the Agricultural Experiment Station, it is the Center's privilege and duty to provide services and expertise related to Colorado's complex climate.

As a recognized State Climate Office, the Center strives to collect and observe data with the purpose of monitoring the climate, placing individual events into historical perspective, disseminating climate information to the user community, and providing climate expertise as part of the decision-making process.



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Call for emergency action to limit global temperature increases, restore biodiversity, and protect health



The UN General Assembly in September, 2021, will bring countries together at a critical time for marshalling collective action to tackle the global environmental crisis. They will meet again at the biodiversity summit in Kunming, China, and the UN Climate Change Conference of the Parties (COP26) in Glasgow, UK. Ahead of these pivotal meetings, we—the editors of health journals worldwide—call for urgent action to keep average global temperature increases below 1.5°C, halt the destruction of nature, and protect health.

Health is already being harmed by global temperature increases and the destruction of the natural world, a state of affairs health professionals have been bringing attention to for decades.¹ The science is unequivocal; a global increase of 1.5°C above the pre-industrial average and the continued loss of biodiversity risk catastrophic harm to health that will be impossible to reverse.^{2,3} Despite the world's necessary preoccupation with COVID-19, we cannot wait for the pandemic to pass to rapidly reduce emissions.

Reflecting the severity of the moment, this Comment appears in health journals across the world. We are united in recognising that only fundamental and equitable changes to societies will reverse our current trajectory.

The risks to health of increases above 1.5°C are now well established.² Indeed, no temperature rise is “safe”. In the past 20 years, heat-related mortality among people older than 65 years has increased by more than 50%.⁴ Higher temperatures have brought increased dehydration and

renal function loss, dermatological malignancies, tropical infections, adverse mental health outcomes, pregnancy complications, allergies, and cardiovascular and pulmonary morbidity and mortality.^{5,6} Harms disproportionately affect the most vulnerable, including children, older populations, ethnic minorities, poorer communities, and those with underlying health problems.^{2,4}

Global heating is also contributing to the decline in global yield potential for major crops, falling by 1.8–5.6% since 1981; this, together with the effects of extreme weather and soil depletion, is hampering efforts to reduce undernutrition.⁴ Thriving ecosystems are essential to human health, and the widespread destruction of nature, including habitats and species, is eroding water and food security and increasing the chance of pandemics.^{3,7,8}

The consequences of the environmental crisis fall disproportionately on those countries and communities that have contributed least to the problem and are least able to mitigate the harms. Yet no country, no matter how wealthy, can shield itself from these impacts. Allowing the consequences to fall disproportionately on the most vulnerable will breed more conflict, food insecurity, forced displacement, and zoonotic disease—with severe implications for all countries and communities. As with the COVID-19 pandemic, we are globally as strong as our weakest member.

Rises above 1.5°C increase the chance of reaching tipping points in natural systems that could lock the

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world into an acutely unstable state. This would critically impair our ability to mitigate harms and to prevent catastrophic, runaway environmental change.^{9,10}

Encouragingly, many governments, financial institutions, and businesses are setting targets to reach net-zero emissions, including targets for 2030. The cost of renewable energy is dropping rapidly. Many countries are aiming to protect at least 30% of the world's land and oceans by 2030.¹¹

These promises are not enough. Targets are easy to set and hard to achieve. They are yet to be matched with credible short-term and longer-term plans to accelerate cleaner technologies and transform societies. Emissions reduction plans do not adequately incorporate health considerations.¹² Concern is growing that temperature rises above 1.5°C are beginning to be seen as inevitable, or even acceptable, to powerful members of the global community.¹³ Relatedly, current strategies for reducing emissions to net zero by the middle of the 21st century implausibly assume that the world will acquire great capabilities to remove greenhouse gases from the atmosphere.^{14,15}

This insufficient action means that temperature increases are likely to be well in excess of 2°C,¹⁶ a catastrophic outcome for health and environmental stability. Crucially, the destruction of nature does not have parity of esteem with the climate element of the crisis, and every single global target to restore biodiversity loss by 2020 was missed.¹⁷ This is an overall environmental crisis.¹⁸

Health professionals are united with environmental scientists, businesses, and many others in rejecting that this outcome is inevitable. More can and must be done now—in Glasgow and Kunming—and in the immediate years that follow. We join health professionals worldwide who have already supported calls for rapid action.^{1,19}

Equity must be at the centre of the global response. Contributing a fair share to the global effort means that reduction commitments must account for the cumulative, historical contribution each country has made to emissions, as well as its current emissions and capacity to respond. Wealthier countries will have to cut emissions more quickly, making reductions by 2030 beyond those currently proposed^{20,21} and reaching net-zero emissions before 2050. Similar targets and emergency action are needed for biodiversity loss and the wider destruction of the natural world.

To achieve these targets, governments must make fundamental changes to how our societies and economies are organised and how we live. The current strategy of encouraging markets to swap dirty for cleaner technologies is not enough. Governments must intervene to support the redesign of transport systems, cities, production and distribution of food, markets for financial investments, health systems, and much more. Global coordination is needed to ensure that the rush for cleaner technologies does not come at the cost of more environmental destruction and human exploitation.

Many governments met the threat of the COVID-19 pandemic with unprecedented funding. The environmental crisis demands a similar emergency response. Huge investment will be needed, beyond what is being considered or delivered anywhere in the world. But such investments will produce huge positive health and economic outcomes. These include high quality jobs, reduced air pollution, increased physical activity, and improved housing and diet. Better air quality alone would realise health benefits that easily offset the global costs of emissions reductions.²²

These measures will also improve the social and economic determinants of health, the poor state of which may have made populations more vulnerable to the COVID-19 pandemic.²³ But the changes cannot be achieved through a return to damaging austerity policies or the continuation of the large inequalities of wealth and power within and between countries.

In particular, countries that have disproportionately created the environmental crisis must do more to support low-income and middle-income countries to build cleaner, healthier, and more resilient societies. High-income countries must meet and go beyond their outstanding commitment to provide US\$100 billion a year, making up for any shortfall in 2020 and increasing contributions to and beyond 2025. Funding must be equally split between mitigation and adaptation, including improving the resilience of health systems.

Financing should be through grants rather than loans, building local capabilities and truly empowering communities, and should come alongside forgiving large debts, which constrain the agency of so many low-income countries. Additional funding must be marshalled to compensate for inevitable loss and damage caused by the consequences of the environmental crisis.

As health professionals, we must do all we can to aid the transition to a sustainable, fairer, resilient, and healthier world. Alongside acting to reduce the harm from the environmental crisis, we should proactively contribute to global prevention of further damage and action on the root causes of the crisis. We must hold global leaders to account and continue to educate others about the health risks of the crisis. We must join in the work to achieve environmentally sustainable health systems before 2040, recognising that this will mean changing clinical practice. Health institutions have already divested more than \$42 billion of assets from fossil fuels; others should join them.⁴

The greatest threat to global public health is the continued failure of world leaders to keep the global temperature rise below 1.5°C and to restore nature. Urgent, society-wide changes must be made and will lead to a fairer and healthier world. We, as editors of health journals, call for governments and other leaders to act, marking 2021 as the year that the world finally changes course.

FG serves on the executive committee for the UK Health Alliance on Climate Change and is a Trustee of the Eden Project. RS is the Chair of Patients Know Best, has stock in UnitedHealth Group, has done consultancy work for Oxford Pharmagenesis, and is chair of the *Lancet* Commission of the Value of Death. The other authors declare no competing interests.

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This Comment is being published simultaneously in the multiple journals (appendix). This full list of journals, as well as a further list of supporting journals, can also be found on the BMJ website.

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See Online for appendix

For the full list of journals and supporting journals see <https://www.bmj.com/content/full-list-authors-and-signatories-climate-emergency-editorial-september-2021>

World Scientists' Warning of a Climate Emergency

WILLIAM J. RIPPLE, CHRISTOPHER WOLF, THOMAS M. NEWSOME, PHOEBE BARNARD, WILLIAM R. MOOMAW, AND 11,258 SCIENTIST SIGNATORIES FROM 153 COUNTRIES (LIST IN SUPPLEMENTAL FILE S1)

Scientists have a moral obligation to clearly warn humanity of any catastrophic threat and to “tell it like it is.” On the basis of this obligation and the graphical indicators presented below, we declare, with more than 11,000 scientist signatories from around the world, clearly and unequivocally that planet Earth is facing a climate emergency.

Exactly 40 years ago, scientists from 50 nations met at the First World Climate Conference (in Geneva 1979) and agreed that alarming trends for climate change made it urgently necessary to act. Since then, similar alarms have been made through the 1992 Rio Summit, the 1997 Kyoto Protocol, and the 2015 Paris Agreement, as well as scores of other global assemblies and scientists' explicit warnings of insufficient progress (Ripple et al. 2017). Yet greenhouse gas (GHG) emissions are still rapidly rising, with increasingly damaging effects on the Earth's climate. An immense increase of scale in endeavors to conserve our biosphere is needed to avoid untold suffering due to the climate crisis (IPCC 2018).

Most public discussions on climate change are based on global surface temperature only, an inadequate measure to capture the breadth of human activities and the real dangers stemming from a warming planet (Briggs et al. 2015). Policymakers and the public now urgently need access to a set of indicators that convey the effects of human activities on GHG emissions and the consequent impacts on climate, our environment, and society. Building on prior work (see supplemental file S2), we present a suite of graphical vital signs of climate change over the last 40 years for human activities that can affect GHG emissions and change the climate (figure 1), as well

as actual climatic impacts (figure 2). We use only relevant data sets that are clear, understandable, systematically collected for at least the last 5 years, and updated at least annually.

The climate crisis is closely linked to excessive consumption of the wealthy lifestyle. The most affluent countries are mainly responsible for the historical GHG emissions and generally have the greatest per capita emissions (table S1). In the present article, we show general patterns, mostly at the global scale, because there are many climate efforts that involve individual regions and countries. Our vital signs are designed to be useful to the public, policymakers, the business community, and those working to implement the Paris climate agreement, the United Nations' Sustainable Development Goals, and the Aichi Biodiversity Targets.

Profoundly troubling signs from human activities include sustained increases in both human and ruminant livestock populations, per capita meat production, world gross domestic product, global tree cover loss, fossil fuel consumption, the number of air passengers carried, carbon dioxide (CO₂) emissions, and per capita CO₂ emissions since 2000 (figure 1, supplemental file S2). Encouraging signs include decreases in global fertility (birth) rates (figure 1b), decelerated forest loss in the Brazilian Amazon (figure 1g), increases in the consumption of solar and wind power (figure 1h), institutional fossil fuel divestment of more than US\$7 trillion (figure 1j), and the proportion of GHG emissions covered by carbon pricing (figure 1m). However, the decline in human fertility rates has substantially slowed during the last 20 years (figure 1b), and the pace of

forest loss in Brazil's Amazon has now started to increase again (figure 1g). Consumption of solar and wind energy has increased 373% per decade, but in 2018, it was still 28 times smaller than fossil fuel consumption (combined gas, coal, oil; figure 1h). As of 2018, approximately 14.0% of global GHG emissions were covered by carbon pricing (figure 1m), but the global emissions-weighted average price per tonne of carbon dioxide was only around US\$15.25 (figure 1n). A much higher carbon fee price is needed (IPCC 2018, section 2.5.2.1). Annual fossil fuel subsidies to energy companies have been fluctuating, and because of a recent spike, they were greater than US\$400 billion in 2018 (figure 1o).

Especially disturbing are concurrent trends in the vital signs of climatic impacts (figure 2, supplemental file S2). Three abundant atmospheric GHGs (CO₂, methane, and nitrous oxide) continue to increase (see figure S1 for ominous 2019 spike in CO₂), as does global surface temperature (figure 2a–2d). Globally, ice has been rapidly disappearing, evidenced by declining trends in minimum summer Arctic sea ice, Greenland and Antarctic ice sheets, and glacier thickness worldwide (figure 2e–2h). Ocean heat content, ocean acidity, sea level, area burned in the United States, and extreme weather and associated damage costs have all been trending upward (figure 2i–2n). Climate change is predicted to greatly affect marine, freshwater, and terrestrial life, from plankton and corals to fishes and forests (IPCC 2018, 2019). These issues highlight the urgent need for action.

