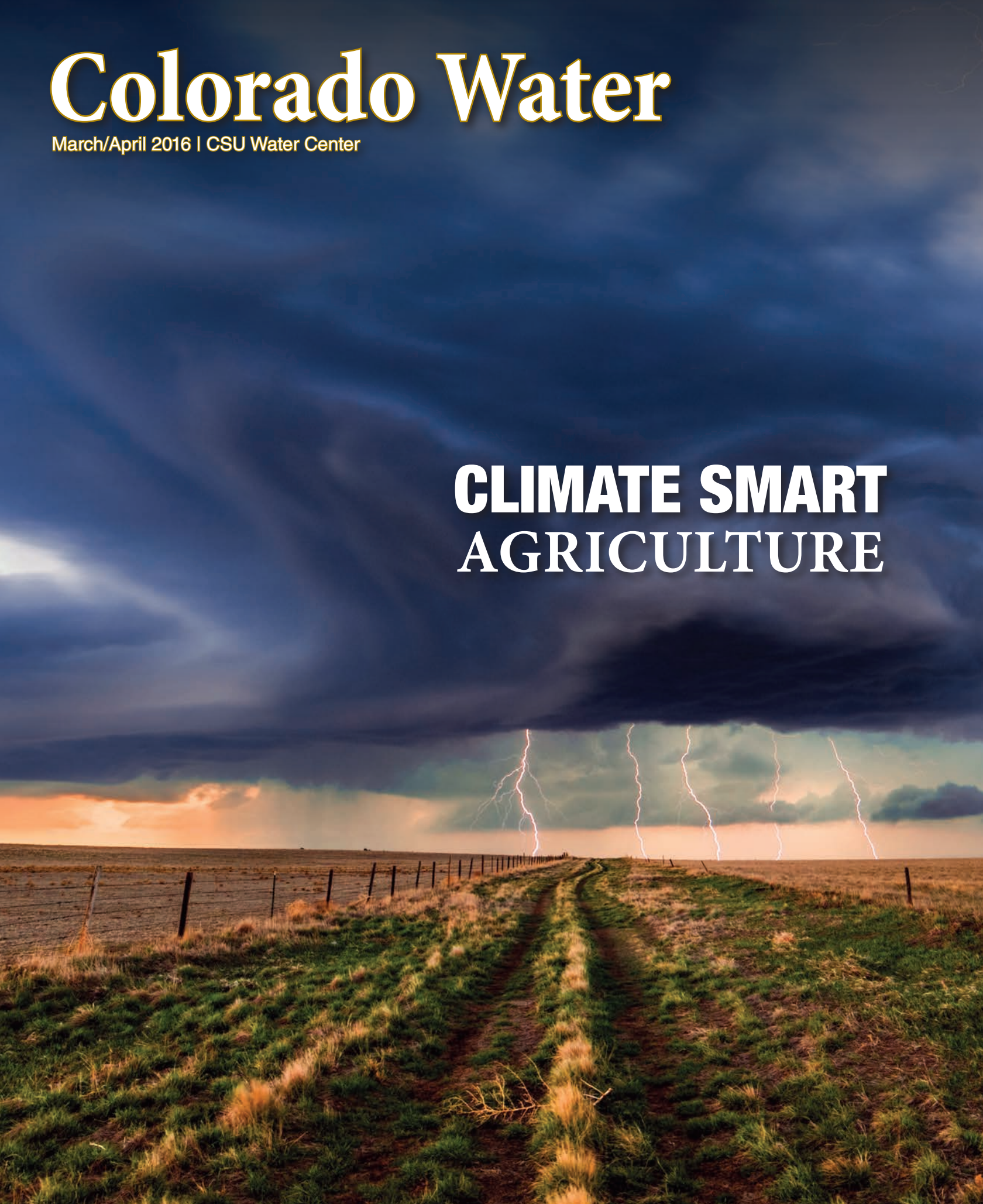


Colorado Water

March/April 2016 | CSU Water Center

CLIMATE SMART AGRICULTURE





I am writing this note at a hotel in downtown Beijing — one of the global posterchildren for the ecological crises and the political, economic and social complexities for addressing climate change. Here, all of your senses vividly register the consequences of human activity on the atmosphere, water, and soils. The Chinese government is feverishly ramping up efforts to mitigate pollution, including nitrate and chemical associated with their agricultural practices. At the end of last year a remarkable event occurred in Paris. After over twenty years of discussions, one failed agreement, and five major scientific assessments involving thousands of scientists, 195 countries agreed

to reduce their emissions of carbon to avoid harmful climate change. One hundred ninety-five countries actually agreed to recognize our common dependency on our planet.

Over my career, including as a Peace Corps Volunteer in western Tunisia, I have watched the climate change issue unfold with major impacts on the ground and have watched the science of climate dynamics mature. Concerns about the future resiliency of agriculture, in Colorado and globally, have led the Office of Engagement to undertake a new initiative on Climate Smart Agriculture to help producers plan for a future with a changing climate and the resulting social and economic adaptations. The goal of this initiative is to reduce the vulnerability of agriculture to a changing climate, including extreme weather events, and to assist our producers in being more nimble and successful in national and global markets. World class research by atmospheric and soil scientists has documented the causal link with human activities that emit greenhouse gases. Globally, agriculture is estimated to emit roughly 10 percent of these gases *but has tremendous potential to reduce and mitigate carbon emissions*. Doing this in an equitable and economic way is critical.

We started this initiative quietly in mid-2015 by holding listening sessions with agricultural and natural resource Extension agents from around the state. We asked them what they were seeing in the field, what their communities were saying about the topic, and what they needed to help prepare for this different future. We also met with our world-class climate scientists at CSU to discuss what an initiative would look like. Extension agents and faculty agree on the imperative of a science-based approach in tackling the climate change issue.

The initiative will be a partnership that includes all units of CSU engaging in climate action, including Extension, CSU Online, the College of Agriculture, the Department of Atmospheric Sciences, the U.S. Department of Agriculture (including their new Climate Hub at CSU), and the State of Colorado. President Tony Frank has endorsed the need for this initiative and supports our efforts to work with the Colorado Department of Agriculture and Department of Natural Resources to provide science-based tools to help agriculture. We plan to offer educational modules and programs and planning and risk management tools for Colorado agriculture. It will be a work in progress as we jointly learn what works and what is needed. This is a new kind of challenge, and one where no one knows all the answers.

The 21st century is bringing a number of challenges to agriculture including competition for water, urban growth, groundwater depletion, changing consumer preferences, and worldwide competition. Climate change is just another one of these challenges, albeit one huge in scale. We are keenly aware that climate change is a controversial subject. However, given the Paris agreement, the mature science, and the weather and climate changes we have already seen, it is irresponsible for CSU to not take this issue head-on. CSU has a long, proud record of working with agricultural producers to bring the best science and economics to bear on difficult problems. Together we will figure out how to adapt, and even thrive, through our research, intelligence, actions, and savvy. Focusing CSU engagement and outreach resources on these issues is an opportunity and responsibility for university-based research and Extension in collaboration with producers and consumers.

Lou Swanson
Vice President for Engagement

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Many theories have been advanced as to the cause of the change in weather. Some scientists feel volcanic dust explains in part why it is a disturbing factor; sun spots, which are variable is chiefly the reason. Since the spots increase and decrease in a more or less uniform pattern every eleven years it is assumed this variation influences the weather. It probably has some effect. Carbon dioxide gas in the atmosphere is at present a tremendous quantity, 235 billion tons. We are now adding 10 billion tons per year. Every time you drive your car around the block you make a contribution of this gas to the atmosphere. This gas together with ozone, water vapor and other gases at high altitude retards the radiation of heat from the earth's surface which increases the temperature of the air somewhat in the nature of the glass roof on a greenhouse. These various natural effects have been known for a long time but since man has little or no control we can only bend our efforts in the direction of safe guarding ourselves in the best possible manner. At the moment there does not appear to be a solution to this problem. Thank you for the privilege of discussing this interesting situation with you. Always a pleasure to attend Rotary.

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On the cover: Akron, Colorado
Photo by Bryce Bradford

Ralph Parshall, one of Colorado's water leaders and an internationally-celebrated member of the CSU faculty, gave a speech in 1957 at the Rotary Club in Fort Collins where he talked about how greenhouse gases emitted by humans could change the climate. Climate has since grown to be a significant international concern. Courtesy of Water Resources Archive, CSU Libraries

Global and Local Climate Change

What We Know and Expect

Bradley H. Udall, Colorado Water Institute, Colorado State University

SYNOPSIS

Anthropogenically-induced changes in climate are set to have global impacts on earth systems. In Colorado, these changes affect vegetation and growing seasons, water use and natural storage, water quality, temperatures, and weather patterns.

Introduction

We have known for almost 200 years that greenhouse gases (GHGs) are critically important for the Earth's climate. In the early 1800s, the French mathematician Fourier discovered that the Earth was approximately 60°F warmer than it should be. He suspected that the atmosphere trapped heat, warming the planet, but could not prove it. In 1864 the Englishman Tyndall discovered that carbon dioxide (CO₂), methane (CH₄), and water vapor were key gases that caused the warming discovered by Fourier. The Swedish scientist Arrhenius in 1898

calculated that doubling of carbon dioxide would increase the temperature of the Earth significantly. English engineer Guy Callendar further investigated the carbon dioxide link to warming in the 1930s.

In 1957, the U.S. became the first nation to track CO₂ concentrations, and we now have more than 50 years of data showing how CO₂ from fossil fuel combustion and other GHGs from human activity are increasing. In the 1960s and 1970s, scientists began to study the problem of climate change seriously. In 1975, rudimentary computer model experiments with doubled CO₂ were performed and they indicated that the water cycle, a primary mover of planetary heat, would change in fundamental ways due to increased heat. In 1979, a National Academy of Sciences panel convened to study climate change concluded that a doubling of CO₂ would increase air temperatures approximately 5°F. This projection is quite consistent with today's projections, which utilize

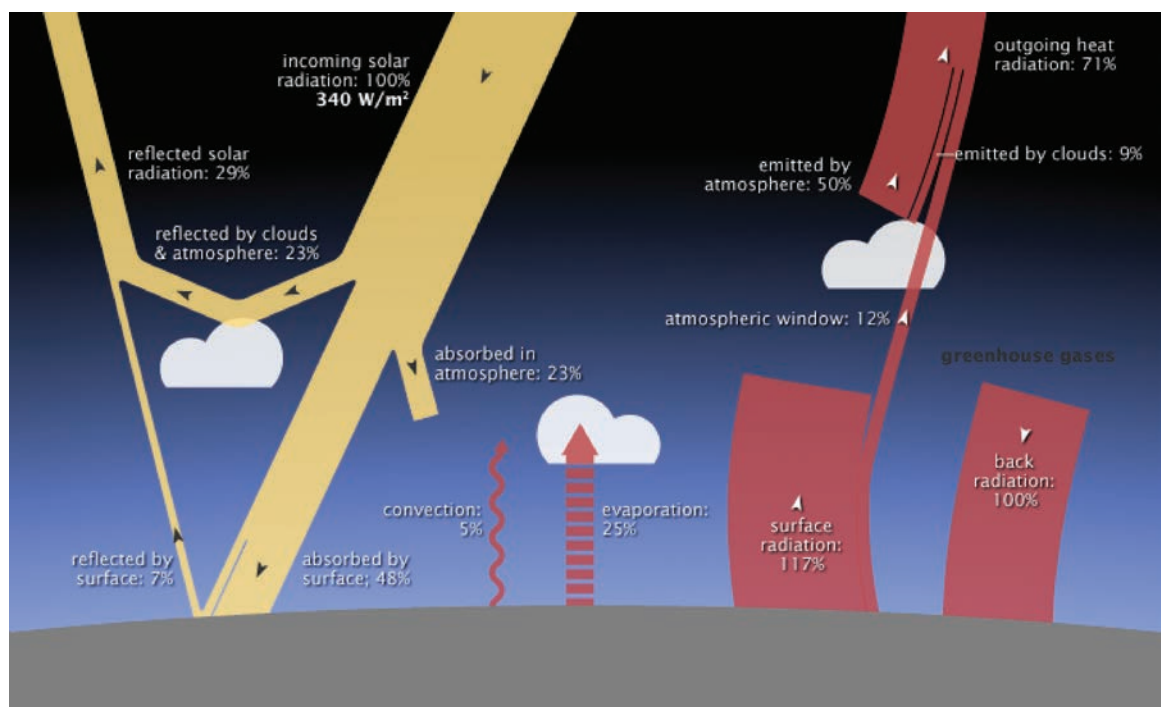
vastly more sophisticated techniques than were available at the time.

The study of what causes the Earth's climate to change is not new and understanding of the critical importance of the role of GHGs is also not new (Figure 1). There is broad and overwhelming agreement among climate scientists—sometimes stated that 97 percent of scientists agree—that climate change is real, serious, and that humans are the most important cause. This introductory article covers the history of climate science, climate science theory, evidence for climate change, and projections both globally and for Colorado.

The Greenhouse Effect

Fourier likened the Earth's extraordinary warmth to how a greenhouse works, although the physics are substantially different. What are now known as GHGs—predominantly CO₂, methane CH₄, and nitrous oxide (N₂O)—capture heat energy that would otherwise escape to

Figure 1. Greenhouse gases in the atmosphere (right) absorb and radiate heat energy in all directions including downward, and this added heating increases the surface temperature. Source: NASA illustration by Robert Simmon, adapted from Trenberth et al. 2009, using CERES flux estimates provided by Norman Loeb.



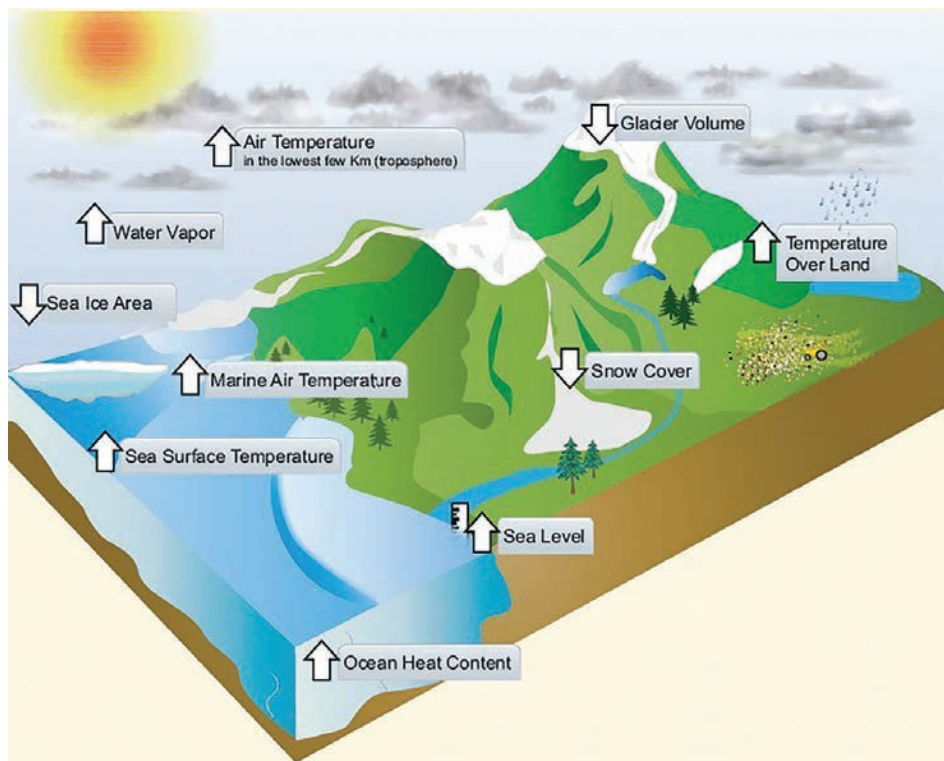


Figure 2. Independent analyses of many components of the climate system that would be expected to change in a warming world exhibit trends consistent with warming (arrow denotes sign of change). Source: WG1 report for the 2013 IPCC 5AR

space. The result is that the Earth's average temperature is above the freezing point of water rather than below it. Since the widespread burning of fossil fuels began in the Industrial Revolution, humans have caused the concentration of CO₂ to increase by nearly 40 percent, rising from 280 parts per million (ppm) to 400 ppm. If we continue on the current trajectory, CO₂ concentrations are expected to exceed 700 ppm by 2100. Other human activities release N₂O and CH₄, two other important GHGs. As a result of these emissions, the Earth's temperature has risen significantly, and will continue to rise so long as we continue to emit these gases. The most recent international assessment of climate change in 2014 said, "Human influence on the climate system is clear, and recent anthropogenic emissions of GHGs are the highest in history."

Emissions Versus Concentrations

We currently emit about 50 billion tons of greenhouse gases every year (see "Greenhouse Gases and Agriculture"). About half of these emissions remain in the atmosphere, and the other half are taken by plants and by

the ocean. The result is that the atmospheric CO₂ concentration has been increasing by about 2 ppm per year for the last decade. It is important to understand that concentrations of GHGs determine the Earth's temperature, not emissions, even though they are tightly coupled. Also, we will not return to a normal, pre-industrial temperature by simply ceasing emissions—this removal is a natural but long-term process taking thousands of years with elevated temperatures during this entire period.