Despite 40 years of global climate negotiations, with few exceptions, we have generally conducted business

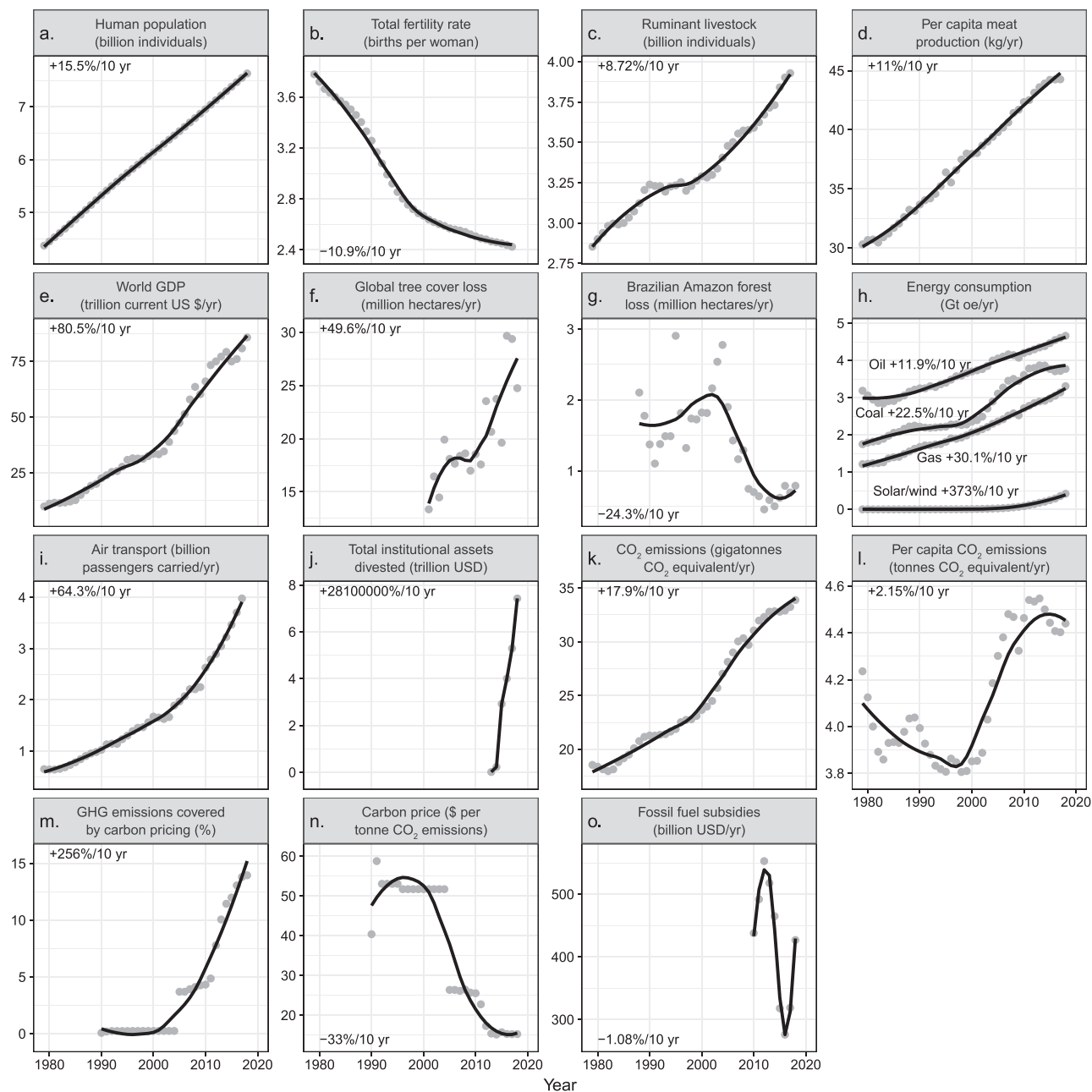


Figure 1. Change in global human activities from 1979 to the present. These indicators are linked at least in part to climate change. In panel (f), annual tree cover loss may be for any reason (e.g., wildfire, harvest within tree plantations, or conversion of forests to agricultural land). Forest gain is not involved in the calculation of tree cover loss. In panel (h), hydroelectricity and nuclear energy are shown in figure S2. The rates shown in panels are the percentage changes per decade across the entire range of the time series. The annual data are shown using gray points. The black lines are local regression smooth trend lines. Abbreviation: Gt oe per year, gigatonnes of oil equivalent per year. Sources and additional details about each variable are provided in supplemental file S2, including table S2.

as usual and have largely failed to address this predicament (figure 1). The climate crisis has arrived and is accelerating faster than most scientists expected (figure 2, IPCC 2018). It is

more severe than anticipated, threatening natural ecosystems and the fate of humanity (IPCC 2019). Especially worrisome are potential irreversible climate tipping points and nature's

reinforcing feedbacks (atmospheric, marine, and terrestrial) that could lead to a catastrophic "hothouse Earth," well beyond the control of humans (Steffen et al. 2018). These climate

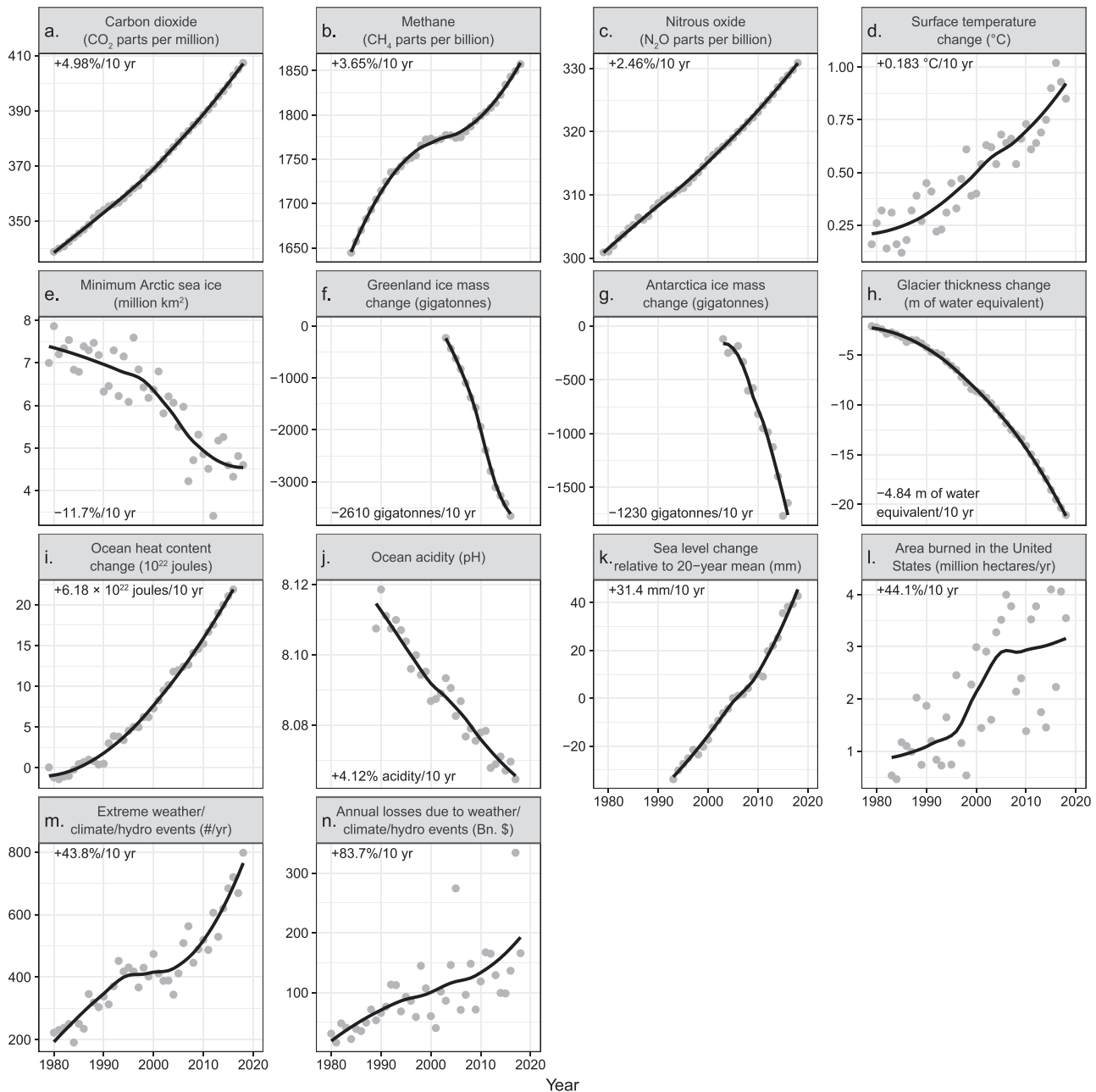


Figure 2. Climatic response time series from 1979 to the present. The rates shown in the panels are the decadal change rates for the entire ranges of the time series. These rates are in percentage terms, except for the interval variables (d, f, g, h, i, k), where additive changes are reported instead. For ocean acidity (pH), the percentage rate is based on the change in hydrogen ion activity, a_{H^+} (where lower pH values represent greater acidity). The annual data are shown using gray points. The black lines are local regression smooth trend lines. Sources and additional details about each variable are provided in supplemental file S2, including table S3.

chain reactions could cause significant disruptions to ecosystems, society, and economies, potentially making large areas of Earth uninhabitable.

To secure a sustainable future, we must change how we live, in ways that

improve the vital signs summarized by our graphs. Economic and population growth are among the most important drivers of increases in CO_2 emissions from fossil fuel combustion (Pachauri et al. 2014, Bongaarts and

O'Neill 2018); therefore, we need bold and drastic transformations regarding economic and population policies. We suggest six critical and interrelated steps (in no particular order) that governments, businesses, and the rest of

humanity can take to lessen the worst effects of climate change. These are important steps but are not the only actions needed or possible (Pachauri et al. 2014, IPCC 2018, 2019).

Energy

The world must quickly implement massive energy efficiency and conservation practices and must replace fossil fuels with low-carbon renewables (figure 1h) and other cleaner sources of energy if safe for people and the environment (figure S2). We should leave remaining stocks of fossil fuels in the ground (see the timelines in IPCC 2018) and should carefully pursue effective negative emissions using technology such as carbon extraction from the source and capture from the air and especially by enhancing natural systems (see “Nature” section). Wealthier countries need to support poorer nations in transitioning away from fossil fuels. We must swiftly eliminate subsidies for fossil fuels (figure 1o) and use effective and fair policies for steadily escalating carbon prices to restrain their use.

Short-lived pollutants

We need to promptly reduce the emissions of short-lived climate pollutants, including methane (figure 2b), black carbon (soot), and hydrofluorocarbons (HFCs). Doing this could slow climate feedback loops and potentially reduce the short-term warming trend by more than 50% over the next few decades while saving millions of lives and increasing crop yields due to reduced air pollution (Shindell et al. 2017). The 2016 Kigali amendment to phase down HFCs is welcomed.

Nature

We must protect and restore Earth’s ecosystems. Phytoplankton, coral reefs, forests, savannas, grasslands, wetlands, peatlands, soils, mangroves, and sea grasses contribute greatly to sequestration of atmospheric CO₂. Marine and terrestrial plants, animals, and microorganisms play significant roles in carbon and nutrient cycling and storage.

We need to quickly curtail habitat and biodiversity loss (figure 1f–1g), protecting the remaining primary and intact forests, especially those with high carbon stores and other forests with the capacity to rapidly sequester carbon (proforestation), while increasing reforestation and afforestation where appropriate at enormous scales. Although available land may be limiting in places, up to a third of emissions reductions needed by 2030 for the Paris agreement (less than 2°C) could be obtained with these natural climate solutions (Griscom et al. 2017).

Food

Eating mostly plant-based foods while reducing the global consumption of animal products (figure 1c–d), especially ruminant livestock (Ripple et al. 2014), can improve human health and significantly lower GHG emissions (including methane in the “Short-lived pollutants” step). Moreover, this will free up croplands for growing much-needed human plant food instead of livestock feed, while releasing some grazing land to support natural climate solutions (see “Nature” section). Cropping practices such as minimum tillage that increase soil carbon are vitally important. We need to drastically reduce the enormous amount of food waste around the world.

Economy

Excessive extraction of materials and overexploitation of ecosystems, driven by economic growth, must be quickly curtailed to maintain long-term sustainability of the biosphere. We need a carbon-free economy that explicitly addresses human dependence on the biosphere and policies that guide economic decisions accordingly. Our goals need to shift from GDP growth and the pursuit of affluence toward sustaining ecosystems and improving human well-being by prioritizing basic needs and reducing inequality.

Population

Still increasing by roughly 80 million people per year, or more than 200,000 per day (figure 1a–b), the world

population must be stabilized—and, ideally, gradually reduced—within a framework that ensures social integrity. There are proven and effective policies that strengthen human rights while lowering fertility rates and lessening the impacts of population growth on GHG emissions and biodiversity loss. These policies make family-planning services available to all people, remove barriers to their access and achieve full gender equity, including primary and secondary education as a global norm for all, especially girls and young women (Bongaarts and O’Neill 2018).

Conclusions

Mitigating and adapting to climate change while honoring the diversity of humans entails major transformations in the ways our global society functions and interacts with natural ecosystems. We are encouraged by a recent surge of concern. Governmental bodies are making climate emergency declarations. Schoolchildren are striking. Ecocide lawsuits are proceeding in the courts. Grassroots citizen movements are demanding change, and many countries, states and provinces, cities, and businesses are responding.

As the Alliance of World Scientists, we stand ready to assist decision-makers in a just transition to a sustainable and equitable future. We urge widespread use of vital signs, which will better allow policymakers, the private sector, and the public to understand the magnitude of this crisis, track progress, and realign priorities for alleviating climate change. The good news is that such transformative change, with social and economic justice for all, promises far greater human well-being than does business as usual. We believe that the prospects will be greatest if decision-makers and all of humanity promptly respond to this warning and declaration of a climate emergency and act to sustain life on planet Earth, our only home.

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Project website

To view the Alliance of World Scientists website or to sign this article, go to <https://scientistwarning.forestry.oregonstate.edu>.

Supplemental material

Supplemental data are available at *BIOSCI* online. A list of the signatories appears in supplemental file S1.

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The 2023 state of the climate report: Entering uncharted territory

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Life on planet Earth is under siege. We are now in an uncharted territory. For several decades, scientists have consistently warned of a future marked by extreme climatic conditions because of escalating global temperatures caused by ongoing human activities that release harmful greenhouse gases into the atmosphere. Unfortunately, time is up. We are seeing the manifestation of those predictions as an alarming and unprecedented succession of climate records are broken, causing profoundly distressing scenes of suffering to unfold. We are entering an unfamiliar domain regarding our climate crisis, a situation no one has ever witnessed firsthand in the history of humanity.

In the present report, we display a diverse set of vital signs of the planet and the potential drivers of climate change and climate-related responses first presented by Ripple and Wolf and colleagues (2020), who declared a climate emergency, now with more than 15,000 scientist signatories. The trends reveal new all-time climate-related records and deeply concerning patterns of climate-related disasters. At the same time, we report minimal progress by humanity in combating climate change. Given these distressing developments, our goal is to communicate climate facts and policy recommendations to scientists, policymakers, and the public. It is the moral duty of us scientists and our institutions to clearly alert humanity of any potential existential threat and to show leadership in taking action. This report is part of our series of concise and easily accessible yearly updates on the state of the climate crisis.

Climate-related all-time records

In 2023, we witnessed an extraordinary series of climate-related records being broken around the world. The rapid pace of change has surprised scientists and caused concern about the dangers of extreme weather, risky climate feedback loops, and the approach of damaging tipping points sooner than expected (Armstrong McKay et al. 2022, Ripple et al. 2023). This year,

exceptional heat waves have swept across the world, leading to record high temperatures. The oceans have been historically warm, with global and North Atlantic sea surface temperatures both breaking records and unprecedented low levels of sea ice surrounding Antarctica (figure 1a–1d). In addition, June through August of this year was the warmest period ever recorded, and in early July, we witnessed Earth's highest global daily average surface temperature ever measured, possibly the warmest temperature on Earth over the past 100,000 years (figure 1e). It is a sign that we are pushing our planetary systems into dangerous instability.

We are venturing into uncharted climate territory. Global daily mean temperatures never exceeded 1.5-degree Celsius (°C) above preindustrial levels prior to 2000 and have only occasionally exceeded that number since then. However, 2023 has already seen 38 days with global average temperatures above 1.5°C by 12 September—more than any other year—and the total may continue to rise. Even more striking are the enormous margins by which 2023 conditions are exceeding past extremes (figure 1). Similarly, on 7 July 2023, Antarctic sea ice reached its lowest daily relative extent since the advent of satellite data, at 2.67 million square kilometers below the 1991–2023 average (figure 1a). Other variables far outside their historical ranges include the area burned by wildfires in Canada (figure 1f), which may indicate a tipping point into a new fire regime.

Anthropogenic global heating is a key driver of many of these recent extremes. However, the specific driving processes involved can be quite complex. For example, rising Atlantic ocean temperatures may be connected to Sahel rainfall and African dust (Wang et al. 2012). Another potential contributor is water vapor (a greenhouse gas) injected into the stratosphere by an underwater volcano eruption (Jenkins et al. 2023). The recent rise may also be linked to a regulatory change mandating the use of low-sulfur fuels in ocean shipping, because atmospheric sulfate aerosols directly scatter sunlight and cause reflective clouds to form

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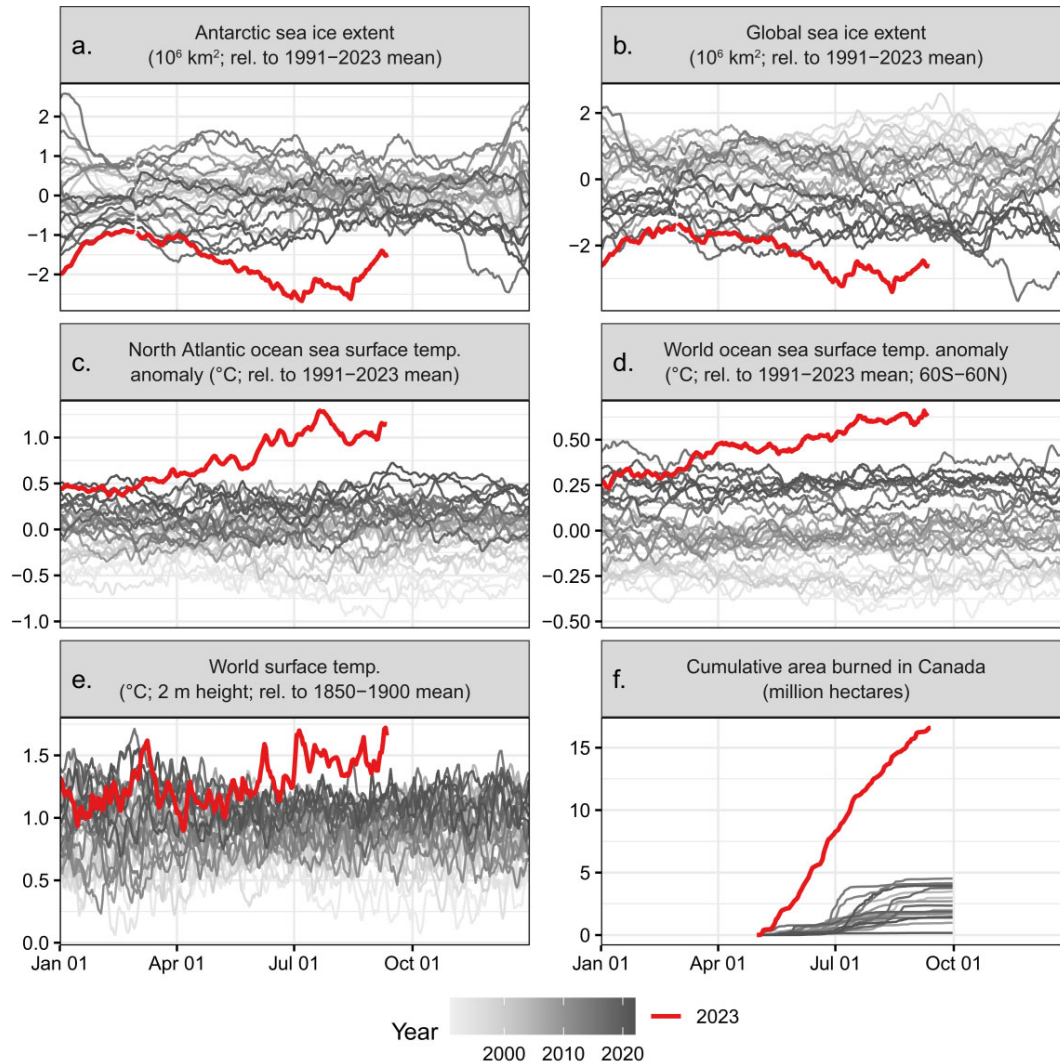


Figure 1. Unusual climate anomalies in 2023 (the red line, which appears bold in print). Sea ice extent (a, b), temperatures (c–e), and area burned in Canada (f) are presently far outside their historical ranges. These anomalies may be due to both climate change and other factors. Sources and additional details about each variable are provided in [supplemental file S1](#). Each line corresponds to a different year, with darker gray representing later years.

(see [supplemental file S1](#) for an extended discussion). The sudden rise in temperatures is also likely contributed to by the onset of an El Niño event—a naturally occurring part of the climate system, which could, itself, be affected by climate change (Cai et al. 2021). In any case, as Earth’s climate system transitions away from conditions associated with human thriving, such anomalies may become more frequent and could have increasingly catastrophic impacts (Xu et al. 2020, Lenton et al. 2023).

Recent trends in planetary vital signs

On the basis of time series data, 20 of the 35 vital signs are now showing record extremes (figures 2 and 3, [supplemental table S1](#)). As we describe below, these data show how the continued pursuit of business as usual has, ironically, led to unprecedented pressure on the Earth system, resulting in many climate-related variables entering uncharted territory (figures 1 and 3).

Energy

It appears the green recovery following COVID-19 that many had hoped for has largely failed to materialize (Zhang et al. 2023). Instead, carbon emissions have continued soaring, and fossil fuels remain dominant, with annual coal consumption reaching a near all-time high of 161.5 exajoules in 2022 (figure 2h). Although the consumption of renewable energy (solar and wind) grew a robust 17% between 2021 and 2022, it remains roughly 15 times lower than fossil fuel energy consumption (figure 2h). A major driver of economic and energy trends is Russia’s ongoing invasion of Ukraine, which has accelerated the transition to renewables in Europe but which may also cause some countries to switch from Russian-supplied gas to coal (Tollefson 2022). Already, this conflict has contributed to a massive 107% increase in fossil fuel subsidies from US\$531 billion in 2021 to US\$1097 billion in 2022 because of rising energy prices (figure 2o). Although these subsidies may partially protect consumers from price increases, they are often not well targeted and help to promote fossil fuel related energy use and profits over low-carbon alternatives (Muta and Erdogan 2023).

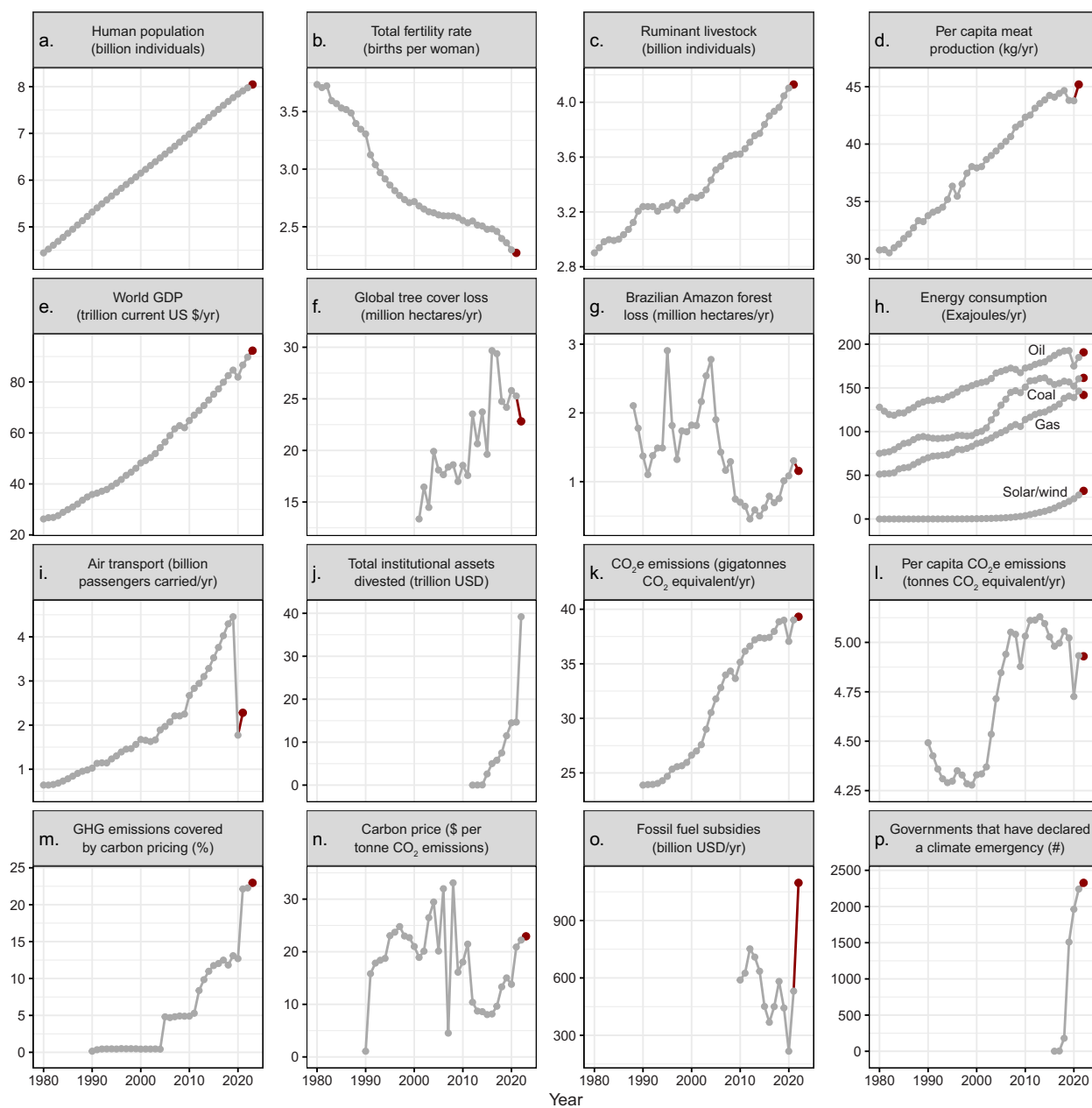


Figure 2. Time series of climate-related human activities. Data obtained since the publication of Ripple and colleagues (2021) are shown in red (dark gray in print). In panel (f), tree cover loss does not account for forest gain and includes a loss due to any cause. For panel (h), hydroelectricity and nuclear energy are shown in [figure S1](#). Sources and additional details about each variable are provided in [supplemental file S1](#).