Global Evidence for Climate Change

There are a large number of physical signs that the Earth is warming. Air temperatures over land are up by 1.8°F since pre-industrial times. Fourteen of the 15 hottest years since humans invented the thermometer have occurred since 2000. Fall sea ice extent in the Arctic Ocean continues to decline along with overall volume. Northern Hemisphere spring snow cover has decreased in extent. Ocean heat content, which absorbs 90 percent of the heat newly trapped by GHGs, continues to rise. (The atmosphere, by contrast, only stores about one percent.) Glaciers

everywhere, with few exceptions, are melting. Sea level is rising and the rise appears to be accelerating. Atmospheric water vapor is now approximately five percent higher. We are seeing more rain and less snow in winter. The lower atmosphere is warming while the upper atmosphere is cooling, a robust fingerprint of additional GHGs. All of these indicators show that the planet is warming (Figure 2).

Global Projections of Climate Change

Scientists are able to use a number of techniques to project the future climate under different GHG emissions trajectories. These techniques can range from using state-of-the-art climate models to a simple series of equations representing the known physics of the Earth's energy balance. Projecting climate is not like predicting weather. Climate is effectively the average of many weather events and even now we can make very accurate projections about climate such as seasonal temperatures and precipitation. Regardless of the complexity of the model used, these techniques invariably project a warmer planet, perhaps much warmer if emissions continue unabated, with a more active hydrologic cycle. We expect to see more evaporation and more precipitation, but with distinct regional winners and losers.

Under business-as-usual emissions, warming in 2100 is approximately 7°F, with a likely range from 6 to 10°F. It will warm more over land than oceans and more at the poles than the equator (Figure 3). Winter and summer will not go away; the seasons are determined by the Earth's 23.5 degree tilt relative to our orbital plane. Both seasons will warm, however, with the result that winter will be shorter and summer longer. Sea level may rise by up to one meter. Heat waves will occur more often and last longer.

With respect to precipitation, areas near the poles are expected to become wetter, and mid-latitude areas are expected to become drier, and portions of the equator wetter. In the U.S., the northern tier is expected to become wetter and the American Southwest drier. Extreme precipitation events will become more intense and frequent and droughts will become more frequent.

Global Water Cycle Changes

Since the earliest days of climate modeling it has been clear that the additional heat trapped by GHGs would modify the water cycle in fundamental ways, including where, when, and how much precipitation we receive. This should not be a surprise—heat from the sun, after all, is what drives the water cycle, and if we increase planetary heat the water cycle should change. Scientists have termed this “intensifying” or “enhancing” the water cycle. National and international assessments of climate change impacts always list changes in the water cycle near the top of the most important impacts of climate change.

There are two fundamental reasons why the water cycle will change significantly. First, a warmer atmosphere holds more water vapor, approximately four percent per degree F, and this increased capacity represents additional atmospheric demand for water. In other words, evaporation will increase. Second, the poles are warming faster than elsewhere, thus changing the Earth’s temperature gradient from equator to pole. That temperature gradient determines the locations of

the jet streams that in turn create storms, storm tracks, and overall weather patterns.

A warmer atmosphere also is more stable, meaning that fewer days will have precipitation with longer dry periods between precipitation events. Short-term droughts are expected to intensify, especially in the Southwest because of this effect. When it does precipitate, it is expected to rain harder. Indeed, this has already been noted throughout the world and the U.S. (Figure 4). The Front Range floods of 2013 were assisted by this additional atmospheric moisture.

One general finding is that wet areas will get wetter, and dry areas will get drier. We expect mid-latitude deserts, such as the Mojave and Sonoran deserts to our south, to expand northward. These changes have already been documented by scientists.

Colorado-Specific Projections

The state of Colorado’s focus on climate change has been predominantly on water, with two different scientific analyses conducted over the last eight years. Colorado has also studied how different economic sectors are vulnerable and even how climate

change might impact our compact obligations in the Colorado River. Front Range utilities have investigated their supply vulnerabilities in the South Platte. The Bureau of Reclamation has conducted a number of studies on how climate change will impact river runoff in the West, including the Colorado and Rio Grande. There are also broad overviews of the impacts of climate change in the American Southwest. It should be noted that global projections and patterns are inherently more certain than regional and state-specific projections.

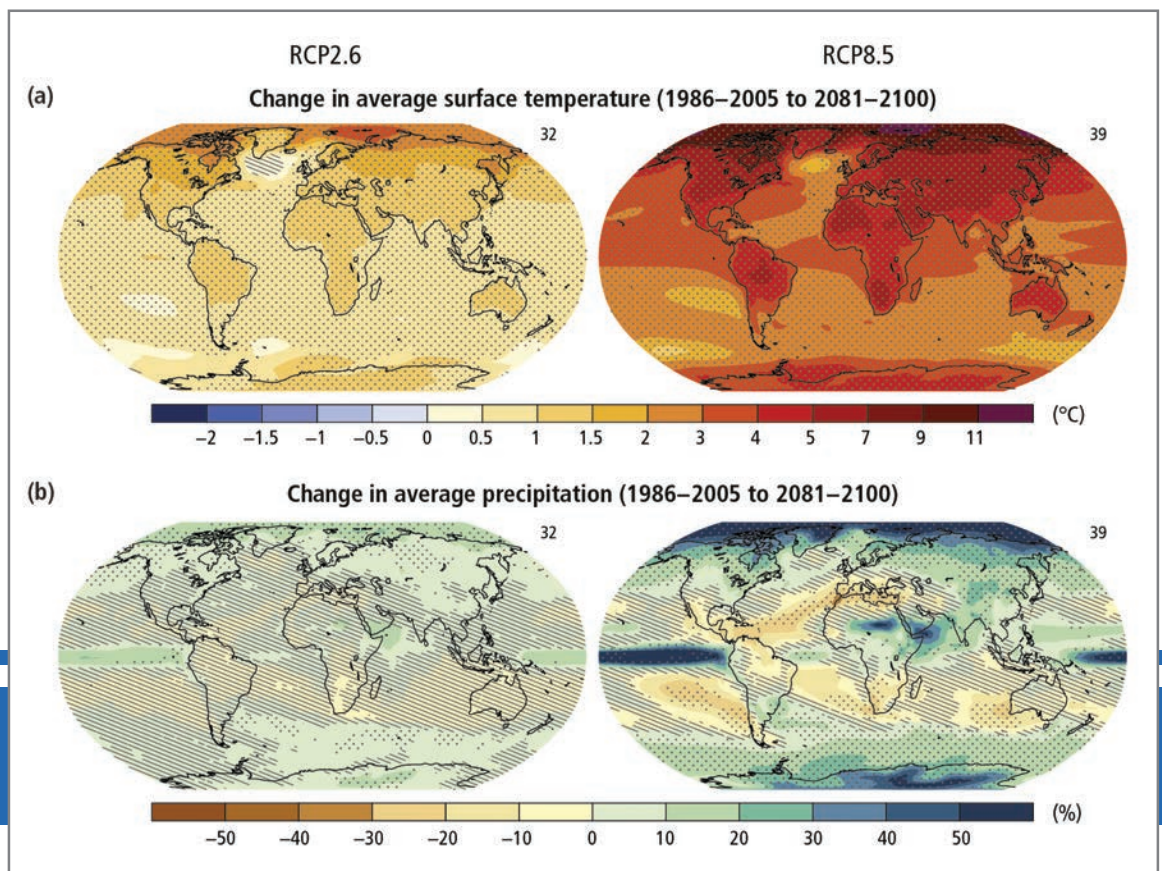
Future Temperatures

We expect to see average Colorado temperatures increase by 2.5 to 6.5°F by mid-century. Summer temperatures are projected to warm more than winter. Even under modest future emissions, typical summer temperatures in 2050 are expected to be similar to the hottest summers in the past 100 years.

Future Precipitation and Runoff

Colorado likely straddles the dividing line between precipitation increases to our north and precipitation declines to our

Figure 3. Change in average surface temperature (a) and average precipitation (b) based multi-model mean projections for end of the 21st century show low emissions at left and high emissions at right. Dots show areas with large changes and hatch marks show areas with small changes relative to current climate. Source: IPCC AR5 WGI.



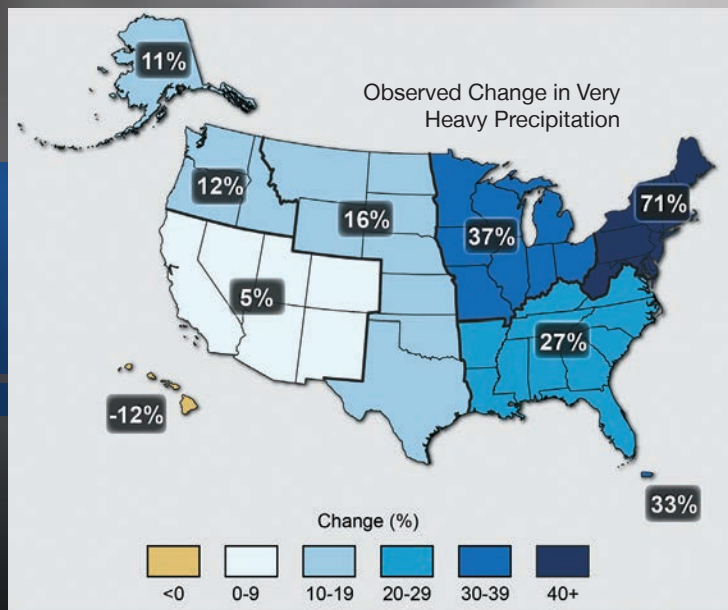


Figure 4. Percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest one percent of all daily events) from 1958 to 2012 are shown for each region of the continental U.S. Adapted from Karl et al. 2009, *Global Climate Change Impacts in the United States*

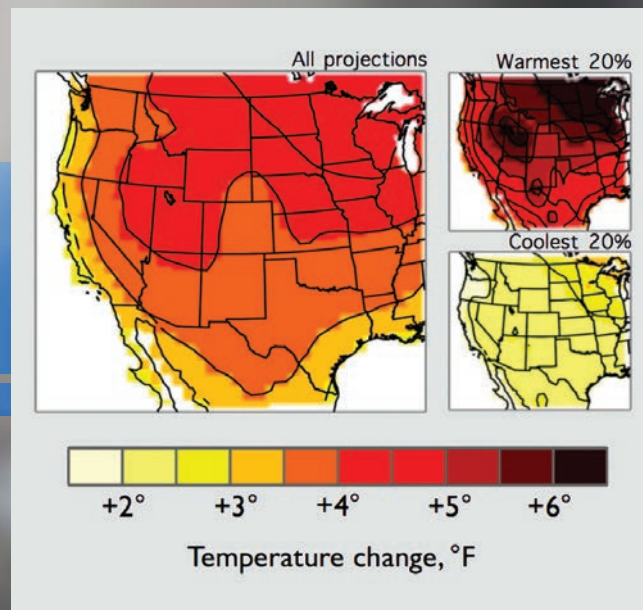


Figure 5. Models of annual average temperature by 2050 (2035–2064) over the western U.S. show substantial warming. Source: Lukas et al., 2014, *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation*

south. (Figure 5). Hence, southern areas in Colorado are likely to see small reductions in precipitation and especially runoff. This would include the Rio Grande, Animas, and San Juan. Northern areas may see modest increases in precipitation including the North Platte, Green, and perhaps the South Platte.

It is critical to note, however, that increased precipitation will not automatically translate into increased runoff. Because future higher temperatures will increase evaporation, and because hot periods in the spring and summer will be longer, modest additional precipitation will likely not result in future flow increases. Studies indicate that warming alone will decrease runoff in the Colorado River by about four percent for every 1°F of warming due to increased evaporation from land surfaces and plants. Throughout the state we expect to see declines in April 1 snowpack due to warming in the spring.

Extremes

In general we expect to see more extremes of all kinds under climate change. Heat waves and droughts will increase in both frequency and severity. Wildfires will increase in both frequency and severity. Heavy precipitation events will similarly increase.

Future Runoff Timing, Rain Versus Snow

In Colorado's snowpack basins, a number of changes will arise. First warmer temperatures will make for shorter winters with a shorter period to accumulate snowpack. By mid-century, we expect to see runoff one to three weeks earlier in the spring, and lower flows in the late summer and fall. (This is in addition to the one to four weeks earlier that runoff has already advanced over the last 30 years.) Projections also include more rain and less snow and with rainfall occurring on the shoulders of fall and spring when it would have snowed historically and at lower elevations where it is slightly warmer.

Water Quality

Water quality is expected to suffer. The combination of more intense precipitation, higher air and water temperatures, lower flows late in the year, and intensifying droughts are expected to decrease water quality in both lakes and streams. Increased sediment, decreased pollutant dilution from lower flows and decreased oxygen from higher water temperatures will lead to decreased water quality. Fire severity is expected to increase as temperatures warm and in recent years Colorado fires have been associated with

both increased sediment and decreased water quality.

River Annual Volume Projections

Reclamation's projections for the Colorado River show a median decline of 9 percent by mid-century with, however, a wide range of possible outcomes. Other studies have indicated reductions ranging from 6 percent to 45 percent by mid-century. The Rio Grande is also expected to decline with median flow reductions of 33 percent by 2100.

Megadroughts and Dust on Snow

The risk of megadroughts, defined as multi-decadal periods with substantially less precipitation, is expected to increase from 10 percent in the 20th Century to over 80 percent in the 21st century. In the first decade of the 21st century dust landing on snow in Colorado's southern mountains impacted Colorado River runoff. The dust darkens the snowpack which leads to faster melting in the spring, earlier runoff by three weeks and flow reductions of five percent (Figure 6). These dust-on-snow events appear to be related to drought in Utah and Arizona, the source areas for the dust, and have a reasonable likelihood of becoming more common in the future at the Southwest dries.

Figure 7. The evolution of flows is projected to 2100 past the Rio Grande Compact index gages in Colorado. Source: Llewellyn and Vaddey, 2013, West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment

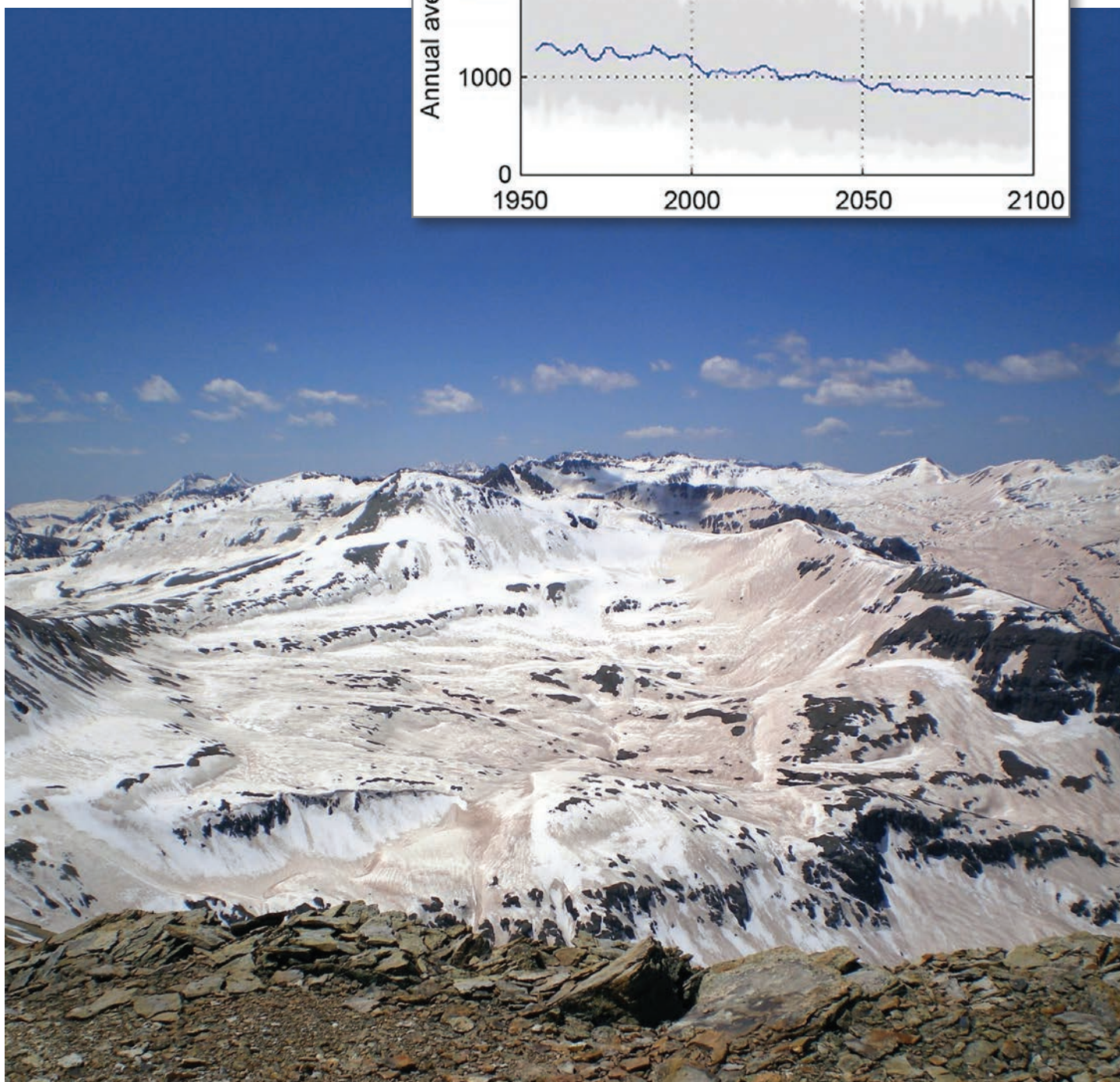
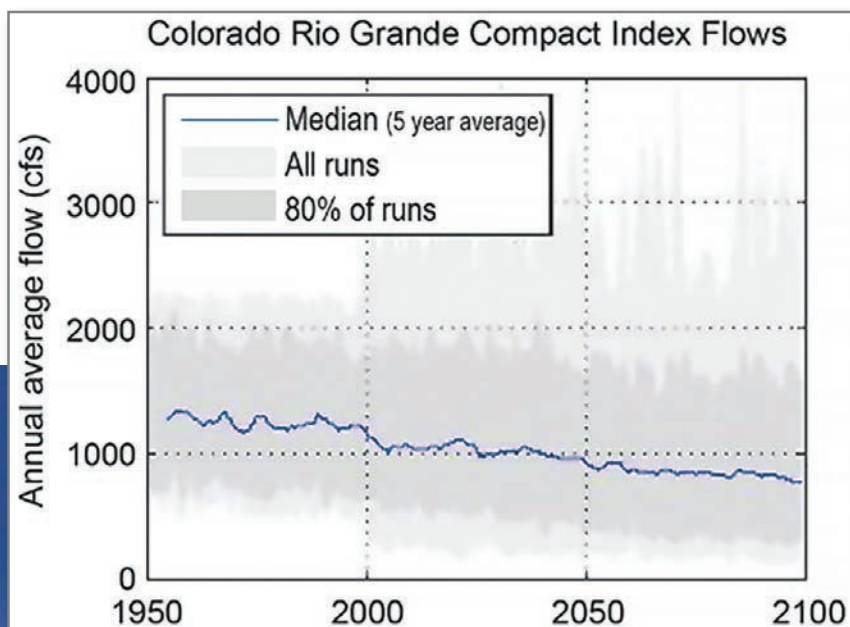


Figure 6. In the Colorado Rocky Mountains snowpack, dust from disturbed deserts of the West has increased by 500 percent and shortened snow cover duration by a month or more. Source: T. H. Painter, Snow Optics Laboratory, JPL/Caltech; NASA

Water Demands, Evaporation

Recent work by Reclamation indicates that perennial crops like hay and alfalfa will use more water—and yield more—because of increased temperatures and the expanded growing season. In some locations it may be possible to harvest additional hay cuttings. Annual crops, on the other hand, may be planted and harvested earlier, perhaps not significantly needing more water. Reservoir evaporation at Lake Powell increases by about six percent and at Elephant Butte Reservoir in the Lower Rio Grande by 7.5 percent in 2100. Another Reclamation study suggested that overall water demands in the Colorado River will increase by about four percent by mid-century.

Changes in Frost-Free Seasons

A 4°F rise in temperature, which is likely by mid-century, would translate into a shift of 20 to 40 additional frost-free days. The largest increase would occur in Colorado's mountains. In the mountains a longer fire season would result. Elsewhere, this additional growing period may not, however, benefit agriculture as additional warmth and dryness could create stresses on plants.

Water Rights

Climate change is expected to impact water rights with changing senior-junior relationships. The shifting annual hydrograph means that more water will run off earlier in the spring and less in the summer and fall. In one study on the South Platte, in the future upstream municipal reservoirs were able to store water in the spring under junior water rights when historically they were called-out by downstream senior South Platte users. In this example, the runoff occurred early in the spring before downstream crops needed significant amounts of water.

Lower flows in the summer and fall mean that some senior users who historically were just in priority would not have water. Water exchanges, which are important in the South Platte River and elsewhere, may be less dependable due to less flow in the late summer and fall to exchange against. Agricultural water rights in Colorado are typically not quantified as to consumptive use and in-priority irrigators are allowed to divert as much water as

necessary to grow crops. With longer growing seasons, very senior rights may choose to continue to divert to get extra hay cuttings.

Colorado's River Compacts

Colorado's interstate compacts are particularly of interest with respect to climate change. Two of these compacts have been studied. Under the Colorado River Compact, the Upper Basin states of

*"We will not
return to a normal,
pre-industrial
temperature by
simply ceasing
emissions."*

Colorado, New Mexico, Utah and Wyoming are not to deplete the flows by more than 75 million acre-feet every ten running years. Under some interpretations of the Compact, were climate change to reduce the flows from the headwaters as seems likely, the state would have to curtail existing post-compact diverters in order to meet this compact requirement.

Many of the most important Colorado River diverters in the state including Denver Water, Colorado Springs, and the Colorado Big-Thompson project are post-compact diverters. The state and others are investigating voluntary ways in which pre-compact diverters, which are exempt from the depletion requirement, could be compensated not to divert, thus allowing economically more important post-compact diverters to continue their water use. Unfortunately, pre-compact diverters are almost all Western Slope agricultural operations and thus this solution would thus focus impacts on one geographic region.

The impacts of climate change on the 1939 Rio Grande Compact have also been studied. Under this compact Colorado has annual delivery requirements to New

Mexico based on index flows at stream gages in Colorado. A 2013 Bureau of Reclamation study looked at climate change impacts. At 2100 median flows decline by 33 percent at Colorado's index gages (Figure 7). Colorado's consumptive use would drop by 25 percent—not 33 percent—because of lower delivery obligations to New Mexico as flows decline. Because of its relatively small and southerly headwaters, the Rio Grande may be the most threatened western U.S. basin to the impacts of flow reductions.

Concluding Thoughts

Over the 4.5 billion years that the Earth has existed its climate has varied tremendously. It has gone through "snowball Earth" phases and the hot swamps of the dinosaur ages. Humans, however, have only been on the planet in their current form for a tiny fraction of this time, the last 200,000 years. And human civilization has grown to its present advanced state only in the last 2000 years, with the last 100 being especially important when we grew from one billion to seven billion people. Our ability to grow food for these inhabitants, to build strong economies, to live in our coastal cities on the shores of oceans, and to maintain stable relationships with other countries are all dependent on the climate of the past 200 years, not some distant and vastly different climate when we were either insignificant or didn't exist at all.

In 2015, CO₂ concentrations reached levels not seen for at least 800,000 years, well before humans in their current form roamed the Earth. Carbon dioxide concentrations could grow to over 700 ppm by 2100 with as much warming (7 °F) as the last ice age was cold (-7 °F). Scientists are certain of the cause of the recent warming—our GHG emissions. Equally important, there is no other viable explanation for the changes that we are experiencing. Climate change is a very serious and pressing threat, but one that can be solved by both adapting to the coming changes (see "Agricultural Climate Change Impacts and Adaptation Opportunities for Colorado") and by reducing GHG emissions using currently available affordable technology, provided we act soon and decisively (see "Solving the Climate Riddle").

State of Colorado Climate Change Actions

Taryn Finnessey, Climate Change Risk Management Specialist, Colorado Water Conservation Board

John Stulp, Special Policy Advisor to the Governor for Water, State of Colorado

SYNOPSIS

State programs are working toward climate change adaptation and mitigation in areas like water use and energy efficiency, but more needs to be done.

Climate change poses many threats to Colorado's economy, natural resources and way of life. Impacts range from the resilience of our iconic native species to the durability of our transportation infrastructure. The state's natural resources and habitats will experience changes as temperatures warm, making conditions more suitable for invasive species and increasing potential for more severe wildfire. In addition to wildfire, other extreme weather events may become more common, ranging from droughts to floods. Streams that flow from the mountains and into our reservoirs will warm, allowing for higher nutrient and bacteria content in the water; and wildfire in watersheds may result in sediment loading from recent burns. Snowpack will likely melt off several weeks earlier, altering flow regimes for fish and water users alike. With warmer temperatures, overall runoff will likely decrease while crops will simultaneously need more water to grow as evapotranspiration rates increase. The challenges we face will affect everyone, and require collaborative solutions; consequently, this is an issue that has the attention of the State government.

At the State level, our response to a changing climate cannot be a partisan issue; rather it is an economic development issue, a public health issue, a natural resource issue, and an emergency response issue. While the science is not perfect and we do not know the exact effects that will result from rising temperatures, we

have enough information and confidence in the science to move forward in addressing this issue in a meaningful way, despite the uncertainty. Being proactive and prepared will ensure that Colorado remains a spectacular, vibrant, and economically diverse state for generations to come.

Over the past eight years, the State has committed millions of dollars, staff time and other resources to examine what climate change means for the state. New staff has been hired and programs developed. We have quantified how climate change may affect water availability and crop irrigation requirements in the Colorado River Basin, both within our state and within the greater basin. We have developed a synthesis of climate change science specific to Colorado, to help water managers and policymakers alike make more informed decisions about management and adaptation. And we have an entire state office dedicated to improve the effective use of all of Colorado's energy resources and the efficient consumption of energy in all economic sectors. Our approach to climate change is, and must continue to be, twofold—we must ensure that we are taking steps to reduce our greenhouse gas emissions in a balanced and responsible way, while also pursuing adaptive strategies that protect the core elements that make Colorado such a desirable place to live, work, and play.

With regard to greenhouse gas emissions reductions, we have focused on energy efficiency and expansion of our renewable energy economy. Since 2004, when Colorado was the first state to establish a statewide Renewable Energy Standard we have increased renewable energy generation by nearly 14 percent. Thirty-five additional energy efficiency bills have passed in the legislature in the last 10 years, some strengthening the 2004 Renewable Energy Standard, others, such as the 2010 Clean Air Clean Jobs act, target emission reductions from coal fired power plants. We are the first state to directly regulate methane (a powerful greenhouse gas)



emissions, from the oil and gas industry and have created a \$50 million alternative fuels grant program. Xcel Energy, one of the state's largest energy providers, has reduced carbon dioxide (CO₂) emissions 26 percent during this time, with an additional 11 percent reduction projected by 2020. At the same time Colorado was recently ranked as the nation's second lowest "energy expensive state" and seventh overall energy efficient state. This study, and many others, make it clear that energy efficiency and use of alternative energy can be successfully expanded without harmful oppressive impacts to rate payers.

"Regulation at the federal level has and will continue to help Colorado reduce overall emissions."

Regulation at the federal level has and will continue to help Colorado reduce overall emissions as well. In the summer of 2013 the Obama Administration released the President's Climate Action Plan, which aims to reduce CO₂ emissions from fossil fuel fired electric generating units, Colorado's largest source of emissions. The Environmental Protection Agency responded with the submission of the Clean Power Plan, in August of 2015, which both reduces emission from existing electric generating units as well as establishing carbon limits for new, modified and existing units. Governor Hickenlooper has committed to implementation of this rule which in Colorado will result in a 38 percent reduction of CO₂ emissions by 2030 and represent Colorado's largest emission reduction initiative.

Public health and the energy sector are not alone in their pursuit and adoption of cleaner innovative technologies and solutions. The agriculture sector has been at the core of Colorado's economy and culture since the beginning and is now finding and implementing solutions. Small scale hydro-electric power is being installed on pressurized irrigation

systems through the Hydropower Partnership Project. As the number of dairy farms populating the state continues to grow, so too does the opportunity for biomass energy production. Anaerobic digestion is one way to responsibly manage waste on dairy operations while also producing clean renewable energy and reducing greenhouse gas emissions. One of the nation's largest digesters is already under construction near LaSalle, Colorado. Once complete, the project will convert feedstock from dairy farms to raw biogas that will be processed into quality natural gas and sold to utilities.

The Colorado Department of Transportation is also committed to reducing emissions through improved public transit, more fuel efficient and alternative fuel vehicles and reduced congestion. Taken together these initiatives will help Colorado as a state reduce our greenhouse gas emissions, clean our air and increase efficiency. Yet, despite all our efforts some impacts of climate change cannot be avoided.

Already we are seeing shifts in the timing of snowmelt runoff, more frequent droughts, and longer frost-free seasons. These impacts require the development of adaptation measures that will help to safeguard the state from those impacts that are unavoidable. This is especially true in the water sector which affects nearly all aspects of Colorado's economy. Consequently, the state has included climate change effects on water resources as a key element in the newly released Colorado's Water Plan. The Plan lays out how to implement water supply planning solutions that meet Colorado's future water needs while supporting those dependent on our limited water resources such as healthy watersheds and environment, robust recreation and tourism economies, vibrant and sustainable cities, and viable and productive agriculture. One component of this includes setting strong water conservation goals for our growing cities and towns.

Colorado has come a long way over the last ten years, expanding our use of clean energy, improving energy efficiency, and developing practical adaptation strategies. Yet in the face of a changing climate, we recognize that there is still more to be done. Over the course of the next year the State will hold a number of sector-specific public engagement sessions where experts and the public alike will have the opportunity to help inform and shape the path we will take going forward to address climate change. We hope to see many of you there. ☺

Uncompahgre Peak, Colorado
Photo by Flickr user Scrubhiker (USCdyer)

Climate Trends in Colorado over the Past Century

Nolan Doesken, Colorado Climate Center, Colorado State University

SYNOPSIS

Colorado is experiencing the same changes in climate that are occurring nationally and globally. This includes higher temperatures, more record setting heat events than cold events, lower snowpack in low elevation areas, and earlier runoff. Hard frost dates have not changed.

It comes as no surprise that there is great interest in observed climate trends here in Colorado these days. But it is not the first time. When the Colorado Agricultural College was first established in the 1870s and 80s (later renamed Colorado State University), the interest in weather and climate was already keen. Weather instruments (thermometers, rain gauges, etc.) were quickly acquired, and a weather station was established to document the local climatic characteristics, seasonal cycles, and year-to-year variations affecting Colorado agriculture, irrigation, water supply, forestry, and mining. There was already talk then of humans changing the climate.

The theory that rain followed the plow had been promulgated by early settlers, developers and railroad publicists to lure more people to the dry West. At times during periods of wet weather that theory seemed plausible. Then, with rapidly expanding irrigated agriculture in Colorado in the late 1800s, many thought that irrigation might be changing the climate just as it was changing the landscapes of Colorado's river valleys. Throughout the 20th century, events like the Dust Bowl of the 1930s, the drought of the 1950s, and the cold waves in the 1960s and 1970s continued to provide fodder for these ideas. But over time, neither the data nor scientific theory provided support for the idea that humans were changing the climate over wide areas by irrigation, reservoirs or other local land use changes.

Meanwhile, carbon dioxide (CO₂) measurements, started in the 1950s, show a steady march upward due to growing global consumption of coal, oil, and natural gas. And throughout the 20th century, our knowledge that CO₂ and other greenhouse gases could change the climate not just locally but globally became stronger and stronger. Multiple scientific

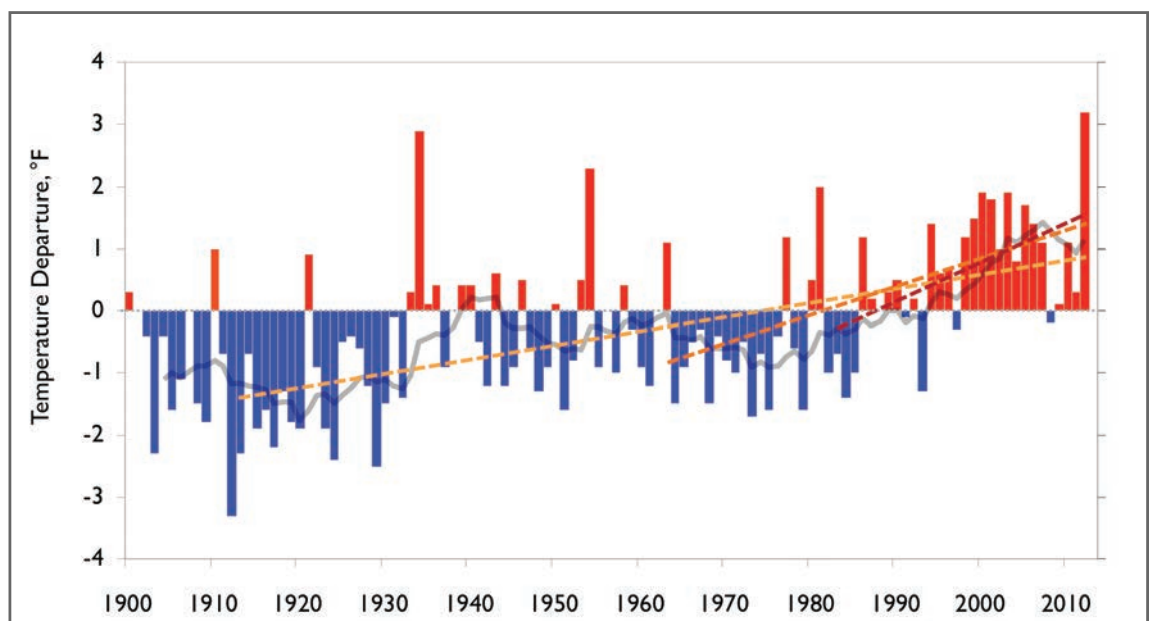
assessments over the last 25 years have now demonstrated that humans are changing the climate because of these gases. Indeed, CO₂ concentrations are now 40 percent higher than they were before humans started burning fossil fuels and global temperatures are now 1.8°F warmer. Unlike the other early ideas for how we might have been changing the climate, we now have scientifically robust cause for anthropogenic, or human-caused, climate change.

This brings us to where we are today—again, keenly interested in our climate. In my many years on the job here I have never seen so much interest in the historic climate records and what they are showing. Fortunately, we've maintained and expanded weather stations and mountain snowpack observations over the past century.

What Do Our Climate Data Tell Us?