Forests

Between 2021 and 2022, the global tree cover loss rate declined 9.7% to 22.8 million hectares (ha) per year (figure 2f). Similarly, the Brazilian Amazon forest loss rate decreased by 11.3% to 1.16 million ha per year (figure 2g), and further reductions are likely to occur as a result of the election of a new president of Brazil and several recent legal decrees (Vilani et al. 2023). However, humanity is not on track to end and reverse deforestation by 2030, despite pledges by more than 100 world leaders in 2021 at COP26 (UNEP 2022a). Moreover, forests are increasingly threatened by powerful climate feedback loops involving processes such as insect damage, dieback, and wildfire (Flores and Staal 2022, Ripple et al. 2023). For example, the historical record-setting wildfires in Canada, which burned 16.6 million hectares this year as of 13 September

(figure 1f), were partly related to climate change. This resulted in emissions of more than a gigaton of carbon dioxide (Copernicus 2023), which is substantial, given that Canada's total greenhouse gas emissions in 2021 were roughly 0.67 gigatons of carbon dioxide equivalent (Environment and Climate Change Canada 2023). How quickly such emissions can be reabsorbed by postfire recovery is uncertain, and there is a real risk that increasing fire severity will cause unrecoverable carbon loss in a warming future (Bowman et al. 2021).

Global mean greenhouse gases and temperature

On the basis of year-to-date statistics for 2023, three important greenhouse gases—carbon dioxide, methane, and nitrous oxide—are all at record levels (figure 3a–3c). The global average carbon

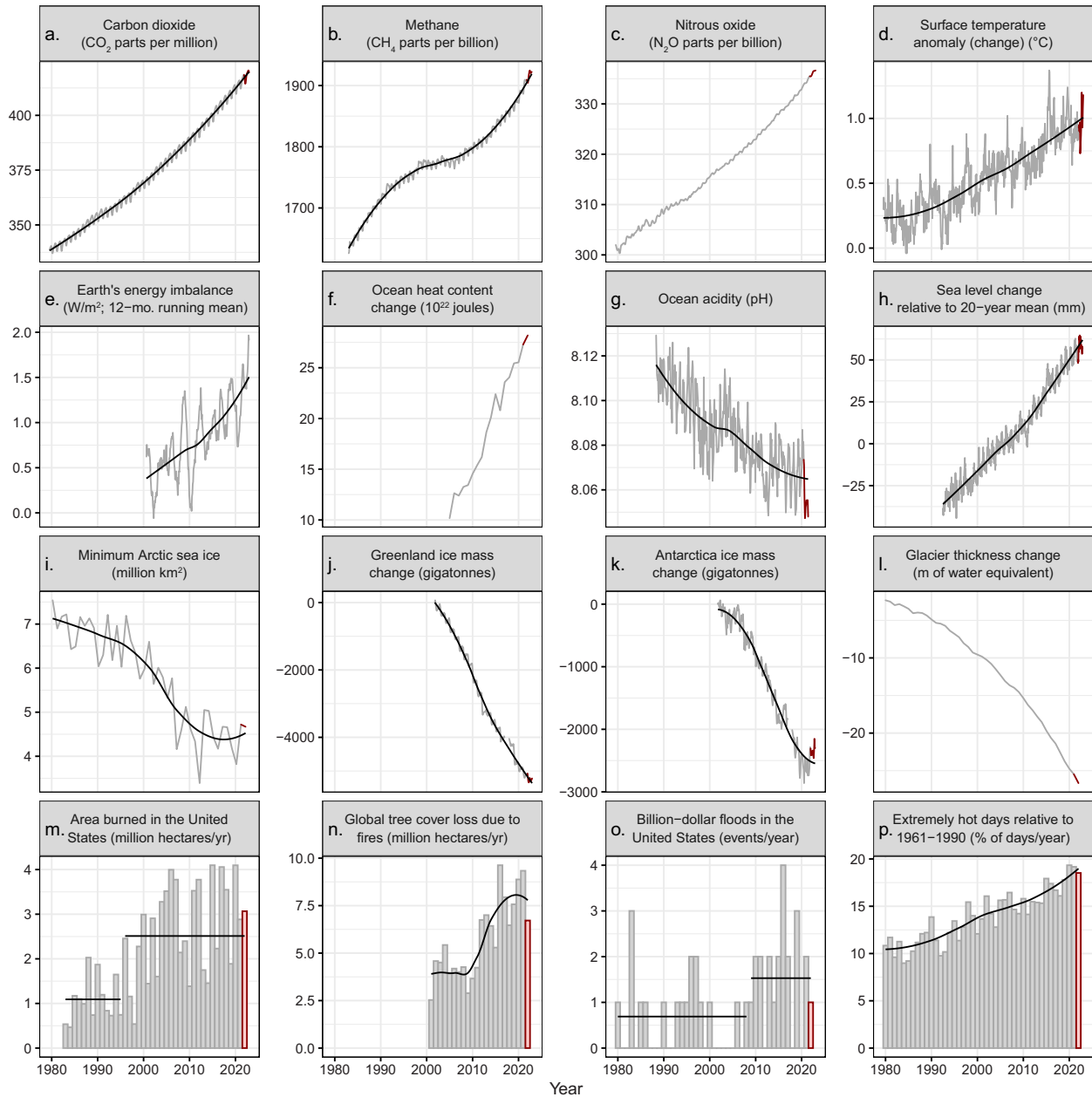


Figure 3. Time series of climate-related responses. Data obtained before and after the publication of Ripple and colleagues (2021) are shown in gray and red (dark gray in print) respectively. For area burned (m) and billion-dollar flood frequency (o) in the United States, the black horizontal lines show change-point model estimates, which allow for abrupt shifts (see the supplement). For other variables with relatively high variability, local regression trendlines are shown in black. The variables were measured at various frequencies (e.g., annual, monthly, weekly). The labels on the x-axis correspond to the midpoints of years. Billion-dollar flood frequency (o) is likely influenced by exposure and vulnerability in addition to climate change. Sources and additional details about each variable are provided in [supplemental file S1](#).

dioxide concentration is now approximately 420 parts per million, which is far above the proposed planetary boundary of 350 parts per million (Rockström et al. 2009). In addition, 2023 is on track to be one of the hottest years on record (figures 1e and 3d). Although fossil fuel-related greenhouse gas emissions are the main driver of rising temperatures, a global decline in sulfur dioxide emissions is likely a contributing factor ([supplemental figure S2](#)). Sulfur dioxide forms sulfates in the atmosphere, which are the strongest anthropogenic cooling agent, hiding part of the greenhouse gas warming (see [supplemental file S1](#) for extended discussion).

Oceans and ice

Ocean acidity, glacier thickness, and Greenland ice mass all fell to record lows (figure 3g, 3j, and 3l), whereas sea level rise and ocean heat content rose to record highs (figure 3f, 3h). The increase in heat content and the rapid rise in sea surface temperatures (figure 1c, 1d) are especially troubling, because they could have many serious impacts, including the loss of sea life, coral reefs dying because of bleaching, and a rise in the intensity of large tropical storms (Reid et al. 2009). There are also growing concerns

Untold Human Suffering in Pictures



Figure 4. Photograph series depicting the impacts of climate-related disasters. First row (left to right): Homeowners sort through debris after wildfires destroyed their home in the state of California (United States, 2008; FEMA/Michael Mancino), “[National] guardsman carrying a woman in waist deep floodwaters” (United States, 2017; Zachary West/National Guard; CC BY 2.0). Second row: “young girls are caught by a sandstorm on their way to school” (Afghanistan, 2019, Solmaz Daryani/Climate Visuals Countdown; Creative Commons), “mature woman seated in her home, submerged in deep water, smoking a cigarette” (Brazil, 2015; Fabrice Fabola, CC BY-SA 2.0). Third row: aftermath of Cyclone Idai (Mozambique, 2019; Denis Onyodi: IFRC/DRK/Climate Centre, CC BY-NC 2.0), “residents walk on a road littered with debris after Super Typhoon Haiyan battered Tacloban city” (The Philippines, 2013; Erik de Castro/Reuters; CC BY 2.0). All quotes are from the Climate Visuals project (<https://climatevisuals.org>). See [supplemental file S1](#) for details and more pictures.

that the Atlantic meridional overturning circulation could pass a tipping point and start to collapse this century, possibly between 2025 and 2095 (Ditlevsen and Ditlevsen 2023), which would significantly alter global precipitation and temperature patterns with potentially major harmful consequences for ecosystems and society, including reduced natural carbon sinks (Armstrong McKay et al. 2022).

Climate impacts and extreme weather

Climate change is contributing significantly to human suffering (figure 4). Climate-related impacts in 2022 included another billion-dollar flood in the United States, which occurred in Kentucky and Missouri between 26 and 28 July, and the third highest frequency of extremely hot days (figure 3o, 3p). Between 2021 and 2022, the area burned by wildfires globally decreased 28%

Table 1. Recent climate-related disasters since November 2022.

Timeframe	Climate disaster
November–December 2022	Record-breaking heat waves in Argentina and Paraguay contributed to power outages, wildfires, and poor harvests. This extreme heat was estimated to have been made 60 times more likely because of climate change.
December 2022–March 2023	Heavy rainfall caused by atmospheric rivers led to multiple floods in the Western United States. There were at least 22 fatalities and property damages were estimated to be US\$3.5 billion. Climate change may be increasing the likelihood of such catastrophic floods, although its effect on these particular storms is less clear.
February 2023	Cyclone Gabrielle caused extreme rainfall in Aotearoa New Zealand's Te Ika-a-Māui (North Island), potentially resulting in billions of dollars in damages and 225,000 homes losing power. This intense rainfall may be partly caused by a warming climate.
March–May 2023	Record-breaking temperatures were recorded in parts of Southeast Asia, China, and South Asia. The extreme heat caused deaths and school closures in India and led to more than 100 students requiring treatment for dehydration in the Philippines. It was likely at least partly because of climate change. For example, climate change has increased the likelihood of such an event to occur over Bangladesh and India by a factor of at least 30.
January–July 2023	Intense wildfires in Canada burned roughly 10 million hectares, displacing 30,000 people at their peak, and worsening air quality across large portions of Canada and the United States. These extreme wildfires may be partly because of climate change, although many other factors are likely involved.
May 2023	Tropical cyclone Mocha is reported to have killed at least 145 people in Myanmar and affected roughly 800,000 people in the region. Climate change may have made such storms more intense.
May–June 2023	Tropical storm Mawar caused flooding and loss of power in parts of Guam. Mawar is the strongest cyclone ever recorded in the northern hemisphere in May. Climate change may be causing an increase in the intensity of tropical cyclones (Wu et al. 2022).
June 2023	Deadly heat led to more than a dozen deaths in the Southern and Midwestern United States. Climate change is leading to an increase in the frequency and duration of such heat waves.
July 2023	Up to six people died in Southwest Japan because of extremely heavy rainfall that caused floods and landslides. Climate change is likely making such heavy rainfall events more severe. Days later, floods and landslides, which may have been partly related to climate change, killed more than 26 people and led to thousands being evacuated in South Korea.
July 2023	Heavy monsoon rain caused flash floods and landslides in northern India that killed more than 100 people. Climate change is likely making monsoons in this region more variable, causing frequent landslides and floods. Heavy monsoon rains also damaged rice crops in India, raising concerns about global food prices and food security and prompting an export ban on nonbasmati varieties.
June–August 2023	Extreme heat in the United States killed at least 147 people. In the absence of climate change, the extreme heat seen in July 2023 in the United States would have been extremely unlikely to occur.
July–August 2023	Beijing, China experienced its heaviest rainfall in at least 140 years, resulting in major flooding that affected nearly 1.29 million people, damaged 147,000 homes, and caused at least 33 deaths. Intense flooding is likely becoming more common because of climate change.
August 2023	In Hawaii, United States, catastrophic wildfires on the island of Maui killed at least 111 people, with more than 1,000 people likely missing, as of 18 August 2023. Climate change may have decreased rainfall and increased temperatures in this region, potentially contributing to these fires.
September 2023	Storm Daniel caused extreme flooding in Libya and parts of southeastern Europe, resulting in thousands of fatalities and more than 2 billion US dollars in damages. Climate change may be increasing the intensity of such storms.