Thanks to a vision for distributed weather stations begun by the Colorado Meteorological Association and then championed by the old US Weather Bureau, the National Weather Service (NWS) and

Figure 1. Annually-averaged statewide temperature for the state of Colorado, in °F, shows 100-year, 50-year, and 30-year trends in light-orange, orange, and red lines, all of which are statistically significant. The gray line shows the 10-year running average. Source: Lukas et al., 2014, *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation*



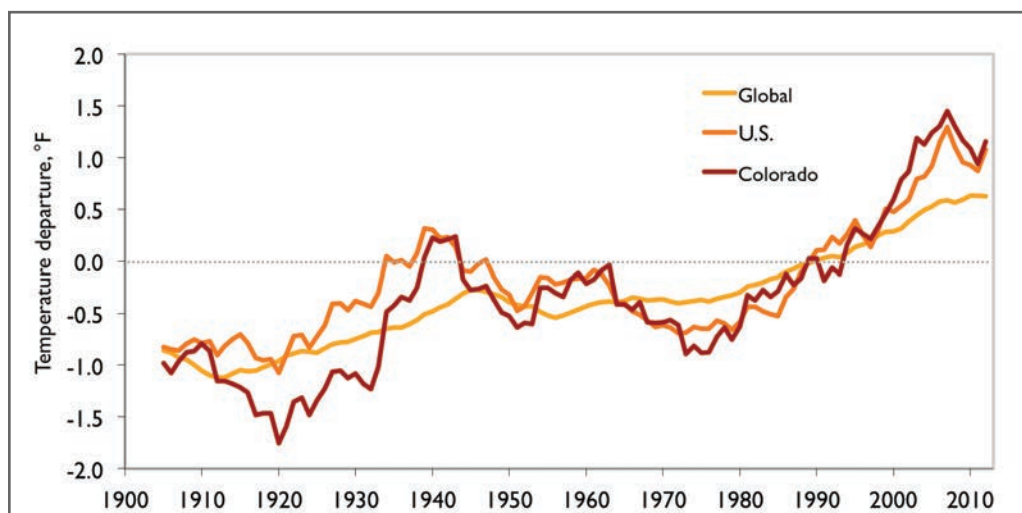


Figure 2. Average annual surface temperatures in °F, observed in Colorado, the U.S., and globally from 1895-2012, are shown as departures from a 1871-2000 baseline. Overall trajectories of the three are similar, though there is more variability and a larger recent warming trend at smaller spatial scales. Source: Lukas et al., 2014, *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation*

the Colorado Agricultural Experiment Station, we now find ourselves with over 125 years of continuous weather data of reasonably high quality. The weather records are good and very useful, but they are not perfect for detecting trends. The reason for this is that there have been changes over this time period in how, when and where measurements are taken.

Most weather stations have been moved to new locations at least once. The Denver weather station has been moved multiple times from downtown, to Stapleton Airport and finally to Denver International Airport. As a result, the Denver climate data cannot be used for detecting trends in climate over these periods.

Thermometers and temperature shelters have changed at most weather stations from traditional glass thermometers in wooden shelters (that was the standard for nearly 100 years) to primarily electronic sensors in plastic housings. These new sensors have systematic, not random, changes with most NWS electronic temperatures reading slightly cooler during the day. Another factor is urbanization and land-use change. Fort Collins is a prime example where a noticeable “urban heat island” is apparent in our campus weather data.

Each of these changes can affect our climate records—sometimes subtly, sometimes noticeably. However, by selecting the right stations, knowing when sensors were changed, and being aware of local land use changes, scientists can remove many of these artifacts with careful

analysis. Hence, despite these imperfections, much of our historic climate data are still very useful for addressing the questions “Are we getting warmer?”, “Are we getting drier?”, “Are we getting less snow?” and “Are growing seasons changing?” With this background in place, let’s look at what our Colorado weather station data are showing.

Temperature Trends

Temperature measurements from Colorado’s most complete and consistent long-term weather stations show upward trends in mean annual temperatures throughout the state of about 2°F during the last 30 years (Figure 1). These results, which first appeared in the 2014 “Climate Change in Colorado” report prepared for the Colorado Water Conservation Board, seemed at the time to exaggerate the shorter term warming trend. This was because 2012, the last year of complete data used in that analysis, was an extraordinarily warm year. Interestingly, now that three more years of data have now been collected and compiled, this upward trend is confirmed and continues. In fact, calendar year 2015 now ranks as the third warmest year in Colorado’s observed history based on statewide averages, behind 1934 and 2012 and just slightly ahead of 1954. Globally, 2015 was the warmest year since humans developed thermometers.

All previous extremely warm years here in Colorado were also years with widespread extreme drought. 2015, on

the other hand, was a relatively wet year. Since the 1990s there has been more of a tendency to see above average temperatures in both dry and wet years. While Colorado temperatures, averaged across the whole state, show considerable year to year variability, their general pattern is quite similar to both the U.S. average and the global average (Figure 2).

From 1900 to the early 1980s, the upward trend was noted at some locations but was not large. Most of the trend was in warming nighttime temperatures that began in the 1980s. However, since the mid 1980s upward trends are observed in all seasons of the year, in most areas of the state, and in both daytime and nighttime temperatures. This Colorado warming also coincides with global temperature increases, and occurred during a period in which greenhouse gas concentrations rose quickly.

Similar patterns emerge when looking only at summer heat and winter cold extremes. While results vary among individual weather stations, most weather stations have seen fewer extreme cold temperatures since the early 1990s and more frequent hot summer temperatures. A similar pattern is seen in the U.S. during the last fifteen years when we have been setting about twice as many high temperature records as cold records. In Colorado this past summer was an interesting exception with very few extremely hot days. Nevertheless, summer seasonal temperatures in 2015 were still consistently warmer than long-term averages.

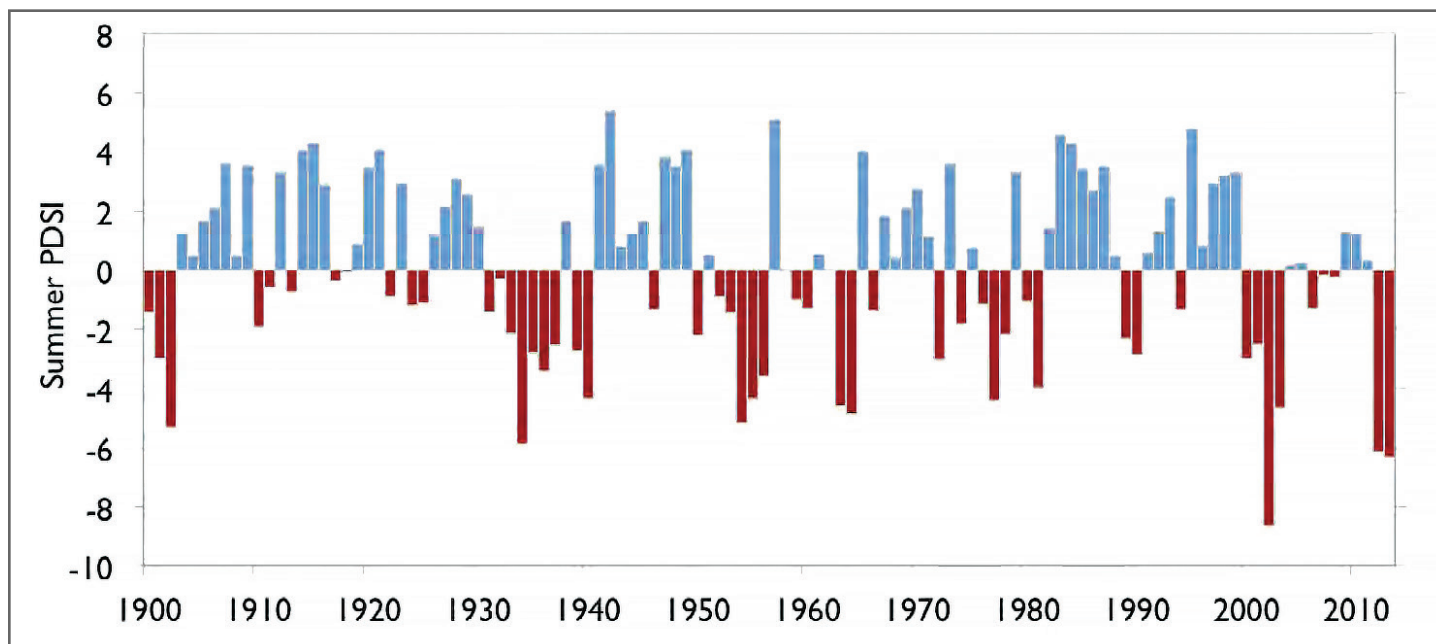


Figure 3. Palmer Drought Severity Index (PDSI) for Colorado summer months (June–August) from 1900–2013 shows multi-year droughts in the 1930s, 1950s, and 2000s. Source: Lukas et al., 2014, *Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation*

Frost Dates and Growing Season

It is tempting to assume that with warmer seasonal and annual temperatures, Colorado would also be experiencing earlier last freezes in the spring, later first freezes in the autumn and overall longer growing seasons. Curiously, this has not been the case for hard freezes defined as 28°F, at least not yet. For some parts of Colorado, 2015 stood out as a particularly long growing season, as did 2012. But overall, no clear trends toward longer growing seasons as measured by hard freezes have been detected at many of our best long-term weather stations. This presents a significant challenge and hazard. With warmer spring temperatures, many plants including fruit trees have been breaking dormancy earlier, only to be nipped by late freezes. Likewise, warmer spring soil temperatures have been tempting farmers to plant earlier, but so far this has been risky.

Precipitation Trends

Most of Colorado is semi-arid (less than 16–20 inches of precipitation annually) with local areas like Grand Junction in Western Colorado, the Four-Corners area of southwestern Colorado, and the San Luis Valley in south central Colorado all averaging less than 10 inches per year. In semiarid areas, year-to-year variations

tend to be very large with annual precipitation ranging from roughly half the long term averages in dry years to double the average in exceptionally wet years. This high variability makes the detection and description of trends difficult.

At this point (2016), statistically significant trends in precipitation have not been identified. The most obvious characteristics of our rain gauge-measured precipitation history are locally unique patterns that average out to show decadal fluctuations with generally wetter weather in the 1910s–1920s, dry in the 1930s, wet again in the 1940s, dry in the early and mid 1950s, extremely variable from 1957 through the 1960s, dry in the 1970s, quite wet 1980s–90s and then dry again 2000–2012 with a return to wetter weather these past three years.

Periodic drought is an ongoing concern (Figure 3). Precipitation data collected over the past 125 years show widespread severe drought visits Colorado quite regularly and rarely do we go more than 20 years without an extreme drought period affecting much of the state. Tree-ring records suggest that this has been the case as far back as records go. Drought and heat often go together, but as the drought of 2012 showed, drought impacts are accentuated by extreme heat.

Detection of trends in extreme

precipitation is even more challenging. Regional studies for the Southwestern U.S. have shown small increases in large precipitation events, but so far here in Colorado we have not yet seen any trend. By comparison, other parts of the country, east and north of Colorado have shown systematic increases in heavy precipitation days. Basic physics and our climate models tell us that we should be experiencing more intense precipitation events and longer dry periods between events.

Snowfall and Snowpack

Measurements of the water content of snow on the ground in the mountains of the West on April 1 each year have long been used by irrigators and municipal water managers to predict with reasonable confidence the water supplies for the coming spring and summer. Several studies of winter snowpack accumulation in the Western U.S. have noted tendencies towards less accumulation and earlier snow melt in the mountains. This is particularly true for the Sierra and Cascade mountains. This is less clear here in Colorado, probably because of our higher elevations, cooler temperatures and greater springtime precipitation. Nevertheless there is some evidence now of decreasing April 1 snowpack at least at

the lower to mid elevation measurement sites between 8,000 and 10,000 feet in elevation although it is not yet statistically significant (Figure 4). Finally, runoff has been occurring one to four weeks earlier over the past 30 years.

Trends in Other Climate Elements

There is interest in other elements such as humidity, cloudiness and winds – factors that would work together to influence evaporation and transpiration rates. This is important for Colorado water resources to determine if more or less of our precipitation is available as surface water supplies. Long-term and historically consistent data for these elements are largely unavailable, unfortunately. Some evidence of increases in cloud cover were noted up through the 1980s, possibly associated with large increases in high level cirrus clouds associated with jet aircraft. Humidity and wind data

resources are inadequate to track trends.

The Colorado Climate Center is attempting to track trends in growing season evapotranspiration for irrigated vegetation using data from the Colorado Agricultural Meteorological Network (CoAgMet). Unfortunately, data only go back to the early 1990s—too short for meaningful trend detection. Much of Colorado had experienced exceptionally high reference evapotranspiration in 2012. Interestingly, 2015 was one of the lowest reference evapotranspiration years (since 1992) despite above average late summer temperatures. This was due to higher humidity and cloudiness last summer following the exceptionally wet May and early June. This shows the enormous complexity of our climate system.

Summary

Coloradans have long been concerned that the activities of humans might be

changing the climate. But the reasons put forth for changes in the late nineteenth and early 20th centuries – irrigation, reservoirs, plowed land, tree cutting—were ultimately not scientifically valid and no long-term trends were found. We now know, however, that the planet is warming because of increased concentrations of greenhouse gases, most of which have been emitted since the 1950s. Many of the changes that we expect to see from this overall warming are also occurring in Colorado. These include higher temperatures, more record setting heat events than cold events, lower snowpack in low elevation areas, and earlier runoff. We are all particularly wary of drought. While the frequency of drought does not appear to be any more or less than in the past, warmer temperature may mean sharper and higher-impact drought such as we experienced here recently in 2012. ☁

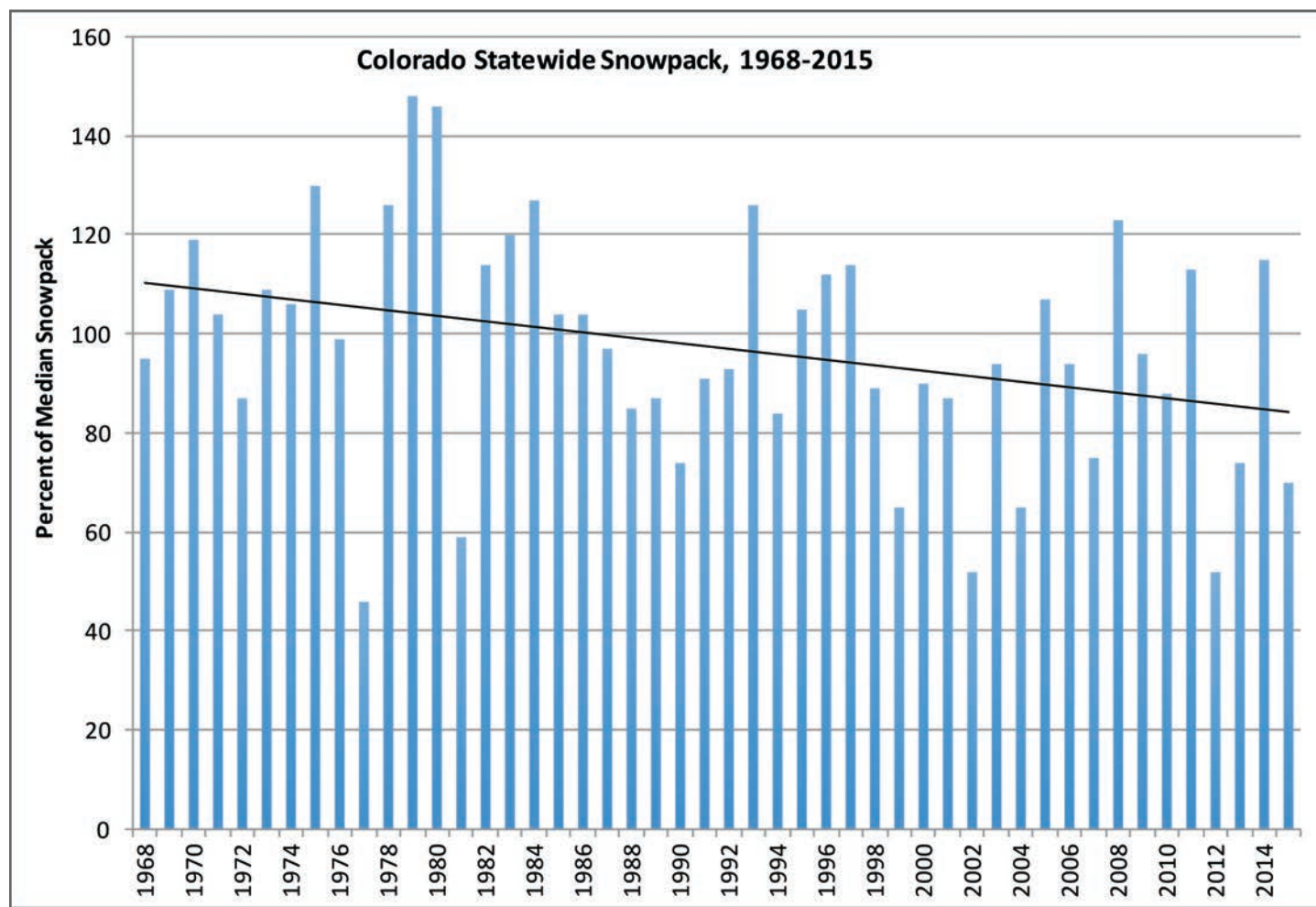


Figure 4. Statewide April 1 snow water equivalent as measured by the NRCS from 1968-2015 shows a decreasing trendline. Data Source: nrcs.usda.gov/wps/portal/nrcs/detail/co/snow/products/?cid=nrcs144p2_063325