Note: We list numerous recent disasters that may be at least partly related to climate change. This list is not intended to be exhaustive. Because of the recent nature of these events, our sources often include news media articles. For each event, we generally provide references indicating that the likelihood or strength of such an event may have increased because of anthropogenic climate change. References to scientific articles are given directly in the table, and links to news articles are provided in [supplemental file S1](#). Some of these disasters may be at least partly because of climate-related changes in jet streams (Stendel et al. 2021, Rousi et al. 2022).

(from 9.34 million ha to 6.72 million ha), but wildfire activity in the United States rose by 6.3% (from 2.88 million ha to 3.07 million ha) over the same period (figure 3m, 3n). Many climate impacts are expected to further intensify in the coming years, and we may have already experienced abrupt increases in certain types of extreme weather, possibly surpassing the rate of temperature rise (figures 3m, 3o, S3, S4; Calvin 2020).

In 2023, climate change likely contributed to a number of major extreme weather events and disasters. Several of these events demonstrate how climate extremes are threatening wider areas that have not typically been prone to such extremes; for example, severe flooding in northern China, around Beijing, killed at least 33 people. Other recent disasters include deadly flash floods and landslides in northern India, record-breaking heat waves in the United States, and an exceptionally intense Mediterranean storm

that killed thousands of people, primarily in Libya (see table 1 for details and attribution). As these impacts continue to accelerate, more funding to compensate for climate-related loss and damage in developing countries is urgently needed. The United Nations' new loss and damage global fund established at COP27 is a promising development, but its success will require robust support by wealthy countries.

Scientists' warning recommendations

Motivated by recent events and trends, we continue to issue specific warnings and recommendations involving topics ranging from food security to climate justice. Coordinated efforts in each of these areas could help to support a broader agenda focused on holistic and equitable climate policy.

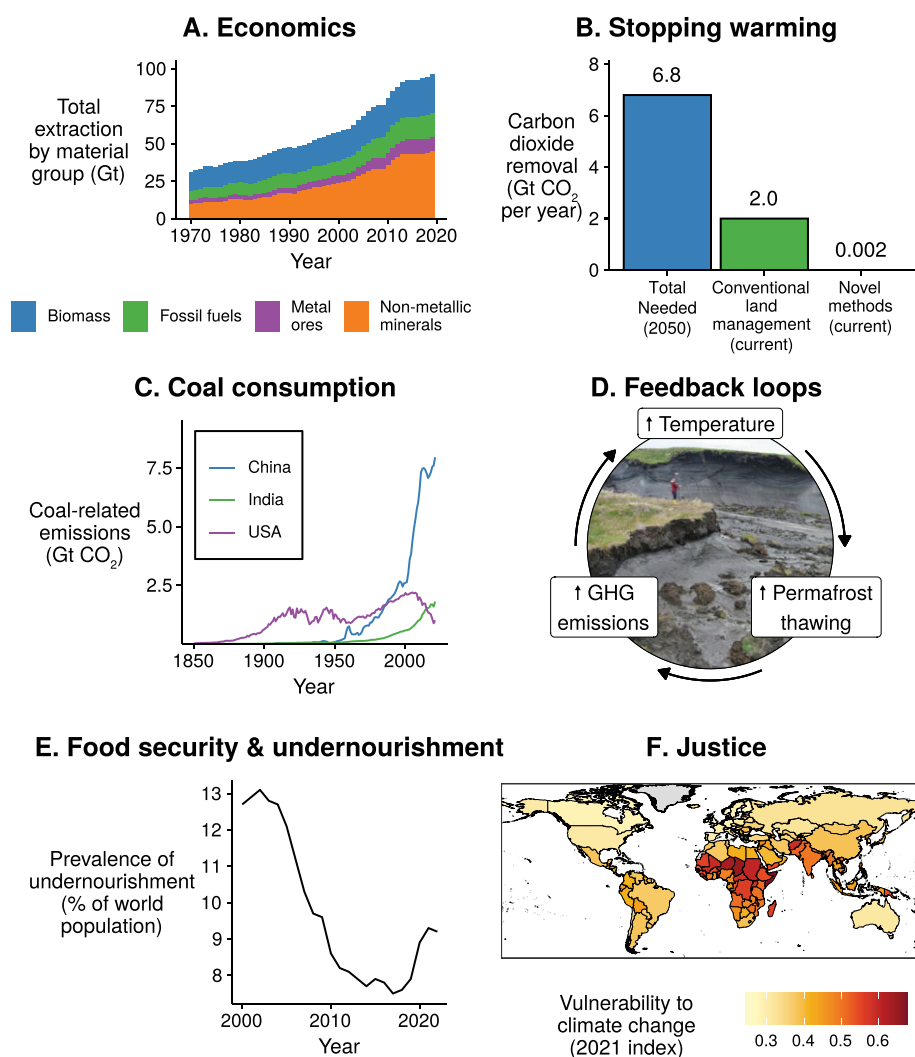


Figure 5. Climate action special topics. Many models assume that GDP growth can be mostly decoupled from emissions and other consumption-related environmental impacts (a) and that carbon capture methods can be quickly scaled up (b). If these assumptions are not realistic and the use of coal and other fossil fuels is not immediately curtailed (c), then Earth system feedback loops (d) could lead to rapidly accelerating climate impacts, including undernourishment (e) and climate disasters, which will be especially severe in less wealthy countries that have had little historical emissions (f). See [supplemental file S1](#) for data sources and details. Photograph: Boris Radosavljevic (CC BY 2.0).

Economics

Economic growth, as it is conventionally pursued, is unlikely to allow us to achieve our social, climate, and biodiversity goals. The fundamental challenge lies in the difficulty of decoupling economic growth from harmful environmental impacts (figure 5a). Although technological advancements and efficiency improvements can contribute to some degree of decoupling, they often fall short in mitigating the overall ecological footprint of economic activities (Hickel et al. 2021). The impacts vary greatly by wealth; in 2019, the top 10% of emitters were responsible for 48% of global emissions, whereas the bottom 50% were responsible for just 12% (Chancel 2022). We therefore need to change our economy to a system that supports meeting basic needs for all people instead of excessive consumption by the wealthy (O'Neill et al. 2018).

Stopping warming

The elevated rates of climate disasters and other impacts that we are presently seeing are largely a consequence of historical and ongoing greenhouse gas emissions. To mitigate these past emissions and stop global warming, efforts must be directed toward eliminating emissions from fossil fuels and land-use change and increasing carbon sequestration with nature-based climate solutions. However, it is crucial to explore other possible strategies to efficiently remove additional carbon dioxide, which can contribute to long-term planetary cooling. Negative emissions technologies are in an early stage of development, posing uncertainties regarding their effectiveness, scalability, and environmental and societal impacts (figure 5b; Anderson and Peters 2016). As such, we should not rely on unproven carbon removal techniques. Although research efforts should be accelerated, depending

heavily on future large-scale carbon removal strategies at this juncture may create a deceptive perception of security and postpone the imperative mitigation actions that are essential to tackle climate change now.

Stopping coal consumption

In addition to its destructive effects on ecosystems and global health, coal accounts for more than 80% of carbon dioxide added to the atmosphere since 1870 and roughly 40% of current carbon dioxide emissions (Burke and Fishel 2020). As of 2022, global coal consumption is near record levels (figure 2h). In 2021, coal-related carbon dioxide emissions were greatest in China (53.1%), followed by India (12.0%), and the United States (6.7%; figure 5c). Coal usage in China has accelerated rapidly in the past decades, and the country now still produces nearly a third of all fossil fuel carbon dioxide and methane emissions (supplemental table S2; Normile 2020). In response to this situation, we support the Powering Past Coal Alliance and recommend the adoption of the international Coal Elimination Treaty to phase out coal and, more broadly, the Fossil Fuel Non-Proliferation Treaty (van Asselt and Newell 2022). These treaties could provide support for less wealthy countries in transitioning away from coal and other fossil fuels, including funding to build out renewable energy capacity and retrain and transition workers from the fossil fuel industry.

Feedback loops

Climate feedback loops directly affect the relationship between emissions and warming. For example, warming causes permafrost soils to thaw, emitting methane and carbon dioxide that result in further warming (figure 5d). As such, reinforcing feedback loops amplify the effects of greenhouse gas emissions, leading to additional warming. Therefore, understanding feedback loops and their interactions can inform climate mitigation and adaptation strategies. Despite their importance, the combination of multiple amplifying feedback loops are not well understood, and the potential strengths of some dangerous feedback loops are still highly uncertain (Ripple et al. 2023). Because of this uncertainty, we call for an Intergovernmental Panel on Climate Change (IPCC) special report that focuses on the perilous climate feedback loops, tipping points, and—just as a precaution—the possible but less likely scenario of runaway or apocalyptic climate change.

Food security and undernourishment

After declining for many years, the prevalence of undernourishment is now on the rise (figure 5e). In 2022, an estimated 735 million people faced chronic hunger—an increase of roughly 122 million since 2019 (FAO et al. 2023). This rise, which has pushed humanity far off track from achieving zero hunger by 2030, is due to multiple factors, including climate extremes, economic downturns, and armed conflict (FAO et al. 2023). Climate change has reduced the extent of global agricultural productivity growth (Ortiz-Bobea et al. 2021), so there is danger that hunger will escalate in the absence of immediate climate action. In particular, there may be serious and underestimated future risks of synchronized harvest failures caused by increased waviness of the jet stream (Kornhuber et al. 2023). Because of the growing risks of concurrent major crop losses in multiple regions of the world, adaptation-focused efforts are needed to improve crop resilience and resistance to heat, drought, and other climate stressors (Raza et al. 2019). A shift toward plant-based diets, particularly in wealthy countries, could improve global food security and help mitigate climate change (Figure 2d; Cassidy et al. 2013).

Justice

The impacts of climate change are already catastrophic for many. However, these impacts are not unfolding uniformly across the entire globe. Instead, they disproportionately affect the world's most impoverished individuals, who, ironically, have had the least role in causing this issue (figure 5f; Harlan et al. 2015). To achieve socioeconomic justice and universal human well-being, it is crucial to strive for a convergence in per capita resource and energy consumption worldwide. This entails working toward balanced and equitable levels of energy and resource consumption for both the global north and south (Hickel et al. 2021).

Conclusions

The effects of global warming are progressively more severe, and possibilities such as a worldwide societal breakdown are feasible and dangerously underexplored (Kemp et al. 2022). By the end of this century, an estimated 3 to 6 billion individuals—approximately one-third to one-half of the global population—might find themselves confined beyond the livable region, encountering severe heat, limited food availability, and elevated mortality rates because of the effects of climate change (Lenton et al. 2023). Big problems need big solutions. Therefore, we must shift our perspective on the climate emergency from being just an isolated environmental issue to a systemic, existential threat. Although global heating is devastating, it represents only one aspect of the escalating and interconnected environmental crisis that we are facing (e.g., biodiversity loss, fresh water scarcity, pandemics). We need policies that target the underlying issues of ecological overshoot where the human demand on Earth's resources results in overexploitation of our planet and biodiversity decline (figures 5a, S5; McBain et al. 2017). As long as humanity continues to exert extreme pressure on the Earth, any attempted climate-only solutions will only redistribute this pressure.

To address the overexploitation of our planet, we challenge the prevailing notion of endless growth and overconsumption by rich countries and individuals as unsustainable and unjust (Rockström et al. 2023). Instead, we advocate for reducing resource overconsumption; reducing, reusing, and recycling waste in a more circular economy; and prioritizing human flourishing and sustainability. We emphasize climate justice and fair distribution of the costs and benefits of climate action, particularly for vulnerable communities (Gupta et al. 2023). We call for a transformation of the global economy to prioritize human well-being and to provide for a more equitable distribution of resources (Hickel et al. 2021). We also call to stabilize and gradually decrease the human population with gender justice through voluntary family planning and by supporting women's and girls' education and rights, which reduces fertility rates and raises the standard of living (Bongaarts and O'Neill 2018). These environmentally conscious and socially equitable strategies necessitate far-reaching and holistic transformations in the long run that could be achieved through gradual but significant steps in the short term (i.e., radical incrementalism; Halpern and Mason 2015).

As scientists, we are increasingly being asked to tell the public the truth about the crises we face in simple and direct terms. The truth is that we are shocked by the ferocity of the extreme weather events in 2023. We are afraid of the uncharted territory that we have now entered. Conditions are going to get very distressing and potentially unmanageable for large regions of the world, with the 2.6°C warming expected over the course of the century, even if the self-proposed national emissions reduction commitments of

the Paris Agreement are met (UNEP 2022b). We warn of potential collapse of natural and socioeconomic systems in such a world where we will face unbearable heat, frequent extreme weather events, food and fresh water shortages, rising seas, more emerging diseases, and increased social unrest and geopolitical conflict. Massive suffering due to climate change is already here, and we have now exceeded many safe and just Earth system boundaries, imperiling stability and life-support systems (Rockström et al. 2023). As we will soon bear witness to failing to meet the Paris agreement's aspirational 1.5°C goal, the significance of immediately curbing fossil fuel use and preventing every further 0.1°C increase in future global heating cannot be overstated. Rather than focusing only on carbon reduction and climate change, addressing the underlying issue of ecological overshoot will give us our best shot at surviving these challenges in the long run. This is our moment to make a profound difference for all life on Earth, and we must embrace it with unwavering courage and determination to create a legacy of change that will stand the test of time.