Greenhouse Gases and Agriculture

Bradley H. Udall, Colorado Water Institute, Colorado State University

Introduction

Worldwide total greenhouse gas emissions in 2010 were just shy of 50 billion tons (gigatons or 'Gt') of CO₂ and CO₂ equivalents (CO₂eq) (Figure 1). By type of greenhouse gas, 76 percent of total global emissions come from CO₂, mostly derived from the burning of fossil fuels to generate energy (65 percent) and from deforestation and other land use change in developing countries (11 percent). Methane, CH₄, is responsible for 16 percent of total emissions. It comes from agriculture (manure and enteric fermentation

from ruminants), petroleum development, landfills, wastewater treatment, and coal mining. Nitrous oxide, N₂O, provides about six percent of total emissions. It is almost exclusively tied to agriculture (fertilizer and manure) with a small amount coming from fossil fuel combustion. There are also very small contributions (about two percent) from fluorinated gases associated mostly with air conditioners. Combining all three gases, agriculture is responsible for about 10-12 percent of total emissions worldwide. Deforestation

Figure 1. Global anthropogenic greenhouse gas emissions from 1970-2010 show increasing trends. Source: IPCC AR5

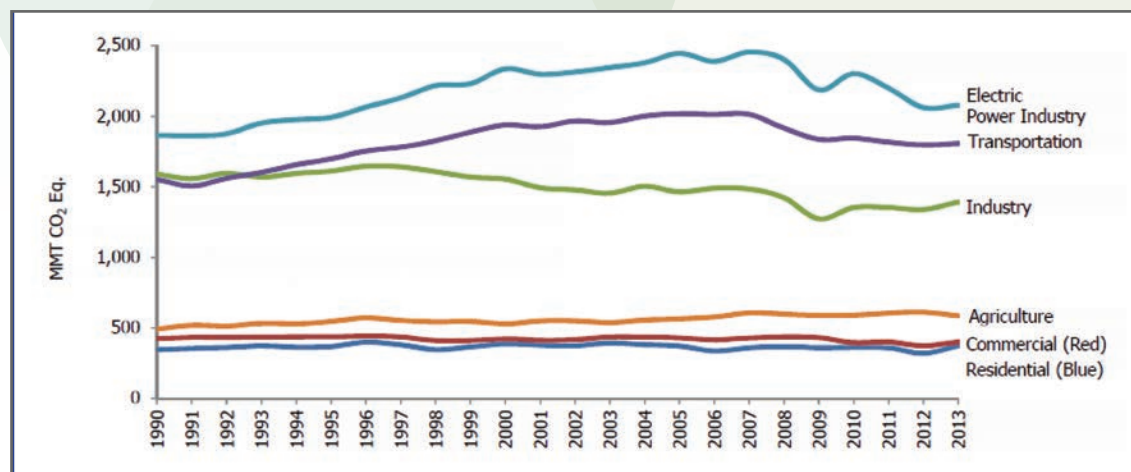
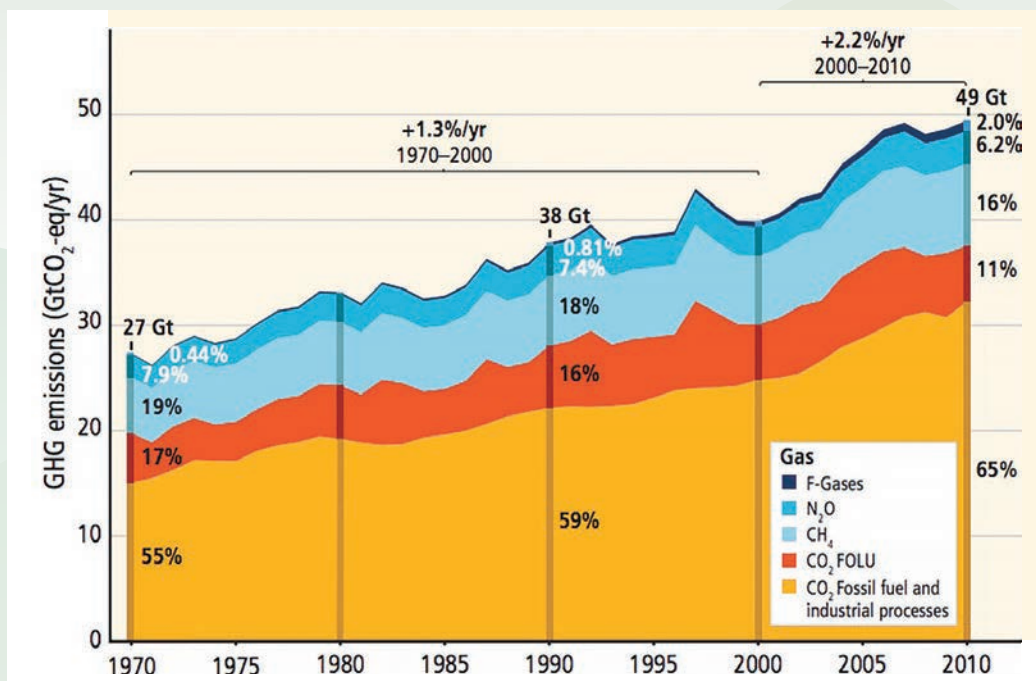


Figure 2. U.S. anthropogenic greenhouse gas emissions by economic sector from 1990-2013. Source: EPA 430-R-15-004

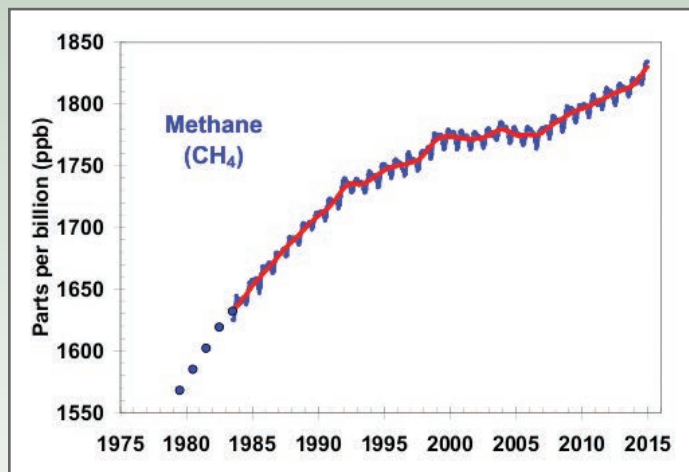


Figure 3. Methane concentrations in the atmosphere have increased since 1980. Source: NOAA Annual Greenhouse Gas Index

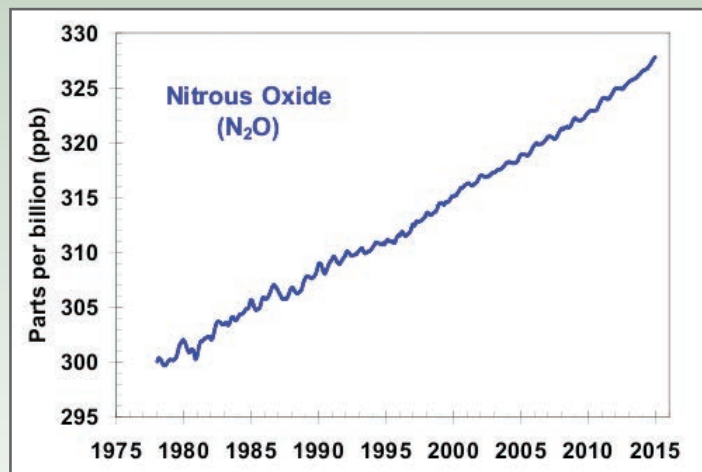


Figure 4. Nitrous oxide concentrations in the atmosphere have increased since 1975. Source: NOAA Annual Greenhouse Gas Index

and other land use changes, associated with agricultural practices in developing countries, account for another 12 percent. For comparison, electricity generates 25 percent, transport 14 percent and industry 21 percent of worldwide emissions.

U.S. Emissions by Economic Sector

In the U.S., agriculture is responsible for about nine percent of total emissions, with those emissions mostly coming from nitrous oxide and methane. U.S. agriculture also has a relatively small footprint from energy-related activities that generate CO₂. The U.S. has slightly lower agricultural greenhouse gas emissions than developing countries because our agricultural operations are highly concentrated and generally more efficient with fertilizer and energy use. Emissions from other U.S. sectors include electricity generation at 32 percent, transportation at 28 percent, industry at 20 percent, commercial at five percent, and residential at five percent of the total (Figure 2). These sectors mostly generate carbon dioxide and some methane.

Agricultural Methane

Methane emissions from all sources are approximately 10 percent of total U.S. emissions. About one-third (37 percent) of these come from agriculture. Enteric fermentation—the process by which ruminant animals such as cattle, sheep, and goats digest woody plants—is the single largest source of CH₄ emissions in the U.S., accounting for 26 percent of U.S. methane releases. Beef cattle (about 70 percent) and dairy cows (about 25 percent) are the biggest contributors to emissions from enteric fermentation. Manure

management is another source of methane emissions contributing almost 11 percent of all methane emissions. Other U.S. methane emissions come from natural gas systems (25 percent), landfills (18 percent), coal mining (10 percent), and wastewater treatment. Although methane is released in much smaller quantities than CO₂, molecule for molecule it is about 25 times more powerful. World-wide methane concentrations are up about 20 percent since 1980 and they are increasing at about eight parts per billion (ppb) per year (Figure 3).

Some solutions to reduce methane emissions include food additives that can reduce emissions from enteric fermentation and different manure storage techniques. In large confined animal feeding operations, for example, lagoon covers can capture methane for bioenergy.

Agricultural Nitrous Oxide

Nitrous oxide emissions (Figure 4) from all sources represent about five percent of total U.S. emissions, with 80 percent originating from agricultural activities and the remainder from fossil fuel combustion. Nitrous oxide is strongly tied to agriculture, making it unique among the three main greenhouse gases—CO₂ and CH₄ come from multiple uses and many sectors. In the agricultural sector, nitrous oxide emissions come from two main sources: nitrogen-based fertilizer (75 percent) and manure management (five percent). The remainder of U.S. nitrous oxide emissions come from burning fossil fuels that contain small amounts of nitrogen. On a per molecule basis, nitrous oxide is 300 times more powerful than CO₂. Since 1980, world wide concentrations of N₂O are up about about 10

percent and they continue to increase at about one ppb per year.

Some solutions to reduce N_2O emissions are using advanced fertilizer formulations that include slow release technologies and nitrification inhibitors, and using fertilizer in the right time, right place, right amount and right form.

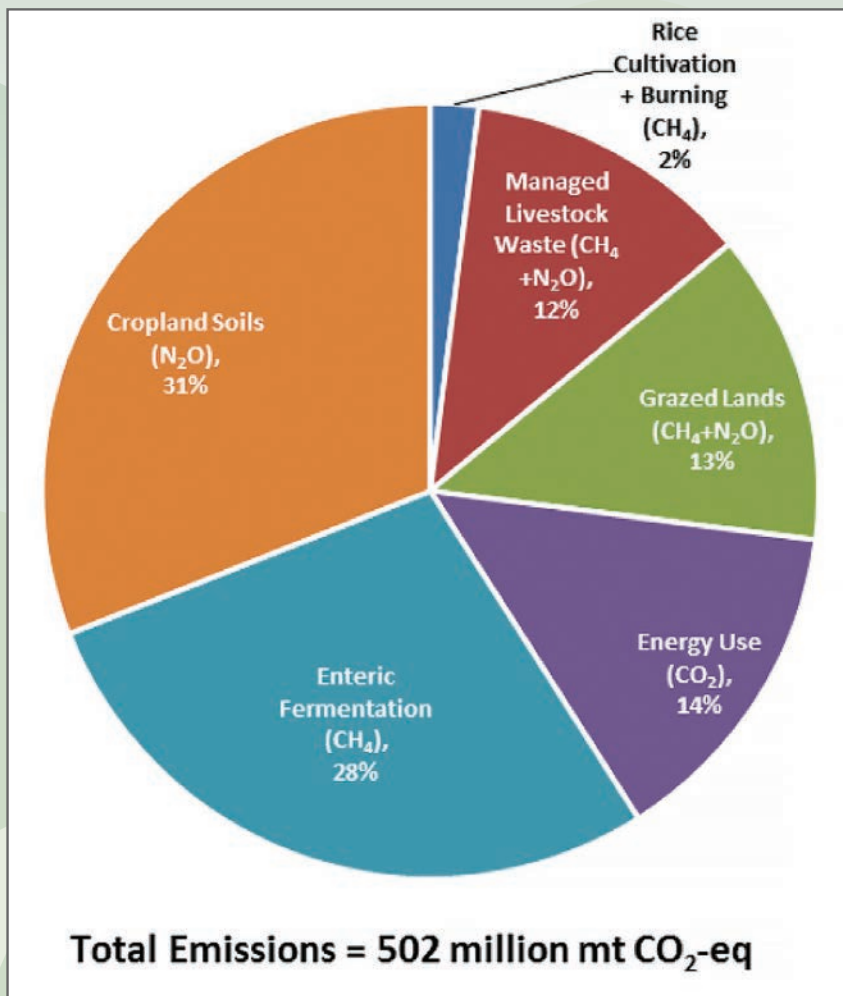
Agricultural Carbon Dioxide

The remainder of U.S. agriculture emissions, about 14 percent of the total, come from on-farm energy use. This is approximately one percent of total U.S. emissions.

Emissions by Agricultural Activity

Agricultural emissions can also be grouped by the type of activity that generates the emissions. Under this accounting, the USDA calculates that of total agricultural emissions, cropland soils generate 31 percent (nitrous oxide), livestock waste 12 percent (methane and nitrous oxide), grazed lands 13 percent (methane and nitrous oxide), enteric fermentation 28 percent (methane), rice cultivation and burning two percent (methane), and energy use (CO_2) 14 percent (Figure 5).

Figure 5. Agricultural sources of greenhouse gas emissions in 2008 totaled the equivalent of 502 million metric tons of carbon dioxide. Source: USDA (2011)



Agricultural Climate Change Impacts and Adaptation Opportunities for Colorado

Reagan Waskom, Colorado Water Institute, Colorado State University

Dennis Ojima, Ecosystem Science and Sustainability, Colorado State University

SYNOPSIS

Agriculture in Colorado already adapts to a wide variety of stressors, but additional planning may be needed to prepare for climate-related changes like extreme weather events, longer and hotter growing seasons, and extreme drought.

Agriculture is appropriately recognized as one of the most weather-sensitive sectors, and protecting Colorado's food production capacity should figure prominently in discussions about climate adaptation. Adaptation and risk management is what crop and livestock producers are engaged in on a daily basis—they adapt to changing markets, technology, regulations, consumer demand and preference. Flood, drought, hail, wind, untimely freezes or heat are the abiotic stresses that cause most crop failure and livestock losses.

Agriculture is very well equipped to adjust to long-term shifts in average temp, humidity, evapotranspiration (ET), rainfall, frost-free days, and other typical variations in climate. However, a key difference from past adaptations may be changes in the frequency and intensity of extreme weather events, a more rapid rate of change in regional weather conditions, and seasonal shifts in precipitation patterns and extended drought. Climate adaptation in agriculture is already occurring, but in an unplanned manner for the most part.

Expected Climate Impacts in Colorado

The Colorado Water Plan recognizes that average temperatures have increased in Colorado by 2° F in the past 30 years, affecting snowmelt timing and peak runoff. While there are potential benefits associated with these trends, such as earlier green-up of mountain and range forage for livestock, agricultural scientists and hydrologists are concerned that increased vulnerabilities that producers may face include longer, hotter growing seasons; extreme weather events; and drought.

Longer, Hotter Growing Seasons

Earlier arrival of spring results in longer growing seasons and prolonged hot periods during the growing season can affect the selection of crops and crop varieties. Longer, warmer growing seasons may enhance the growth of non-native weeds (for example, cheat grass, smooth brome, Kentucky bluegrass and Dalmatian toadflax). Warmer and drier summers will likely reduce forage production and crop yields as precipitation or irrigation are inadequate to keep up with crop ET demands. The Colorado Climate Center documented record reference ET rates during the hot summer of 2012 in Colorado. Longer and more intense fire seasons pose a risk to agriculture by reducing grazing lands available for livestock, altering critical wildlife habitat, and impacting water quantity and quality from forest watersheds

Extreme Weather Events

Extreme events can dramatically influence farmer and rancher livelihoods and enterprises. The early October 2013 snowstorm (named "Atlas") resulted in tens of thousands of livestock deaths in western South Dakota and northwestern Nebraska with ripple economic effects to the businesses and local economies of these agricultural communities. Excessive rainfall in September 2013 in Colorado flooded crops and farmland, damaged houses and agricultural structures, and impaired water quality downstream.

Drought

The extensive and extreme drought conditions of 2012 had substantial negative economic results for land managers and local rural economies. Forage and hay production was less than half of average, resulting in low stocks of hay. Over 2,000 counties nationwide were designated as disaster areas due to the 2012 drought. The Northern Plains largely recovered from the 2012 drought by late 2013 and fully by 2014 with continued increase

in cattle numbers (driven by movement of cattle from the Southern Plains northward).