Supplemental Material

Supplemental data are available at [BIOSCI](#) online. The methods and details of planetary vital sign variables used in this report, along with other discussion appear in supplemental file [S1](#). A list of the scientist signatories for Ripple and colleagues (2020) as of 29 March 2023 appears in supplemental file [S2](#). These signatures are not for the current report.

The article “World scientists’ warning of a climate emergency” (Ripple et al. 2020) now has more than 15,000 signatories from 163 countries, and we continue to collect signatures from scientists. To sign or learn more, visit the Alliance of World Scientists website at <https://scientistswarning forestry.oregonstate.edu>. To read about science-based advocacy and view *A Scientist’s Warning*, a new documentary film on scientists speaking out, visit www.scientistswarningfilm.org.

Acknowledgments

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Testimony on SB24-159: Modifications to Energy and Carbon Management Processes

March 28, 2024

Mr. Chairman and Members of the committee, I am honored to testify before you today.

I am Lisa McKenzie, an Associate Professor at the Colorado School of Public Health. I hold a PhD in environmental chemistry from the University of Montana and an MPH in epidemiology from the University of Colorado. I have been researching the public health implications of oil and gas development for the past 14 years.

Our studies indicate oil and gas development negatively impacts the health of Colorado's children. We found that infants born with a congenital heart defect were 70 percent more likely to have a mother that lived in Colorado's most intensive areas of oil and gas development. This risk almost doubled in Colorado's rural areas. We found that children in Colorado's rural areas with leukemia were 4.3 times more likely to live in areas of intensive oil and gas development. In Broomfield, we observed that children living within two miles of Broomfield's multi-well oil and gas pads experienced more respiratory, gastrointestinal, and acute health symptoms than children living more than 2 miles from the pads.

Our studies indicate adverse health impacts to Colorado's adults as well. Our study of adults in Greeley, Windsor, and Fort Collins, found that people living in the most intensive oil and gas development areas had elevated blood pressure and other cardiovascular disease risk factors. Our study of adults concerned about air pollution, noise, and odors and living in Broomfield found

that adults living within 1-mile of Broomfield's multi-well oil and gas sites experienced more respiratory, mental health, neurological, gastrointestinal, and acute health symptoms than adults living more than 2 miles from the well pads.

Nationally, more than 60 peer reviewed studies report that people living within and beyond 1 km (3,281 feet) of oil and gas wells experience greater adverse health impacts compared to those living farther away in both urban and rural areas. Additionally, higher density of oil and gas development in the vicinity of residences is also associated with greater adverse health risks compared to lower density of oil and gas development. Finally, increased production volume of hydrocarbons is associated with increased adverse health impacts. These studies observed a range of adverse health effects, with the strongest evidence being for impacts in early life. Because so many studies have observed increased adverse health effects with oil and gas development, it is likely that oil and gas development adversely impacts health, particularly in early life.

There is also robust body of scientific literature indicating oil and gas well sites can and have emitted hazardous air pollutants and noise at levels that could harm health. Numerous studies both in Colorado and other areas have documented increased hazardous air pollutant concentrations and noise in areas of active oil and gas development. Our study of a large well site in Greeley observed that noise measured 1000 feet from the site consistently exceeded levels associated with sleep disturbance and cardiovascular disease during all phases of development and into production. Our 2018 human health risk assessment estimated that adverse health outcome risks begin to increase at approximately 2000 feet from O&G and rise steeply with shorter distances.

Phasing out new oil and gas drilling and ensuring proper well plugging and environmental remediation, as proposed in SB24-159, would eliminate nearly all environmental stressors associated with oil and gas wells and is thus the best strategy for protecting the health of Coloradans.

Thank you again for this opportunity to testify on these important modifications to Colorado's Energy and Carbon Management Processes.

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Climate change is having a significant impact on our planet. Fracking is a major contributor.

According to the National Academy of Science, for each 1°C temperature rise crop yields decline by 7.4% for corn, 6% for wheat, 3.2% for rice, 3.1% for soy. Temperatures have already risen more than 2°C in 15 of our counties.

Science Daily says 80% of world's croplands will be affected by water scarcity due to climate change

In 2019 20 million acres couldn't be planted in the US due to flooding and heavy rainfall - USDA
New invasive pest species proliferate under warmer conditions (like the corn ear worm that hit our Olathe sweet corn and the grasshopper 'invasion' last year) — CABI Ag and Bioscience
More CO2 causes loss of nutritional value so lowers commodity prices (impacting levels of zinc, iron, copper, magnesium and calcium in rice, wheat and soybeans) - source NIH

Enough is enough. The time is now to protect our children's future and leave something for future generations. Later is too late.

To the Honorable Chairperson, Senator Roberts, and Committee,

On behalf of the Colorado Livestock Association and its more than 350 member families statewide, we write to express our opposition to Senate Bill 159, Mod to Energy & Carbon Management Processes, and what lasting impacts it may cause in rural economies.

The bill as written mandates a reduction and prohibition of all well permits by 2029 and the annihilation of oil and gas in the state by 2032. This is the destruction of an industry that is vital to poor and often rural communities in this state. Oil and gas operations on agricultural properties often offset the costs of doing business, provide a livelihood, or receive existential benefits from living in a community that receives necessary funding due to oil and gas production. Is this body of people's elected representatives going to decide that these communities should suffer, lose their livelihoods, or lose the supplemental income that allows them to feed, educate, and produce the food and fiber for the ever-growing population that continues to make it harder each day? We cannot pass legislation that seeks to cause harm to already struggling areas of our state.

This piece of legislation brings many other concerns for our members and the unintended consequences to their communities. Many of these small communities receive severance tax dollars that allow them to provide for the needs of the community but will no longer receive those funds. Rural education systems suffer due to a lack of funding, a decrease in population, and an increased hardship in finding teachers with many of these families moving away to find jobs. Although this bill references the use of the OFW study enacted in HB23-1074, this will not be the one-answer fixes-all approach to the loss of thousands of jobs and economic benefits that the oil and gas industry brings to this state.

In section 3 of this bill, by striking out the language of oil and gas operations and changing it to encompass any activity regulated by the Energy and Carbon Management Commission this bill now takes in all family farms that are regulated in some way by the ECMC. This now encompasses the possibility for oil and gas, agriculture, and other entities regulated by the ECMC to be required to mitigate potentially significant environmental impacts. However, it is not found in this bill's language a definition of significant adverse environmental impact. How is the commission planning on identifying these impacts and the thresholds they will be held to, how do they plan on identifying violations, and whether or not a solution is feasible? These unanswered questions for the commission create subjectivity in the application of unknown standards by non-experts, which could lead to the elimination of vital industries. The costly litigious future if this bill is passed is certain and these companies could possibly go out of business.

This bill does not consider these and many other unintended consequences and the lasting impact that will be felt by the entire state. We cannot pass more legislation that will destroy industries that provide jobs and the necessary monetary lifeblood in already struggling communities. The Colorado Livestock Association opposes Senate Bill 159.

Sincerely,

Zach Riley, Colorado Livestock Association, CEO

SB 159 Hearing 03/2/2024

To whom it may concern;

To the committee and the community, I would like to request further consideration and information on many pieces of this bill.

It is noted in Section 3 “Expanding mitigation to include mitigation of adverse environmental impacts as a result of any activity regulated by the commission,” will the commission regulate the activity of disposing of and or recycling fossil fueled vehicles and equipment? In 2021 there were approx. 1,496,310 vehicles registered in the State of Colorado.

Will this include mitigation of burying wind turbines that had a functioning life of <10 years to be the burden of those foreign operating companies? Is there research on the leaching of chemicals and plastics from this disposal?

Where will the factories be built to create renewable panels, towers, and batteries?

How much import and dependence of non-local products and services will this create?

How will the Agricultural industry function when the cost of fuel continues to increase? Will that burden be put onto the farmer, the marketer, or the consumer? The current food dollar already cuts the ability of farmers to profit. Inputs are at an unprecedented peak and will only continue to increase.

Governor Polis has stated the two most important industries to Colorado are Agriculture and Tourism, which he has pointed are harmed by the Oil and Gas Industry. It is unfathomable that farmers who are receiving benefit from Oil and Gas leases would be able to use their land in the same way if it was developed into solar panels towers as the current well heads, production facilities, or pumping units. That is simple math in land usage.

To the renewable future, the current cost of living in Colorado is difficult for many to make ends meet. How will higher energy rates to heat homes, travel to and from work correlate to wages? How will commerce keep up with the correlated expenses of business, including those wage increases?

“Oil, natural gas and coal mining operations on federal lands in Colorado generated more than \$393 million in lease and fee revenues in 2022 for the federal and state governments — the most in 14 years.” Colorado Sun

How will the commission replace this revenue?

This does not include the payroll and livelihood of the countless residents of Colorado affected by the reduction of new leases and continued industry.

The questions are never ending and we can all agree the understanding of doing better for our environment and our future is crucial. However, the scale being tipped by bills like 159 and attacks on a key industry is deceptive to your constituents. The energy industry has made extreme advances in remediation and reclamation since its start and each new lesson provides opportunity for continuous improvement. This commission has failed to produce consistent and effective studies on the pollution and harm caused by the industry, and will continue to bring about shrouded results for the benefit of their personal interests.

Thank you,

A concerned citizen and lifelong resident of Colorado.

Jenna Pralle
3039903823

SB 159 Hearing 03/2/2024

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In opposition to SB24-159 Mod to Energy & Carbon Management Processes

3/27/2024

Hi, my name is Greg Satriano. I'm a native of Colorado, got my degree in Chemical Engineering from the beautiful CSM campus, and now have lived in Aurora with my wife and kids for 9 years. Among other things, my family and I enjoy the outdoors here in Colorado, especially trips to the mountains to ski and hike.

With our goal as a community being to preserve the natural beauty of our state, I believe it is more important than ever to prioritize and foster the development of natural gas wells in this state. Natural gas is the earth's cleanest burning hydrocarbon. Its combustion emits zero ash, zero sulfur oxides, and negligible nitrogen into the air. However, the production of horizontal gas wells when charted over time peaks early and then quickly drops off and stabilizes at a lower rate for many years.

Introducing legislation which bans issuing new permits to drill for oil and gas would make our goals un-reachable as it would cause the supply of natural gas in our state to quickly dwindle and force us to import more expensive natural gas.

Natural gas is so important to this state as it allows us to achieve the goal of adding more wind and solar power by providing a stable back up to the grid when these alternative energy sources are not available. Natural gas also allows us to achieve the goal to add more EV's and electrify appliances through generation of increased amounts of electricity to meet demand. I myself have been working with clients in this state to implement innovative designs which serve to reduce the carbon emissions associated with oil and gas installations.

If this bill is passed, I will no longer have these opportunities to provide engineering services to companies in this state, and I run the risk of having to move out of Colorado to ensure I have a stable job.

Rather than ban the production of natural gas, I believe we should do all we can to safely and efficiently produce it locally. This will ensure that all Coloradoans and their families will have the affordable energy they need to continue to live in this great state of Colorado for years to come.

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Dear members of the Senate Agricultural and Natural Resources Committee:

I am writing to urge you to vote yes SB24-159, the Phase Out and Clean Up Bill. As a Colorado resident I am deeply concerned that our state is not acting quickly enough to reduce our carbon emissions. Climate change is a looming crisis that if unaddressed will result in staggering costs to Colorado residents. The massive wildfires of recent years are just one example of the risks of unabated heating. This unfolding tragedy can be minimized if we reduce climate pollution and rapidly transition to clean energy. SB-159 would take significant steps towards addressing this problem.

Climate change threatens to inflict serious damage on Colorado's economy. The outdoor recreation industry is already facing losses as the winter sports season gets shorter every year, and as wildfires increasingly disrupt summer activities. The risks facing the agriculture industry are real and serious. For every 1 degree Celcius increase in temperature, crop yields decline by 7.4% for corn and by 6% for wheat. Irrigation water will be increasingly scarce. Due to increased flooding and heavy rainfall events, less land will be suitable for planting crops. New invasive pest species will flourish in the warmer conditions, resulting in additional costs for farmers.

It should be clear that while the oil and gas industry profits from extraction, other important Colorado industries, like outdoor recreation and agriculture, are harmed as a result. The Colorado fossil fuel industry has 50,000 wells in production - that's enough. The industry will continue to reap profits from those wells for decades to come. As a significant step toward supporting the transition to clean energy, we should end the drilling of new wells by passing SB-159. We must do this to protect our Colorado economy over the long term, to defend quality of life for Colorado residents, and to cherish our sons, daughters and grandchildren.

We must take action on the climate crisis now. I am counting on you to vote yes on SB-159.

Sincerely,
Philip Beck

Senate Testimony 3/38/24

Thank you for the opportunity to testify.

My name is Scott Denning. I'm Monfort Professor of Atmospheric Science at Colorado State University. My expertise is in climate change, and especially in what happens to CO₂ after it goes into the air.