Livestock production is sensitive to climate effects on grazing lands, livestock health and reproduction, and the supply of feed crops. Hotter and drier climate scenarios would indicate that the adaptive measure needed is to reduce the grazing pressure on these lands—meaning ranchers must run fewer cows and/or feed more hay. Recent droughts have highlighted the indirect effects related to insect borne diseases, such as West Nile on horses and avian flu on chickens. Under these drought conditions reduced availability of surface water has raised the potential for animals and insects and other pests in closer proximity, so additional care is needed to protect livestock under these conditions. While ranchers and others can do this in the short-term, these practices make it difficult to remain economically viable in the long-term. The effect of climate change on agriculturally relevant pests is poorly assessed, but concerns have been raised that warmer climate favors more invasive weed species, and, on rangeland, woody species encroachment. Climate change could affect the administration of grazing on federal (Bureau of Land Management and U.S. Forest Service) allotments, and the industry has a large interest in how this might play out in a changing climate.

Higher temperatures and longer growing seasons may positively affect yields for some crops within some range of temperature increase, but will have damaging effects above a certain threshold level. The severity of impact depends on how precipitation, cloud cover, water availability, management practices, and other factors co-vary with temperature. Warmer nights are known to increase crop respiration and hasten maturation, decreasing the length of the reproductive period and reducing yields. The early spring thaw has the potential to lengthen the growing season; however, an intervening frost may damage emerging buds or seedlings which have come out of their winter dormant period. In addition, much of the agricultural production in

the western U.S. is irrigated and is thus highly dependent upon the accumulation and melting of snowpack and the overall availability of relatively low cost water for irrigation. Changes in the soil moisture recharge and the replenishment of the near surface aquifers will be critical to irrigators and water providers, alike.

USDA has reported that production regions for some plants have been shifting north, which may be at least partially attributable to long-term changes in climatic conditions. Of course, in addition to potential expansion into new areas, it is also possible that production of certain crops will cease in

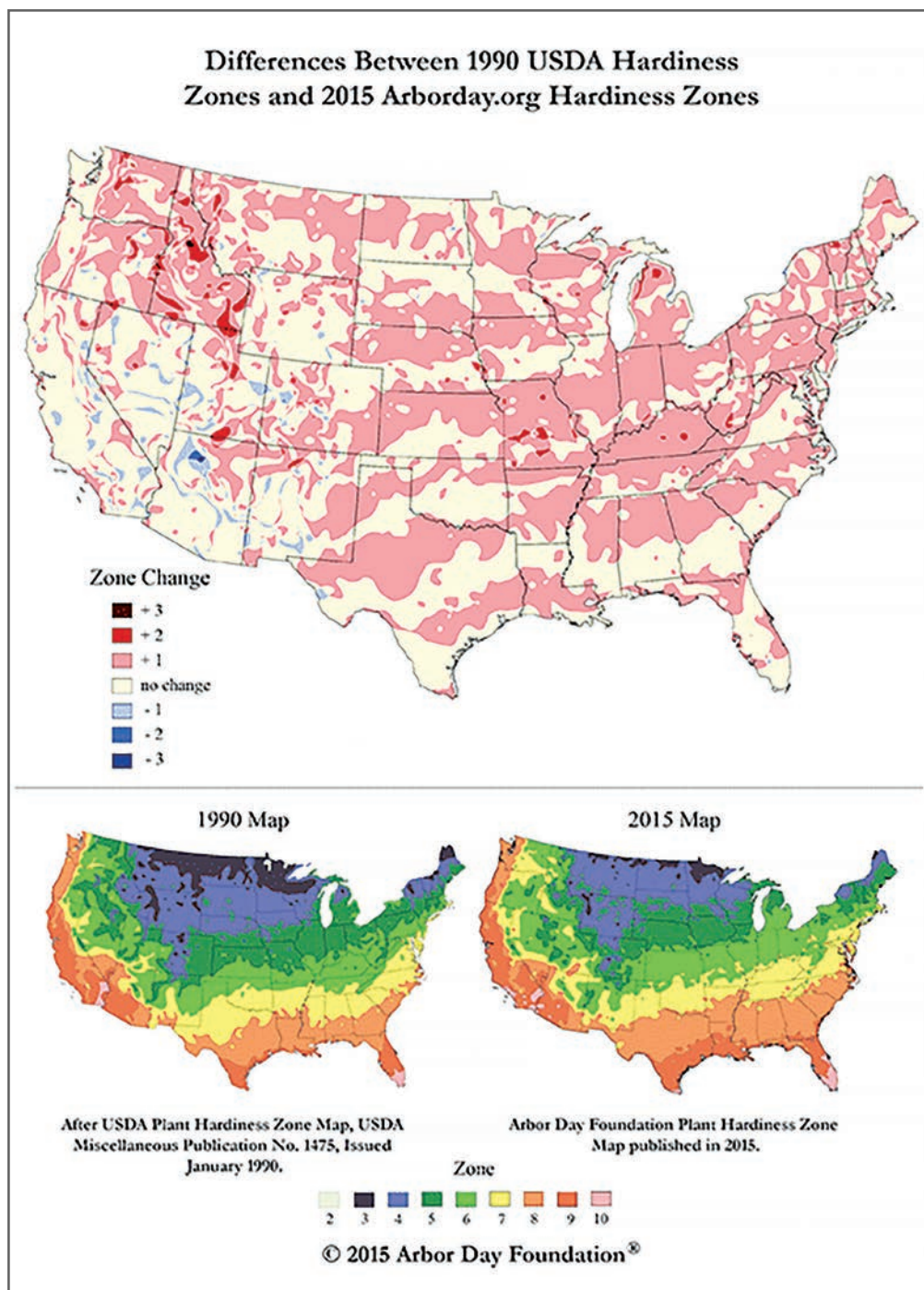


Figure 1. Hardiness Zones show which regions increased or decreased in degrees Fahrenheit between 1990 and 2015 and the resulting changes in growing zones. From arborday.org/media/map_change.cfm, modified under Creative Commons Attribution-No Derivative Works 2.5 License.

Observed Increase in Frost-Free Season Length

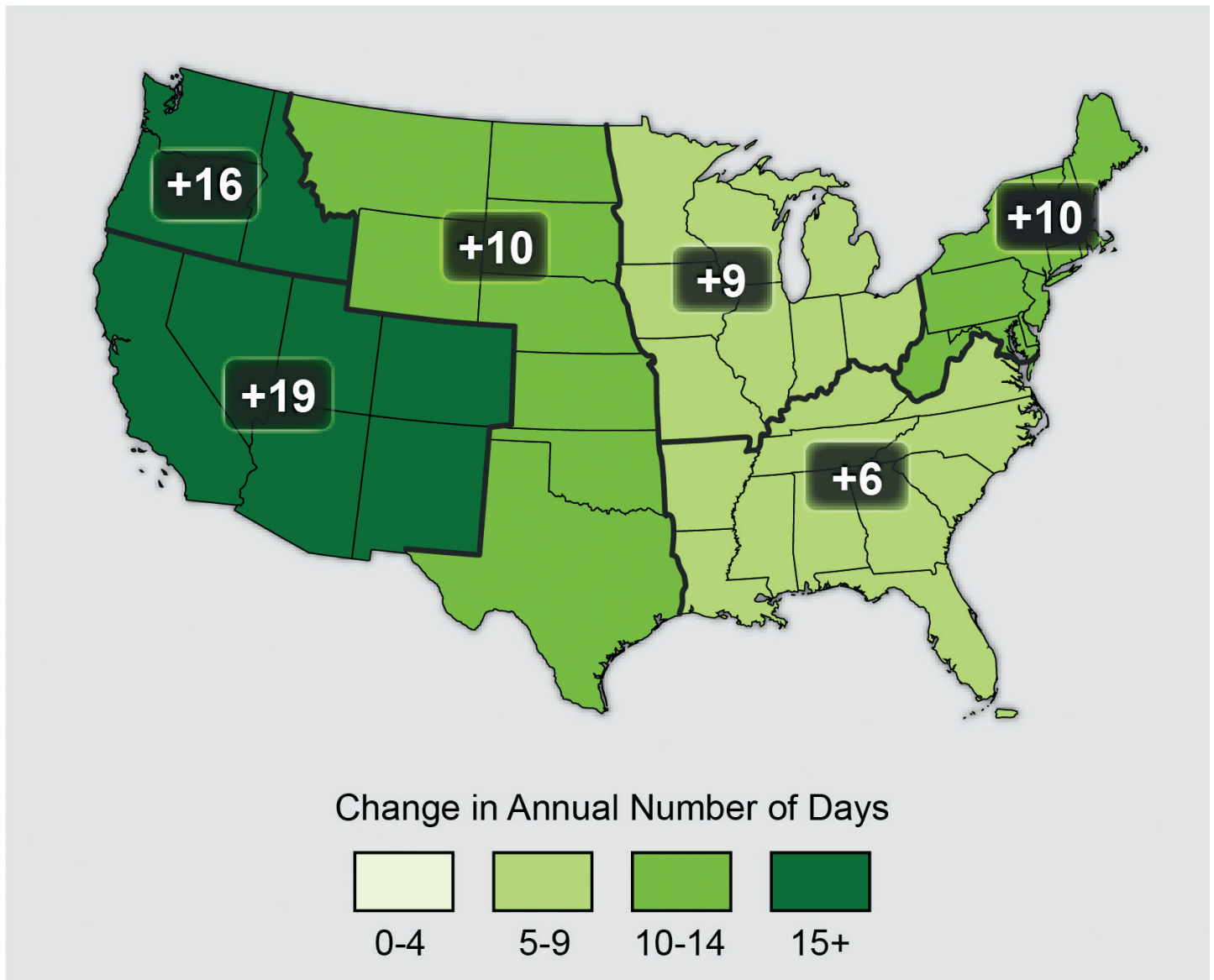


Figure 2. The frost-free season length, defined as the period between the last occurrence of 32°F in the spring and the first occurrence of 32°F in the fall, has increased in each U.S. region during 1991-2012 relative to 1901-1960. Increases in frost-free season length correspond to similar increases in growing season length. Note that numbers are averages for the overall region, not one state. Also, see “Climate Trends in Colorado over the Past Century” for discussion about producer challenges in Colorado due to little change in the “hard frost” (28°F) season length. Kenneth Kunkel, Cooperative Institute for Climate and Satellites

some existing production areas and move to more favorable areas (Figure 1).

A big unknown is how climate change will affect national and global food and feed markets. While commodity prices are expected to trend significantly higher and offset yield losses, the relatively high debt loads in modern agriculture might detract from adaptive capacity by reducing the resources that farmers and ranchers can deploy to switch crops, buy new equipment, acquire more reliable water supplies, or otherwise respond to a changing environment. In a report for the Risk Management Agency, Beach, et al 2010 found relatively small impacts across all crops at the national level using model outputs of four GCMs for the 2045-2055 time period and the EPIC crop model,

consistent with previous studies finding that agricultural impacts of climate change in the U.S. may be relatively small at the national level, at least in the first half of the 21st century. However, this obscures the potential local and regional effects within the U.S. They found significant effects on crop yields under the climate change scenarios modeled, both positive and negative. In general, yields increase in northern areas relative to southern areas for major crops. A result of these changes is that production patterns will change as producers switch crops in response to changes in expected profitability and risk.

Overall, most studies have typically concluded that U.S. agriculture as a whole will likely not see major disruption from climate change over the next few decades, but findings vary

considerably depending on emissions scenario and models used for climate simulations. They also depend on the measure of impact; studies that have looked at farm land value or profitability have tended to find smaller negative or more positive impacts than those focused on crop yields. Because the demand for food is relatively inelastic, widespread reductions in yield could result in an increase in revenue and profits to the farm sector. Also, national level results tend to smooth out potential distributional effects across regions as relative yields and cropping patterns shift across regions. There may also be important differences in impacts between irrigated and non-irrigated crops as precipitation patterns and water resource availability changes. An important issue to consider as one moves far enough out into the future to reach the temperature increases projected for the late 21st century is the potential for non-linear temperature effects such as those found by Schlenker and Roberts (2006) as temperature thresholds are potentially exceeded more frequently.

Crops and Livestock Production Systems Share Similar Potential Vulnerabilities:

- » **Increased potential ET and consumptive use**
- » **Potential for heat stress during crop pollination and maturation – impacting yield and quality.**
- » **Heat stress on livestock – impacting rate of gain and fertility**
- » **Increased number frost free days and growing degree units**
- » **Increased weed competition; insect and disease over-wintering and development**
- » **Increased soil salinity and water quality impacts**
- » **Concern about loss of pollinators, in particular honeybees**
- » **Potential loss of soil carbon**
- » **Concern about wildfires exacerbated by heat and drought, limiting grazing seasons on public and private lands**
- » **Concern about increased listings of threatened and endangered species, possibly curtailing diversions or grazing**

On-Farm and Ranch Adaptive Measures


Adaptation strategies currently used by U.S. farmers to cope with weather and climate include management tools such as changing the timing of field operations, shifting date of planting, harvest, breeding and calving, and optimizing the use of chemical inputs and genetic improvements to control increased pressure from weed, disease and insect pests. Risk management tools for extreme weather events includes spreading planted areas of a given crop across space and time, altering planting dates, crop maturity dates, variety selection and using institutional mechanisms such as forward contracting and crop insurance to mitigate risk. Technological innovations such as new chemicals, precision application, new genetics and biotechnology, irrigation systems, soil monitoring and forecasting models increase the tools available to farmers in some agricultural sectors, but implementation of new technology is often limited to larger scale or more capital-intensive operations.

Cattle and sheep ranches depend for the most part on rain-fed forage grasses for livestock feed. Only a small portion of total grazing, hay and pastureland in Colorado is irrigated. Drought in particular, reduces forage production on livestock grazing lands and is a major concern among ranchers. In the mountains and plains, a rise in winter temperatures may increase livestock birth survival rates compared to present conditions. A rise in spring and fall temperatures and longer frost-free period will increase forage production potential, though warmer temperatures earlier in the year do not negate the possibility of late freezes (Figure 2).

Agricultural producers routinely face a number of production risks (e.g., weather, disease, pests) that can substantially affect their output levels from year to year, as well as input cost and market price risks, both of which affect farm revenue. Crop insurance is one important mechanism for managing the yield, price, and quality risks associated with agricultural production. Agricultural insurance plays an important role in response to weather hazards, and will be a key mechanism for adaptation to climate change. Most agricultural insurance used by farmers and ranchers is funneled through the USDA Risk Management Agency. Federally subsidized crop insurance has been available in the United States since 1938. The U.S. Department of Agriculture (USDA) Risk Management Agency (RMA), created in 1996, operates and manages the Federal Crop Insurance Corporation (FCIC). RMA provides multiple peril crop insurance via the FCIC for more than 75 crop and livestock commodities and continues to support the development of new risk management tools for producers. RMA is evaluating producer and insurer risk exposure and the products available to producers. For example, in the past cropland was insurable as fully irrigated or dryland – no in-between. New insurance products are under development for limited or partial irrigation. More new risk management products will be needed. Increases in frequency and severity of extreme events will cause financial overload on highly debt-leveraged operations that can seldom survive multiple years of crop failure. Agricultural insurance plays an important role in response to weather hazards, and will be a key mechanism for adaptation to climate change. Given

the possibility that climate change could alter the frequency and/or magnitude of extremes, insurance and disaster relief programs may need modifications in the future. In the near term, increased incidence of extreme events such as unpredictable drought, flood, frost is most concerning.

Adapting to reduced water availability may be the most imminent threats to Colorado agriculture from climate change. Current climate adaptation plans for cities, industry, energy and the environment all include future use of agricultural water—this does not bode well for agricultural adaptation. Dryland agriculture is even more vulnerable to a warmer drier future. It is also interesting that every nation's fallback plan for loss of food production capacity is to import food from somewhere else. In the short term, U.S. agriculture has significant adaptive

capacity and the tools to do so. A primary mechanism crop producers have to enhance resiliency to climate risks is to increase crop residue cover through no-till or minimum tillage regimes – this will provide for soil stabilization for extremes in drought, wind and flood; will help capture precipitation, will store soil carbon and will allow unexpected fallowing in the case of water supply interruption or other disruptions that cause unintended fallowing. In the longer term, adaptation will be more difficult and costly because the physiological limits of plant and animal species will be exceeded more frequently, and the productivity of crop and livestock systems will become less reliable. More radical and systemic adaptation may be needed to produce food for a growing world population while sustaining critical ecosystem services. 

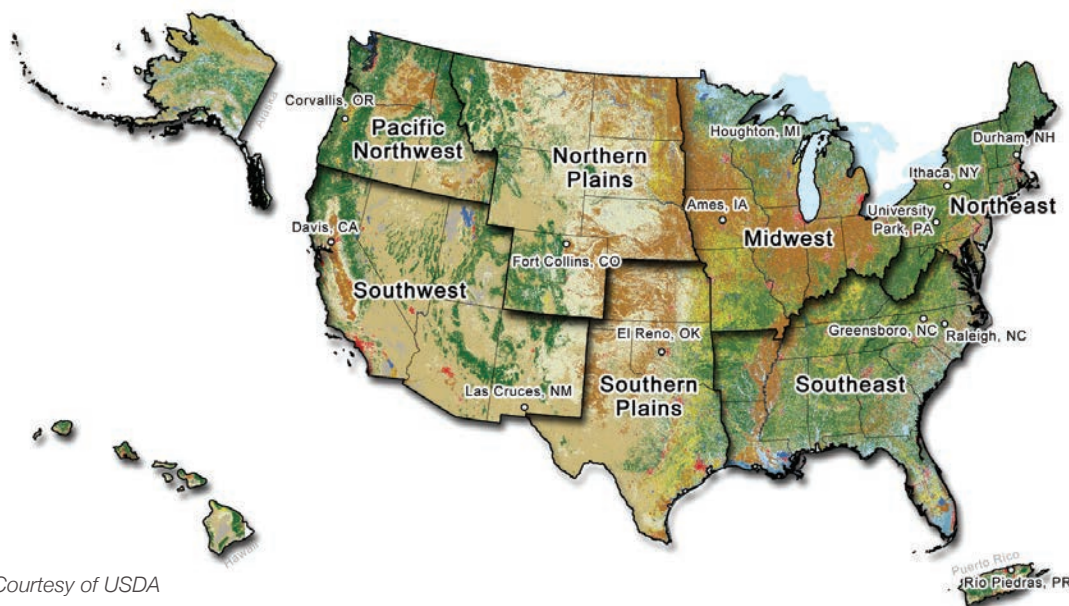
USDA CLIMATE HUBS

U.S. Department of Agriculture (USDA) Secretary Vilsack established 10 regional climate hubs in February of 2014, with the Northern Plains Hub based at Colorado State University. The hubs are designed to provide science-based knowledge, practical information and program support to farmers, ranchers, forest landowners, and resource managers to support climate-informed decision-making in light of the increased risks and vulnerabilities associated with a changing climate.