I'm here to share three ideas with you today:

- 1) A lot of the CO₂ we produce this year by burning coal, oil, and gas will still be in the air warming the climate thousands of years from now;
- 2) Global warming doesn't depend on the amount of coal, oil, and gas burned this year, but rather on the total amount ever burned in all of history; and
- 3) Stein's Law.

1. We burn coal, oil, and gas because when they react with oxygen, we get energy out of them. The CO₂ that is produced in this way is *spent carbon*. It doesn't react any further. Unlike toxic smog, it will never "break down" into something else because it's already fully oxidized. CO₂ is the thermodynamic ashes of the carbon cycle. In principle, we could capture and store it, but that takes WAY more energy than we got from burning it in the first place.
2. Global warming is the result of the CO₂ in the air. Since the stuff is permanent, warming will continue until emissions cease. Cutting emission by half would mean warming would only be half as fast as now. It will get hotter and hotter as long as we burn coal, oil, and gas, and then it won't cool off when we stop. The thermostat only goes up, never down.
3. STEIN'S LAW states that "if something can't continue forever, it will stop." Burning oil & gas will stop. Forever. Don't build more oil & gas infrastructure. It's a dead end. It's a huge liability for our economy and our way of life.

Please vote in favor of the bill before you.

Megan Bodin
535 W 8th Street
Loveland, CO 80537
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310-486-3947
3/27/2024

Senate Agriculture and Natural Resources
200 E Colfax Ave.
Denver, CO 80203

SB24-159 Mod to Energy & Carbon Management Processes

Dear Honorable Members of the Committee,

My name is Megan Bodin, and I am writing to express my strong support for Senate Bill 24-159, which aims to reduce and phase out new oil drilling permits in our state. As a concerned citizen of Loveland, Colorado, born and raised, I am deeply troubled by the visible air pollution and its impact on our community's health and environment, particularly the impacts of ground-level ozone pollution (smog).

After spending 10 years in Los Angeles, a hiatus between college at UNC-Greeley and graduate work at CU-Boulder, I became aware of ground-level ozone pollution in both states, so I naturally assumed that it was a nationwide problem, but it is not. According to the EPA Green Book for air pollution, ozone nonattainment areas are primarily in California, northern Colorado, New York, Washington DC, Chicago, and parts of Texas.

Colorado's stunning natural beauty and outdoor recreational opportunities are among the reasons why many of us choose to call this state our home. However, continuing to drill new oil and gas sites poses a significant threat to our environment and public health. Oil and gas operations are the top emitter of ozone causing substances as reported by CDPHE. 4 million Coloradans are at risk from exposure to ground level ozone at levels known to cause cardiovascular and respiratory emergencies and scar healthy lung tissue. I can attest to aggravated asthma and one emergency room visit on high ozone days.

Despite being the 5th highest oil producer and the 8th highest natural gas producer in the country, Colorado's consumption figures tell a different story. In 2022, the state ranked 21st for motor gasoline consumption and 20th for natural gas consumption nationwide, according to the U.S. Energy Information Administration. It's evident that we should reconsider our current levels of production and exports, particularly when they pose risks to the health and well-being of our beloved state.

Senate Bill 24-159 represents a crucial step towards safeguarding the health and environment of Colorado. By reducing permits in 2028 and 2029 and ceasing new permits by 2030, we can

mitigate the harmful effects of air pollution, protect public health, and preserve the natural beauty of Colorado for future generations. It's imperative that we act now in 2024 to ensure we meet these goals in time.

I urge you to support Senate Bill 24-159 and take decisive action to address the pressing environmental and health concerns posed by the oil and gas industry. Together, we can ensure a cleaner, healthier future for all Coloradans.

Thank you for your attention to this matter.

Sincerely,

Megan Bodin

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March 27, 2024

Senate Agriculture and Natural Resources Committee
200 E. Colfax Ave
Denver, CO 80203

SB24-159 Mod to Energy & Carbon Management Processes

Dear Honorable Members of the Committee,

I am writing to offer my full support for SB24-159, which proposes to phase out new oil and gas permits by 2030, assigns responsibility to producers for capping wells, and supports a study on workforce transition. As a concerned constituent deeply invested in the well-being of our environment and communities, I believe this bill represents a crucial step towards a more sustainable and equitable future for Coloradoans.

The phased approach to ending new oil and gas permits is imperative for the preservation of our environment and the health of our communities. The adverse effects of fossil fuel extraction and combustion are well-documented, ranging from air and water pollution to accelerating climate change. By gradually phasing out new permits, we can mitigate these harmful impacts and pave the way for an economic transition in Colorado.

Holding producers accountable for capping wells is a vital component of responsible resource management. Oil and gas companies have exploited loopholes, filed for bankruptcy, and abandoned thousands of wells for far too long. Orphan wells create significant environmental hazards, including methane leakage and groundwater contamination. By requiring producers to properly cap wells, we can ensure that the costs of remediation do not fall on taxpayers.

Colorado currently has the opportunity to leverage our collective knowledge and experience to create an economy that is better for the environment and workers. Extractive industries will be replaced by renewable industries sooner or later, and now is the time to train workers, make rules, and provide pathways to a greener economy. Pipefitters can transition to geothermal energy, electricians can work on solar projects, and we will all breathe a bit easier.

Thank you for considering my testimony. This bill is crucial and would signal that Colorado is moving towards a more sustainable and equitable future. I urge you to support this important legislation.

Sincerely,

Ashleigh Knapp

Re: 3/28/24 Hearing for SB24-159

Chair Roberts and members of the Committee:

My name is Karyn Karlson, and my statement represents my own views. I have lived in Colorado all my 71 years. I have a degree in physics, have traveled throughout Colorado, and contributed over the years to my community in Denver and in the San Luis Valley.

I urge you to vote **YES** on SB24-159.

Pollution from oil and gas operations is harming the air we breathe, our land and our water. It is time to take seriously transitioning away from fossil fuels.

Also, taxpayers should not have to pay for cleaning up out-of-use oil and gas wells.

Further, regarding fracking, the process of pumping damaging chemicals into the earth to garner fossil fuels and then storing the toxic waste from that process on the earth is inane.

The oil and gas industry has already drilled over 120,000 wells and has nearly 50,000 in production. Oil and gas corporations export around 40% of the oil and 75% of the gas they extract in Colorado, so Coloradans get the pollution while these corporations get the profit.

There is no need for new wells. Existing wells will continue producing more than Colorado needs for decades, so Colorado will still have enough energy even after the oil and gas industry is required to stop polluting our neighborhoods with new wells.

I realize we cannot stop all oil and gas operations quickly. However, this bill will take important steps in solving these problems.

SB24-159 would not affect production from current wells. And it will require follow up on the in-progress study required by HB23-1074 to determine how to support oil and gas workers and communities impacted by the transition away from oil & gas expansion.

Our family owns and drives an electric car. We have a solar panel array next to our home in southern Colorado. The electric configuration allows our car to be charged by the energy from the sun. This could be the future for Colorado.

Please have the foresight and leadership to create change that matters.
Please vote YES on SB24-159.

Thank you,

Karyn Karlson
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CONTACT

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jessica.gelay@westernresources.org

March 21, 2024

Senate Agriculture and Natural Resources Committee
Colorado General Assembly
200 East Colfax Avenue
Denver, CO 80203

Support SB24-171 Restoration of Wolverines (Sen. Will, Sen. Roberts and Rep. McLachlan, Rep. Mauro)

Chair Roberts, Vice Chair Danielson, and Members of the Committee:

My name is Brendan Witt and I am a policy advisor at Western Resource Advocates, an organization that has worked for more than 30 years to ensure our communities thrive in balance with nature. I am writing today in support of SB 24-171, Restoration of Wolverines.

Passing this bill will give Colorado Parks and Wildlife the ability to continue their longstanding work to restore the wolverine species to Colorado and bring back a missing piece of the historic makeup of our high-alpine ecosystems. We are grateful to Senator Roberts and Senator Will for bringing this bill forward. SB 24-171 is essential because it provides authorization required under the Endangered Species Act for Colorado Parks and Wildlife to ensure the success of those restoration efforts in tandem with Colorado communities.

Colorado is estimated to have the largest proportion of remaining, uninhabited, high-altitude habitat with sufficient snowpack required to allow wolverines to not only persist but thrive. As the impacts of climate change will continue to diminish snowpack in lower elevation portions of the wolverine's range, it is vital that Colorado do its part to help this iconic Western species thrive and call our state home once again.

Thank you again to Senator Will and Senator Roberts for sponsoring this bill and to Committee members for your attention. We urge you to vote "yes" on SB 24-71.

Sincerely,
Brendan Witt
Western Lands Policy Advisor, Western Lands Program
Western Resource Advocates
brendan.witt@westernresources.org

3/14/2024

Hello,

My name is Maya Beauvineau and I'm from Nederland, Colorado. I'm currently a student at Dartmouth College, majoring in Environmental and Indigenous studies. Typically, when people ask me where I'm from, I'm proud to say Colorado—the state which brings to mind gorgeous mountains, sunny days and fluffy snow. However, I am not proud to say that Colorado is the fifth highest producer of oil and the eighth highest producer of natural gas in the US, making us one of the driving forces of US greenhouse gasses.

SB 24-159 is a necessary and hope-inspiring step toward a just energy transition in Colorado. The bill will phase out new drilling in CO by 2030, while allowing existing wells to continue producing for their lifespan, possibly into 2070. Therefore the bill promises to increase the rate of the energy transition to renewables, all while allowing for the transition to occur over time.

The parts of the bill I am most excited about include the provisions for justice within the energy transition. First, SB24-159 will prioritize the phase out in permitting in disproportionately impacted communities. Communities of color are disproportionately impacted by the health impacts of pollution from oil and gas extraction. This bill centers this issue and provides measures to address it, to ensure the phase-out helps those most impacted. Additionally, the bill recognizes the importance of supporting the job transition for workers in the fossil fuel industry. By passing the bill, Colorado can act as a bold leader for a just transition, and can inspire other states to follow suite!

As a young person concerned about climate change, I see many possible futures. I feel anxious when I think of the increasingly intense fire seasons and warming winters I know I will witness, and even moreso when I think of generations to come. However, the extent of the harm wrought by climate change is within our control, with the actions we choose today. Legislative action such as SB24-159 help me look to the future with hope. I hope the committee will choose to support this important step toward climate justice.

With gratitude,

Maya Beauvineau

Written Testimony for SB24-159

I am writing in support of this bill for the following reasons:

This is an urgent issue! We are reaching a tipping point on climate change and you need to do something! Enough is enough. The time is now to protect our children's future and leave something for future generations. Later is too late.

We have enough wells. Existing wells will continue producing more than Colorado needs for decades, so Colorado will still have enough energy even after the oil and gas industry is required to stop polluting our neighborhoods with new wells.

This is not a huge part of our economy. And we must support workers and communities. The bill supports current workforce transition efforts.

YOU ARE THE LEADERS WHO CAN MAKE A CHANGE! ACT LIKE LEADERS.

The facts:

1. **Pollution from oil and gas production has impacted the health of Coloradans** for decades. Oil and gas companies have drilled more than 100,000 oil and gas wells releasing massive amounts of air, water, soil and climate pollution. These companies are often not held responsible for cleaning up the pollution they have caused.

Many residents living near oil and gas wells have reported to the Colorado Dept. of Public Health and Environment (CDPHE) that they suffer from respiratory symptoms including problems with nasal passages, lungs and throat; neurological symptoms such as headaches, dizziness, learning problems and sensory function problems; and gastrointestinal problems like stomach aches, nausea, and intestinal problems; anxiety; and sleep disturbance from vibrations and noise from drilling.

2. **4 million people in Colorado are at risk from ground level ozone at levels known to cause cardiovascular and respiratory emergencies and scar healthy lung tissue.** Oil and gas operations are the top emitter of ozone causing substances as reported by CDPHE.

3. **288,898 people in Colorado live within ½ mile of oil and gas facilities.** Health risks of living this close to wells include respiratory symptoms, neurological symptoms, gastrointestinal problems. this close to oil and gas facilities, within a threat radius that also includes 159 schools and daycares, 39,364 students and 6,034 square miles of land. [Map here](#).

4. **The oil and gas industry is Colorado's top climate polluter, higher even than transportation and electric power generation.** Climate change is reported by 200 medical journals to be the number one public health threat. Coloradans are already suffering health and other impacts of climate change, with low-income communities and people of color at greater risk.

5. **Scientific assessments show the need to end new fossil fuel development** to achieve net-zero emissions globally by 2050, which will lead to a 50% chance of limiting global warming to 1.5 degrees Celsius. At COP28, parties unanimously agreed to a transition away from fossil fuels and 128 of these parties called for a phase out of fossil fuels.