At each hub the Agricultural Research Service, the Natural Resource Conservation Service, and the Forest Service provide leadership with all other USDA agencies including the Farm Service Agency, Rural Development, and the Risk Management Agency contributing to the effort. Partners to the hubs include universities, Extension, private sector companies, tribes, local and regional governments.

The Hubs provide periodic regional assessments of risk and vulnerability in the agriculture and forestry sectors to help land managers better understand the potential direct and indirect impacts of a changing climate. The Hubs also translate climate change projections into potential impacts on the agricultural and forestry sectors. Using science-based risk management principles, the hubs provide outreach, education, and extension to farmers, ranchers, forest landowners, and rural communities.

USDA Hub activities coordinate with and complement efforts by the Department of Interior Climate Science Centers (North Central CSC at CSU – revampclimate.colostate.edu) and Landscape Conservation Cooperatives (LCCs) along with NOAA Regional Sciences and Assessment Programs (Western Water Assessment at CU – wwa.colorado.edu).



Courtesy of USDA

USDA BUILDING BLOCKS

TO REDUCE GREENHOUSE GAS EMISSIONS

NITROGEN STEWARDSHIP

Focus on the right timing, type, placement and quantity of nutrients to reduce nitrous oxide emissions and provide cost savings through efficient application.

CONSERVATION OF SENSITIVE LANDS

Use the Conservation Reserve Program (CRP) and the Agricultural Conservation Easement Program (ACEP) to reduce GHG emissions through riparian buffers, tree planting, and the conservation of wetlands and organic soils. By 2025, USDA aims to enroll 400,000 acres of CRP lands with high greenhouse gas benefits, protect 40,000 acres through easements, and gain additional benefits by transferring expiring CRP acres to permanent easements.

LIVESTOCK PARTNERSHIPS

Encourage broader deployment of anaerobic digesters, lagoon covers, composting, and solids separators to reduce methane emissions from cattle, dairy, and swine operations. USDA plans to support 500 new digesters over the next 10 years, as well as expand the use of covers on 10 percent of anaerobic lagoons used in dairy cattle and hog operations.


SOIL HEALTH

Improve soil resilience and increase productivity by promoting conservation tillage and no till systems, planting cover crops, planting perennial forages, managing organic inputs and compost application, and alleviating compaction. USDA aims to increase no-till implementation from the current 67 million acres to over 100 million acres by 2025.


GRAZING AND PASTURE LANDS

Support rotational grazing management, avoiding soil carbon loss through improved management of forage, soils and grazing livestock. By 2025, USDA plans to support improved grazing management on an additional 4 million acres, for a total of 20 million acres.

Rotational grazing, as pictured in Weld County, Colorado, is a management-intensive system of raising livestock on subdivided pastures to promote soil and plant health.



In mid-2015, U.S. Department of Agriculture (USDA) Secretary Vilsack announced a comprehensive, detailed and voluntary approach to support farmers, ranchers and forest owners who want to respond to climate change. The framework contains 10 building blocks that reduce greenhouse gas emissions, increase carbon storage, or provide alternative energy. USDA will use the authorities in the 2014 Farm Bill to provide incentives and technical assistance to implement the initiative. USDA estimates that the initiative should reduce total U.S. emissions by two percent nationally in 2025.

Participation will be entirely voluntary within USDA's existing 'cooperative conservation' model. The program will be focused on multiple economic and environmental benefits including efficiency improvements, increased yields and reduced risks. This strategy is designed for working farms, ranches, forests, and production systems. Quantitative goals and objectives will be established for each building block and USDA will track and report on progress. Opportunities to leverage efforts by industry, farm groups, conservation organizations, municipalities, public and private investment products, tribes, and states will be sought. 

STEWARDSHIP OF FEDERAL FORESTS

Reforest areas damaged by wildfire, insects, or disease, and restore forests to increase their resilience to those disturbances. USDA plans to reforest 5,000 additional post disturbance acres by 2025.

ENERGY GENERATION AND EFFICIENCY

Promote renewable energy technologies and improve energy efficiency. Through the Energy Efficiency and Conservation Loan Program, work with utilities to improve the efficiency of equipment and appliances. Using the Rural Energy for America Program and other programs, develop additional renewable energy, bioenergy and biofuel opportunities. Support the National On-Farm Energy Initiative to improve farm energy efficiency through cost-sharing and energy audits.

PRIVATE FOREST GROWTH AND RETENTION

Through the Forest Legacy Program and the Community Forest and Open Space Conservation Program, protect almost 1 million additional acres of working landscapes. Employ the Forest Stewardship Program to cover an average of 2.1 million acres annually (new or revised plans), in addition to the 26 million acres covered by active plans.

PROMOTION OF WOOD PRODUCTS

Increase the use of wood as a building material, to store additional carbon in buildings while offsetting the use of energy from fossil fuel. USDA plans to expand the number of wood building projects supported through cooperative agreements with partners and technical assistance, in addition to research and market promotion for new, innovative wood building products.

URBAN FORESTS

Encourage tree planting in urban areas to reduce energy costs, stormwater runoff, and urban heat island effects while increasing carbon sequestration, curb appeal, and property values. Working with partners, USDA plans to plant an average of 9,000 additional trees in urban areas per year through 2025.

Farm and Ranch Carbon Footprints Made Easy

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SYNOPSIS

A growing interest in the emissions and sequestration (storage) potential of agricultural lands has led to the development of tools like COMET-Farm (CarbOn Management and Evaluation Tool), a free, online tool that evaluates current land management practices and potential management scenarios.

“What’s the carbon footprint of my operation?” That’s not a question that is (yet) on the mind of most farmers and ranchers in Colorado. Most people associate carbon footprints and greenhouse gas emissions with the cars and trucks, power plants, and industrial processes that are largely powered by fossil fuels—coal, oil and gas. However, that view is changing. As it turns out, growing food has almost as much of a carbon footprint as do other parts of our normal, everyday lives.

As with virtually all sectors of the economy, land use—farming,

ranching and forestry—also contribute to greenhouse gas (GHG) emissions that collectively impact the energy balance and climate of the Earth. Wise management of our fields, pastures, and forests, however, reduces greenhouse gas emissions and also increases the uptake and removal of carbon dioxide—the most abundant greenhouse gas—from the atmosphere, thereby playing an important role in mitigating climate change. Researchers at Colorado State University are on the forefront of developing methods and tools for quantifying and managing greenhouse gas emissions and carbon sequestration (storage of carbon in solid or liquid rather than gas form) from land use, paving the way for farmers and ranchers to incorporate ‘carbon farming’ as part of their management plans and products.

How are Greenhouse Gases Associated with Land Use Activities?

Trace gases in the atmosphere—including carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), water vapor, and man-made chlorofluorocarbons—are effective at trapping heat in the atmosphere by absorbing long-wave (infrared) radiation coming from



the Earth's surface and reflecting a portion of that back to Earth. The higher the concentrations of these gases, the more of this infrared radiation (heat) (which would otherwise escape into space) is reflected back to Earth, increasing global temperatures. As has been extensively documented and reported, human activities over the past two centuries, since major industrialization began, have increased CO₂ concentrations overall by more than 40 percent with the biggest contribution coming from CO₂ from fossil fuel use. Methane and nitrous oxide have also increased dramatically, and as we'll describe in a moment, agriculture plays a major role for those gases.

All three of the major GHGs—CO₂, CH₄ and N₂O—are also produced through natural processes in the environment, but their emissions have been strongly amplified by the way we grow crops—food, fuel, and fiber. The backdrop for agriculture's role is the vast increase in the land area devoted to crops and grazing, and the land use intensification that occurred over the past two or three centuries as the world's population has grown from less than a billion to more than seven billion today. This roughly parallels the time frame over which industrialization occurred, driving the enormous increase in burning fossil fuels. Historically, land conversion to agriculture has produced large CO₂ emissions from forests when they are burned and cleared and from soils when they are plowed. Intensive tillage and drainage of wetlands and wet soils for crops, and leaving little crop residue on soils after harvest, further depleted the original soil C stocks. Likewise, nitrous oxide emissions have increased due to the large amount of artificial fertilizer (as well as more N additions from manure and legumes) utilized in modern agriculture. The expansion of livestock as well as rice production has increased global methane emissions.

Plants take up CO₂ from the atmosphere through photosynthesis for their production and growth. Following senescence, much of the remaining plant biomass is rapidly decomposed and CO₂ is released (through microbial respiration) back to the atmosphere; however, part of the decaying biomass can be incorporated into organic matter ("humus") in soils which can be stored for decades to centuries. In fact, soils contain more carbon in soil organic matter—globally around 1,500 billion metric tonnes in the top three feet—than in the atmosphere and all vegetation combined. Most agricultural soils are depleted in soil carbon due to past land use conversion and management. By adopting conservation practices (e.g., improved crop rotations, conservation tillage, rangeland/pasture improvement, etc.) that increase plant residue inputs and reduce organic matter oxidation, carbon stocks in soils can be substantially increased, while also improving the health and fertility of the soil. Thus soils can be a "sink" for CO₂, helping to reduce concentrations of CO₂ in the atmosphere.

Nitrous oxide is produced by soil microorganisms through two different processes, called nitrification (which occurs in aerated soils) and denitrification (which occurs in anaerobic—e.g., waterlogged soils). In both cases the large amount of added N used in modern agriculture—including industrial fertilizer, manure and nitrogen-fixing legumes such as beans and alfalfa—stimulates these processes and greatly increases emissions above the background levels occurring in native ecosystems. On average about

0.5 to three percent of added N is emitted as (and additional 'indirect' N₂O emissions occur from leached or volatilized) N that is lost and then redeposited away from the fields where fertilizers were originally applied). That percent of N lost may seem small, but N₂O is a more potent GHG (roughly 300 times) than CO₂, and thus contributes disproportionately to warming. In fact, agricultural soils are the largest single source of N₂O emissions globally. However, improved N management practices, where the amount, timing and placement are better tailored to plant demand, can substantially reduce N₂O emissions. Furthermore, advanced fertilizer formulations that include slow-release technology and nitrification inhibitors have proven effective at further reducing N₂O emissions, for example in irrigated corn-based systems in Colorado. An additional benefit of improved N management is less leaching and runoff of nitrate-N that is a major pollutant of ground- and surface waters.

Methane is produced by microorganisms living in anaerobic (i.e., low oxygen) environments. In the agricultural setting those environments occur in three major places: 1) in the digestive tract of livestock, particularly ruminant animals such as cattle and sheep; 2) in animal waste storage (e.g., manure piles and waste lagoons); and 3) in flooded rice crops (where flooding greatly inhibits the diffusion of oxygen from the atmosphere into the soil). Some reductions in methane from ruminant digestion (termed enteric emissions) are possible with improved diets and animal breeding as well as feed supplements that inhibit methanogens and possibly even development of inhibitory vaccines. However, enteric emissions per unit product for livestock in the U.S. are already fairly low compared to many other parts of the world. A bigger bang for the buck might be achieved by improving how manure from large livestock operations is handled. One example is to use anaerobic digesters, which capture CH₄ from manure and make it available to heat water and buildings or generate electricity. While rice is not grown commercially in Colorado, growers in California and in the lower Mississippi Delta are beginning to change how they manage water and soil to reduce methane emissions from growing rice, including draining fields periodically to reduce CH₄ emissions.

In summary, numerous practices have been developed that can reduce N₂O and CH₄ emissions in agriculture, as well as actively remove and sequester CO₂ from the atmosphere into soil organic matter (Figure 1). Agriculture can potentially play a major role in reducing greenhouse gases in the atmosphere. Major challenges include refining agricultural technologies to reduce emissions and increase carbon sequestration, improving outreach to farmers and ranchers around these issues, and incentivizing producers to adopt practices that reduce emissions, improve soils and increase their bottom-line.

What's In It for Agriculture?

Several different policy approaches are emerging to engage farmers and ranchers in achieving GHG reductions in the agricultural sector. Government agencies such as USDA's Natural Resource Conservation Service have begun promoting GHG-friendly practices and including GHG impacts in determination of assistance programs such

as EQIP and Conservation Reserve Program. Financial assistance to farmers and ranchers through USDA programs will increasingly emphasize practices that reduce farm and ranch carbon footprints.

There is growing interest by the agricultural products industry in marketing more environmentally-sustainable products to consumers. For many food and fiber (e.g., clothing, fabrics) products, the largest portion on their full 'life-cycle' GHG emissions are associated with the commodity production (e.g., grain, forage, cotton, wool) that occurs inside the farm-gate. Some companies are adapting their supply chains by offering premiums for products produced with reduced GHG emissions.

Finally, GHG offset markets are taking hold. In places such as California and Alberta, entities that can reduce emissions efficiently are able to sell those emissions reductions in regulatory cap-and-trade systems to polluters who are not able to reduce emissions as cost-effectively. There is also a growing international 'voluntary' emission reduction market opening up to agriculturally-based projects. Projects focusing on improved N management in field crops (to reduce N_2O), rice management to abate methane, and protecting wetland soils from development (to avoid emissions of CO_2 from soil C losses) in the northern Great Plains are examples of new GHG offset projects. Beginning this year in California, a new incentive program will offer payments to farmers and ranchers for a wide-range of agricultural conservation practices that have been shown to reduce GHG emissions.

How Can the COMET-Farm Tool Help?

How do farmers and ranchers demonstrate that their improved cropping and livestock management practices reduce greenhouse gases? Directly measuring GHG emissions and changes in carbon in soils and trees in the field is time-consuming and requires expensive, dedicated equipment and skilled operators. Thus it's not a practical approach in most cases for on-farm GHG inventory and assessment. A more feasible approach is to make use of the on-farm knowledge of past and present management practices, together with available spatially-resolved data on soil properties (e.g., from soil maps) and weather, to drive computer models that have been developed from extensive field research results. With this approach, the main requirement for land managers and other participants in emission mitigation efforts is to document and verify the change in management practices.

That is where COMET-Farm comes in. COMET-Farm (CarbOn Management and Evaluation Tool) is a free web-based tool (cometfarm.nrel.colostate.edu) that allows farmers and ranchers to conduct what we call "Conservation Scenario Analysis" (Figure 2). Basically this means describing how they grow crops or raise livestock now, and then evaluating changes in their crop and livestock management to assess the potential changes in GHG emissions and carbon sequestration. For example, a corn grower can assess how changing tillage affects emissions, or the manager of a dairy or swine operation can assess the benefits of adding an anaerobic digester.