6. With nearly 40,000 wells currently in production, preproduction, or with active permits, new wells are not needed to meet in-state demand. Colorado currently has 48,186 wells defined by the ECMC as active, with 36,851 wells are producing, 1266 wells that have begun pre-production but are not yet producing, and over 1000 wells that are permitted but not yet drilled. Wells can produce oil and gas for 40 years or more. (Source: ECMC dashboard) Colorado produces far more oil and gas than the in-state energy consumption. From 2017 to 2022 oil and gas companies produced 3.8 times more natural gas than Colorado consumed, and from 2017 to 2021 (the latest year figures are available), oil and gas companies produced 1.7 times more oil than Colorado's energy consumption of petroleum. (Source: Energy Information Administration)

7. The oil and gas industry in Colorado is a small fraction of our economy. It contributes only 3.3% of our GDP and less than 1% of jobs. All revenue and fees from the oil and gas industry, including severance tax and property tax equals only 1.2% of total revenue to state and local governments. (Source: Colorado Fiscal Institute)

We need to set an end date to the fracking industry's relentless expansion by phasing out new permits.

- A transition is already underway and this is responsible policy to manage it.
- Industries such as agriculture and outdoor recreation are already suffering damages from climate change and we need to do everything we can to avert further disaster.
- Drought is expected to worsen in Colorado and new oil and gas wells use billions of gallons of surface water and groundwater.
- Climate change and agriculture
 - According to the National Academy of Science, for each 1°C temperature rise crop yields decline by 7.4% for corn, 6% for wheat, 3.2% for rice, 3.1% for soy. Temperatures have already risen more than 2°C in 15 of our counties.
 - Science Daily says 80% of world's croplands will be affected by water scarcity due to climate change
 - In 2019 20 million acres couldn't be planted in the US due to flooding and heavy rainfall - USDA
 - New invasive pest species proliferate under warmer conditions (like the corn ear worm that hit our Olathe sweet corn and the grasshopper 'invasion' last year) — CABI Ag and Bioscience
 - More CO2 causes loss of nutritional value so lowers commodity prices (impacting levels of zinc, iron, copper, magnesium and calcium in rice, wheat and soybeans) - source NIH

Testimony in favor of SB24-159 - Modifications to Energy and Carbon Management Processes

My name is Ann Karlberg, and I am submitting this written testimony as a Colorado citizen who is concerned about environmental justice. I am strongly in favor of SB24-159. I became concerned about climate change when I was in high school. Now, 50 years later, it has developed into a climate crisis, and we are at a point in history where our decisions are critical to the survival of the planet and future generations. I believe it is crucial that we stop investing in fossil fuel extraction and production and move our state toward a more sustainable energy economy.

SB24-159 supports this goal by phasing out new oil and gas permits over the next 6 years. It also requires operators to clean up old wells that are no longer productive rather than burden communities with the responsibility and cost of clean-up. Finally, the bill also has a provision to follow up on the workforce transition study (HB23-1074) regarding how to support oil and gas workers in transitioning to other industries.

This is the part of SB24-159 I would like to focus on. In 2019, the Office of Just Transition (OJT) was created within the Colorado Department of Labor and Employment. The purpose of this newly created office, the first of its kind in the country, was to help coal workers prepare for and obtain good paying jobs in other industries as coal-burning power plants closed. A recent article in the Sierra Club's spring magazine highlighted the success of the OJT's efforts in Nucla, Colorado. It further stated that in 2022, the state allocated \$15 million to the OJT to provide similar support for 8 other coal communities in our state.

These efforts are laudable. The work of the OJT to facilitate just transitions for coal workers and their communities is exactly the kind of support needed for oil and gas workers as we begin to reduce drilling permits and move toward renewables. I'm proud of Colorado's initiative in developing and funding the Office of Just Transition and want to see us do more of this kind of progressive planning as we move into the future.

This is why I urge you to support SB24-159. Its provisions are a reasonable way for our state to begin scaling down oil and gas drilling, address the environmental risks associated with orphaned wells, and facilitate new economic opportunities for workers and communities currently dependent on the fossil fuel industry. Please vote "yes" on SB24-159.

Ann Karlberg
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Denver CO 80204
Akarlberg0630@outlook.com
303-906-0630

March 27, 2024

Written testimony in support of Senate Bill 24-159

Dear Chairman Roberts and Committee Members:

My name is Michael Rose. I am a member of *Colorado Jewish Climate Action* and because I have other commitments on Thursday, March 28th, I am respectfully submitting my testimony in written form in support of Senate Bill 24-159 as I am quite concerned about the health of Coloradans and the health of the economy.

Studies abound connecting Colorado's air pollution problems with poor health. In April 2023, in the American Lung Association's "State of the Air" report, Denver, ranked 6th, Fort Collins ranked 15th, and Colorado Spring ranked 20th among the 25 worst US cities for ozone pollution. The report covered the period from 2019 to 2021. Particulate pollution also worsened during this period.

Clearly, this trend must stop as an increase in respiratory disease impacts Coloradans leading to missed school attendance, work absenteeism, and impacts our economy. It is particularly tragic that oil and gas industry production unjustly exposes communities of color, causing them significantly higher rates of respiratory illness, mortality, and increased risk of hospitalization.

SB-24-159 and other bills addressing Colorado's pollution problems provide opportunities to address our state's health and economic well-being, in the near term, but also climate change in the long term. We need a healthy state that supports a healthy economy now, and a healthy country and a healthy planet for people in the immediate future.

This bill does mandate a phasing out of new well in the future, but contrary to the scare tactics of the oil and gas industry, it absolutely allows existing wells to continue to produce but doing so in a way that does not jeopardize the health of Coloradans. The bill also demands that inactive wells be cleaned up by the oil and gas producers and not by taxpayers.

Thank you for kindly considering my testimony on this bill.

Respectfully,

Michael Rose,
Denver, Colorado

Written Testimony of Peter Morgan, Senior Attorney, Sierra Club in Support of Senate Bill 24-159

Chairman Roberts, members of the committee, thank you for the opportunity to submit this written testimony. My name is Peter Morgan. I'm a Senior Attorney with Sierra Club, based in Denver. My work focuses on issues related to the abandonment of oil and gas wells nationwide, and I provide these comments to you today in that expert capacity.

I support passage of SB159, and specifically the provisions expanding the definition of "responsible party" to include prior owners and operators.

It is a fundamental part of the oil and gas industry's business model to avoid costs associated with well plugging and clean-up by transferring low-producing wells to operators who lack the resources to complete the required plugging.¹ This places the burden of well cleanup on Colorado communities and taxpayers, rather than with the companies that profited from the wells' early production.²

Bonding alone will not solve this problem.³ The Colorado Energy and Carbon Management Commission (ECMC) current holds approximately \$268 million in bonding for the approximately 48,000 wells currently listed as active.⁴ This amounts to average per-well coverage of approximately \$5,600, or just 6% of the average cost of clean-up, which ECMC estimates as \$92,710 per well.⁵

The current financial assurance scheme suffers from four primary weaknesses that preclude the state from being able to rely solely on bonding.⁶ First, the updated financial assurance requirements are being phased in slowly, such that companies aren't required to provide full bonding for up to 20 years.⁷ Second, the heavy reliance on blanket bonding⁸ means that even if there were 100% compliance by operators, bonding would still fall far short of covering actual reclamation costs because by definition blanket bonding is intended to cover only a fraction of costs. And third, the regulatory provision allowing out of service wells to avoid bonding⁹ means that the most vulnerable wells are at greatest risk of being passed off to taxpayers. The industry-funded \$10 million Orphan Wells Mitigation Fee Enterprise Fund is not adequate to cover the anticipated bonding shortfall because failure of a single operator and abandonment of its wells can exhaust that entire fund.¹⁰

If, in 20 years, the financial assurance requirements have been fully implemented and funded and proven to be adequate, then the legislature may

consider rescinding the predecessor liability requirement of SB159 and relying solely on bonding. Until then, predecessor liability remains necessary.

Colorado would not be an outlier in holding prior owners and operators responsible for ensuring clean-up of their wells. Louisiana and California both provide for recovery of costs from prior operators, as does the Bureau of Land Management for wells on federal leases.

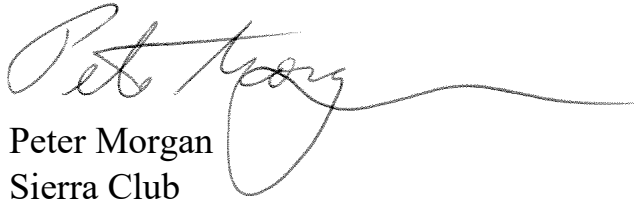
Louisiana law provides, subject to certain limitations, that if the state has to perform well plugging or remediation work, the regulator “shall seek to recover all costs incurred . . . and other relief from any party who has operated or held a working interest in such site . . .” La. Stat. Ann. § 30:93.

California law provides that if the current operator is unable to fully cover the cost of plugging and abandoning the well, “the immediately preceding operator shall be responsible for the cost” and “[t]he supervisor may continue to look seriatim to previous operators until an operator is found that the supervisor determines has the financial resources to cover the cost.” Cal. Public Resources Code, sec. 3237(c).

Bureau of Land Management (BLM) policy provides that the definition of “legally liable parties” includes “all previous [owners] and [operators] that held an interest in the lease since the surface disturbance occurred or the well was drilled.”¹¹ BLM regulations further inform leaseholders that “[a]fter BLM approves [an] assignment or transfer, you will continue to be responsible for lease obligations that accrued before the approval date . . . includ[ing] responsibility for plugging wells and abandoning facilities you drilled, installed, or used before the effective date of the assignment or transfer.” 43 CFR § 3106.7-2

This is only fair, including as applied retroactively. Fundamental principles of contract law provide that a transfer or assignment of a right to *operate* a well does not by itself relieve the original operator of the clean-up *obligation* it incurred when it drilled the well.¹²

Colorado can and must do better to ensure that wells are cleaned up, and that it is the industry that profited from those wells—rather than communities and taxpayers—that bears those costs. Thank you.



Peter Morgan
Sierra Club

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¹ For example, in 2018, HRM Resources transferred about 200 wells in Adams County to a new company, Painted Pegasus, which promptly went bankrupt, passing well clean-up costs on to the public. HRM Resources itself had received the wells from even larger operators, including Chevron subsidiary Noble Energy, Hilcorp, and Civitas. The cost to plug and remediate those wells is approximately \$20 million, with bonds covering only \$300,000 of that.

² Ensuring prompt and complete well plugging and remediation is critically important because unplugged oil and gas wells are hazards to local communities and, indeed, all Coloradans. Unplugged or improperly plugged wells produce hazardous air pollution, contaminate drinking water wells, contaminate surface and groundwater, and can lead to explosions from migration of gas into buildings and residences. Air pollution from leaking wells includes the potent greenhouse gas methane, as well as carcinogens and ozone pre-cursors linked to asthma. *See* Dominic C. DiGiulio et al., *Chemical Characterization of Natural Gas Leaking from Abandoned Oil and Gas Wells in Western Pennsylvania*, 8 ACS OMEGA 19443 (2023), available at <https://pubs.acs.org/doi/pdf/10.1021/acsomega.3c00676>; Josh Woda, et al., *Methane concentrations in streams reveal gas leak discharges in regions of oil, gas, and coal development*, 737. SCIENCE OF THE TOTAL ENVIRONMENT, 140105 (2020), available at https://www.sciencedirect.com/science/article/abs/pii/S0048969720336251?fr=RR-2&ref=pdf_download&rr=7f521def4fba2bc4

³ Colorado already has an orphan and abandoned well problem. In a December 2021 filing, Colorado listed the state as having 402 orphan wells requiring plugging and remediation. (Colorado’s December 29, 2021 NOI to apply for DOI formula grants at p. 3). As of February 27, 2024, the number of unplugged wells reported by ECOM has grown to 649. <https://sites.google.com/state.co.us/cogcc-owp>.

⁴ ECOM “Daily Activity Dashboard” <https://ecom.state.co.us/DAD.html>

⁵ <https://sites.google.com/state.co.us/cogcc-owp>

⁶ <https://carbontracker.org/reports/false-start/>

⁷ 2 Colo. Code Regs. § 404-1:702(d)(3)(C)(i) (requiring annual contribution of 5% of total bond required)

⁸ 2 Colo. Code Regs. § 404-1:702

⁹ 2 Colo. Code Regs. § 404-1:434(d)(10) (requiring financial assurance for an out of service well only if the operator fails to plug the well within the designated timeframe)

¹⁰ For example, the transfer of 200 wells from HRM Resources to Painted Pegasus, and subsequent bankruptcy, resulted in a \$20 million shortfall between anticipated reclamation costs and the bonded amount.

¹¹ <https://www.blm.gov/policy/im-2021-039>

¹² *See Roget v. Grand Pontiac, Inc.*, 5 P.3d 341, 345 (Colo. App. 1999) (“An assignment does not relieve the assignor from liability under the contract. Rather, after the assignment, the assignee becomes primarily liable for the obligations under the contract, while the assignor remains secondarily liable. The debtor may then sue the assignor, the assignee, or both.”); *see also Pennaco Energy, Inc. v. KD Co. LLC*, 2015 WY 152 (Wyo. 2015) and *Pennaco Energy, Inc. v. Sorenson*, 2016 WY 34, 371 P.3d 120 (Wyo. 2016).