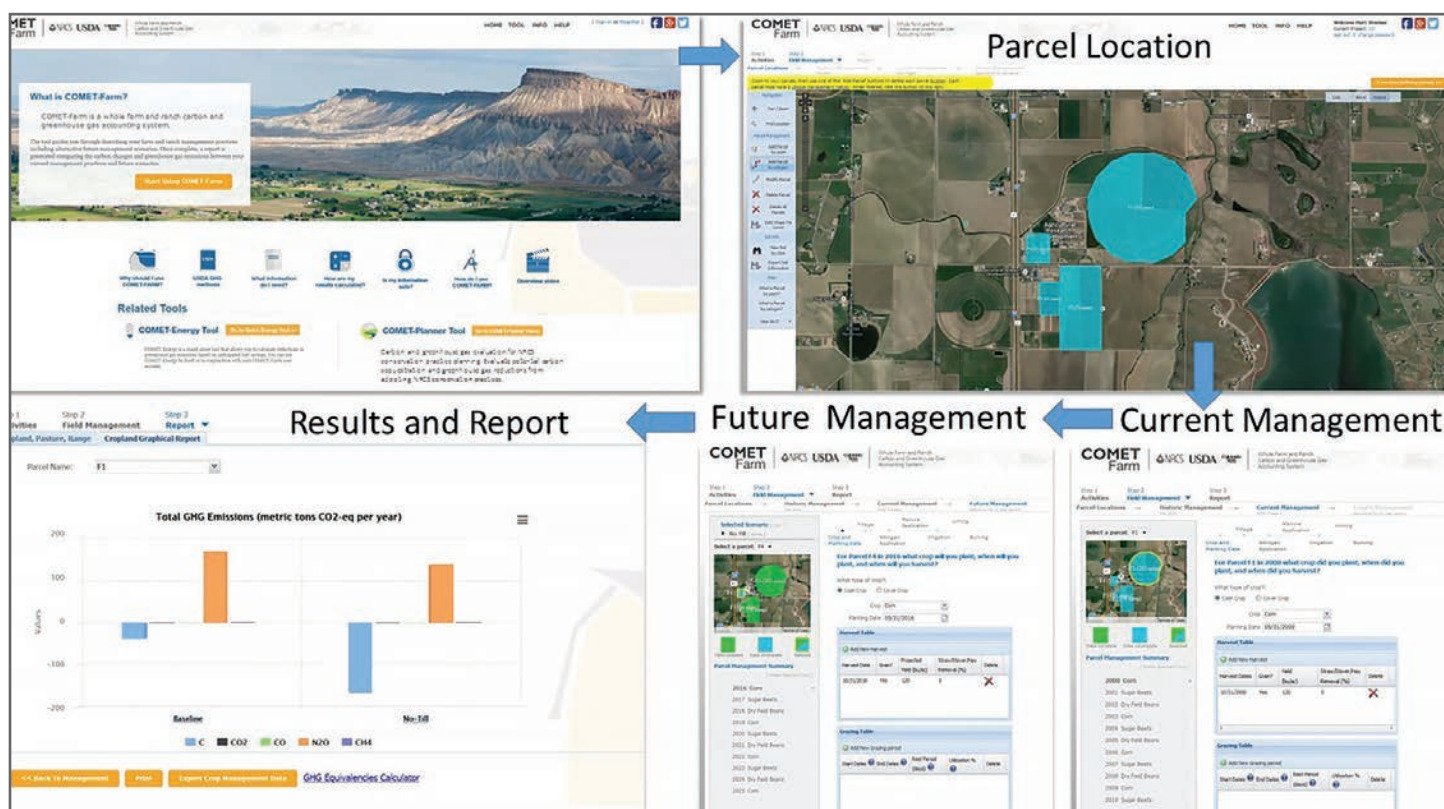


Figure 1. Screen-shots from the COMET-Farm tool, showing the workflow in using the tool. Starting with the COMET-Farm home page in the upper-left)and moving clockwise) users specify the location of their fields and/or livestock operations (upper right), then enter information on their current and projected management practices (lower right), and finally produce a report with available tables and graphs to illustrate summary results as well as detailed results for individual fields, livestock groupings and farm infrastructure.



Figure 2. Examples of farm and ranch practices that can sequester carbon and reduce greenhouse gases include no-till cropping (left), grassed riparian buffers and tree plantings (right), methane digester for animal waste (not pictured), and improved pasture and grazing management (top).

The models and methods used in COMET-Farm have been developed as part of a multi-year effort, conducted by experts from academia, USDA researchers and industry scientists, culminating in the publication of the official USDA entity-scale GHG inventory guidelines.

COMET-Farm is a “whole system” accounting tool for greenhouse gases. This is important because sometimes practices that reduce emissions in one part of the operation can increase emissions in another. For example, adding more fertilizer may lead to greater carbon sequestration, but those sequestration benefits may be offset by greater nitrous oxide emissions from the higher fertilizer amounts.

Through a brief Web-based interview process, growers and natural resource professionals describe aspects of how crops are grown (e.g., planting and harvest dates, tillage, fertilizer type and application rates) and livestock are managed (e.g., feed rations,

manure management, grazing systems). Maps of field boundaries are drawn in the tool and computer models predict the greenhouse gas balance of the enterprise, along with potential emissions reductions from different conservation scenarios. Results show the benefits of the practices compared against the “business as usual” baseline.

Conclusion

Agriculture has been tasked to provide food, feed, fuel and fiber for a growing population, while consumers are becoming more and more interested about where their food is coming from and how it is produced. Society is now asking farmers, ranchers, and forest landowners to improve their land stewardship while providing more and higher-quality commodities for a growing population. To help in meeting these challenges, landowners and managers can use tools like COMET-Farm to help make decisions

on land use and management practices that can reduce greenhouse gas emissions and increase the amount of carbon that is stored in the soil or biomass. Using COMET-Farm, conservation practices focused on improving air, water and soil quality can be evaluated in terms of their GHG mitigation potential. Many landowners may already be implementing practices that reduce greenhouse gas and increasing soil carbon, and not even be aware

of it. COMET-Farm puts state-of-the-art scientific information in the hands of producers, in the form of an easy-to-use tool that fits the many unique systems that grow crops, raise livestock, and provide fuel and fiber. With the ingenuity and adaptive nature of farmers and ranchers, agriculture can apply new methods to help address the challenge of reducing greenhouse gas emissions and improving the environment. 🌀

NATIONAL AND INTERNATIONAL CLIMATE CHANGE ASSESSMENTS

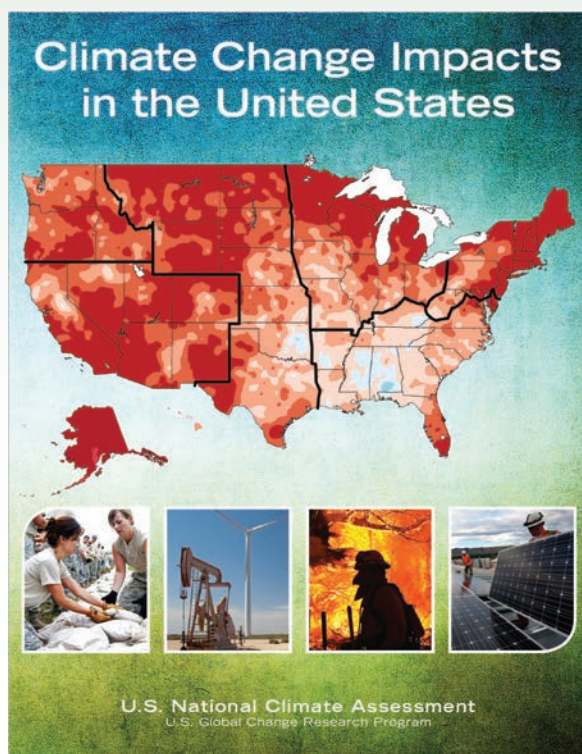
In 1988, the Intergovernmental Panel on Climate Change (IPCC) was created by the United Nations to compile scientific assessments on climate change. The IPCC consists of volunteer scientists from all nations selected for their expertise on different aspects of science. The U.S., and Colorado especially because of our strong scientific expertise at CSU, CU, NOAA, and the National Center for Atmospheric Research, are very well represented in the

3,000+ scientists who participate in this regular effort.

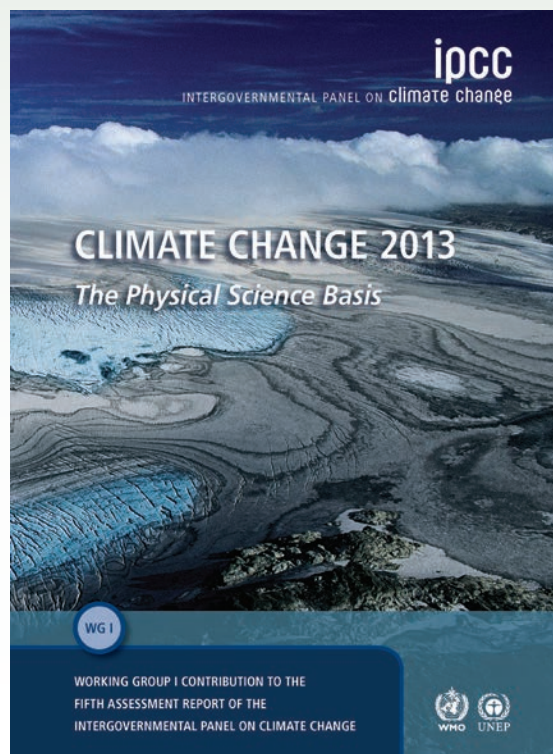
The IPCC in recent years has been composed of three working groups: one on basic physical science of climate change; one on the impacts, vulnerabilities, and adaptation possibilities; and a third group devoted to studying how to reduce greenhouse gas emissions. Every four or five years the IPCC releases a new series of reports. Since 1990 when the first report

was released, the IPCC's findings have become more compelling and detailed about exactly how humans are changing the climate.

Under the 1990 Global Change Research Act, the U.S. government is to release assessments every four years on the impacts of climate change. The most recent assessment was released in 2014. The National Climate Assessment focuses on impacts of climate change on the United States. 🌀



2013 U.S. National Climate Change Assessment – available at nca2014.globalchange.gov/downloads



2013 Intergovernmental Panel on Climate Change report – available at ipcc.ch/report/ar5/wg1

Climate Smart Agriculture

Louis Longchamps, Soil and Crop Sciences, Colorado State University
Rajiv Khosla, Soil and Crop Sciences, Colorado State University

SYNOPSIS

CSU is leading Colorado's adoption of "climate-smart agriculture," a term for practices that achieve short- and long-term agricultural development in terms of climate change and its' potential impacts.

Climate-smart agriculture (CSA) is a recent term that was coined by the United Nation's Food and Agriculture Organization (FAO) in 2010 and is defined as "*an approach to developing the technical, policy and investment conditions to achieve sustainable agricultural development for food security under climate change. It contributes to the achievement of national food security and development goals with three objectives: (i) sustainably increase agricultural productivity and incomes, (ii) adapt and build resilience to climate change, and (iii) reduce and/or remove greenhouse gas emissions where possible.*" The CSA initiative is the FAO response to the growing number of farmers challenged by the effects of climate change on their farm and by the threat that it poses for global food security. CSA aims to help farmers sustainably increase their profitability, build resilience to climate change and contribute to the mitigation of greenhouse gas emissions.

The concept of CSA is based on taking informed decisions for crop management. Because of the great diversity in agriculture, CSA is not a one-size-fits-all approach, but rather a suite of concepts and guidelines to help farmers find the tools, techniques, technologies and sources of information best adapted to their local farm conditions and to use them for the achievement of the CSA goals.

Colorado State University (CSU) is actively involved in to helping Colorado farmers practice CSA in their own farming situation. In fact CSU is a founding member of the Global Alliance on CSA (GA-CSA) and is leading by example in developing and sharing climate smart practices with farmers and farming communities across Colorado. While the terminology "climate-smart agriculture" may be new, the recognition that we must develop and practice good stewardship of the land is not new.

Studies in Colorado and from many other parts of the world have documented that among all anthropogenic sources, agriculture is the largest source of nitrous oxide (N_2O), a greenhouse gas that is about 300 times more potent than CO_2 , into biosphere (Figure 1).

Agriculture-related nitrogen oxide emissions originate from many sources such as manure and crop residues, but the largest

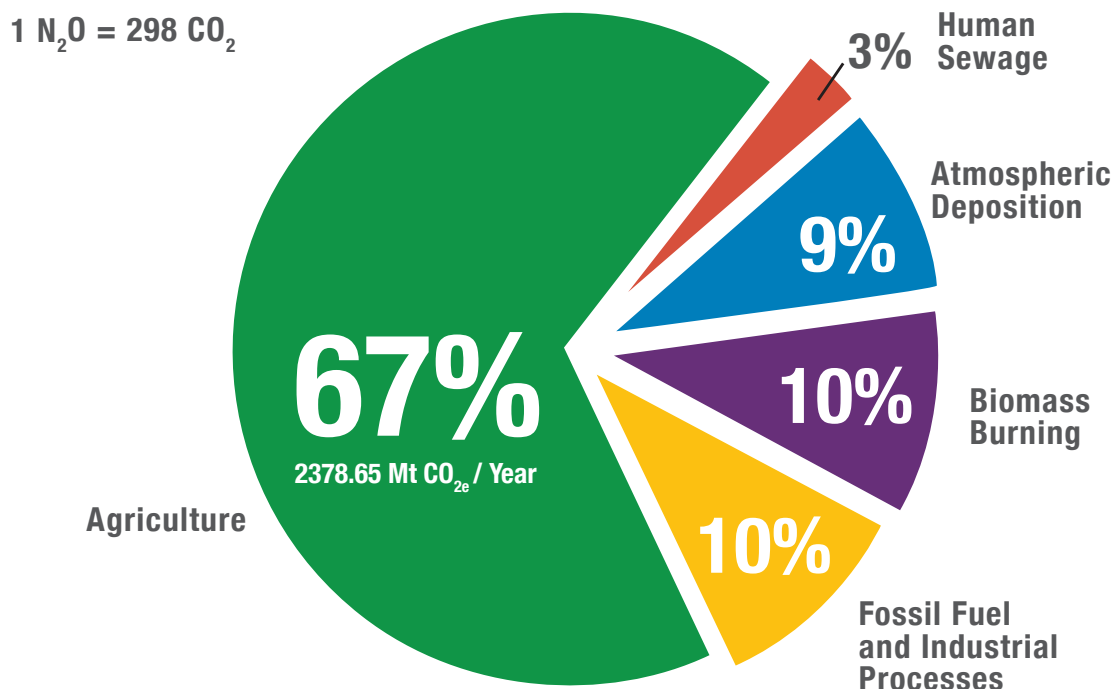


Figure 1. Sources of nitrous oxide in the atmosphere include agriculture, fossil fuel combustion, the burning of biomass, atmospheric deposition, and human sewage. Source: EPA 2013; IPCC 2007

Major Agricultural Systems	Sub-System and Location	Vulnerability			Typical Response Options
		Main Climate Change Exposure	Sensitivity	Adaptive Capacity	
Groundwater-based irrigation systems in interior arid plains	India, China, central USA, Australia, North Africa, Middle East and others	Complex interactions between climate change and groundwater leading to possibilities of increase or decrease of aquifer recharge	High sensitivity to variations and reduction in water supply as most areas are already under water stress	Low due to overexploitation of aquifers and competition with other sectors. Limited possibilities in places through increased water productivity	Increased productivity where possible; better groundwater management through controlled pumping

Table 1. Colorado farming system vulnerability and response options show the potential impact of climate-smart agriculture. Extracted from Annex A.3.1 Palombi and Sessa 2013

contributor is nitrogen fertilization.

In traditional farming systems, producers apply nitrogen (N) fertilizer at a uniform rate across a given field. However, due to inherent spatial variability in fields, not all areas require the same level of N. Because N fertilizer is inexpensive relative to the value of the crop produced, farmers choose to apply inputs such that a fairly high proportion of the field receives an adequate level of N. This results in various areas of the field receiving greater N than necessary and other areas receiving lower N than necessary. The significance is threefold:

1. Excess N is prone to offsite degradation of the environment through runoff, leaching and greenhouse gas emission.
2. Additional N is purchased at a cost that may be unnecessary.
3. Certain areas of the field do not reach their full productivity potential. There is a pressing need to improve N use efficiency (NUE) in crops and particularly in cereals (grains used for food).


Variable rate N management (VRN) has potential to improve NUE by better adjusting N rates to crop needs. Research conducted here in Colorado has indicated that combining both soil and crop information for VRN resulted in the highest NUE while maintaining productivity and decreasing N loadings in the environment. Assessment of the impacts on N₂O emissions showed that, if extrapolated to the entire corn production in the U.S., such VRN practices could reduce N₂O emissions up to 10 percent. Mitigating greenhouse gas emissions using advanced VRN practices is a smart way to practice agriculture as it mitigates greenhouse gas emissions. Mitigation of greenhouse gas emissions is one aspect of CSA and another aspect is the adaptation to climate change.

Agriculture is the largest consumer of water globally, and it is no different in Colorado. Table 1 shows that farming systems similar to the Colorado plains are vulnerable, but also that its adaptive

capacity is low due to overexploitation of aquifers. The most effective response option is to improve water productivity (i.e., produce more crop per drop). This is where the CSA approach can contribute to help farmers meet this challenge.

Conventional irrigation management in Colorado consists of furrow irrigating crops on a regular basis with an irrigation depth increasing during the core of the season and skipping irrigation when rain happens. This approach has served Colorado farmers as it ensures sufficient water levels in the soil profile and is not limiting the yield. However, this practice does not give the best results in terms of water productivity. CSA suggests using the right irrigation system, the right timing of irrigation, and the right placement of water to optimize water productivity.

Not all irrigation systems deliver water the same way and some systems are better than others. Choosing the right irrigation to achieve optimal productivity and profitability is key to building resilience to climate change. Sometimes, including cash crops or opportunity crops such as onion or others in the crop rotation may be necessary to make investment in a precision irrigation system profitable. A more efficient irrigation system helps to build resilience to climate change because it enables to produce the same yield with less water pumped or diverted. While it may not make a large difference every year, it may turn out to be a game changer in drought years.

While the concept of “right time” of irrigation has been in practice for decades in Colorado, the concept of “right place” of irrigation within a field is novel and quite critical. Research conducted at CSU has demonstrated that there is spatial variability of soil water content in most fields, even laser leveled fields, and that this variability can be present in up to two-thirds of a field. Accounting for this scale of spatial variability and managing water using precision irrigation systems capable of applying variable rate irrigation could optimize the irrigation management at every location of the field. By doing so, farmers can further improve water productivity. 

Looking at Climate Change and Global Food Security

Peter Backlund, Associate Director, School of Global Environmental Sustainability

SYNOPSIS

CSU researchers collaborated on a document released at the December 2, 2015 climate change meeting in Paris, France called *Climate Change, Global Food Security, and the U.S. Food System*. The full report is available at usda.gov/oce/climate_change/FoodSecurity.htm.


Food security—the ability to obtain and use sufficient amounts of safe and nutritious food—is a fundamental human need and achieving food security for all is a widely agreed international objective. The Sustainable Development Goals adopted by the United Nations (UN) in September 2015 call for ending malnutrition and hunger by 2030. This is a very difficult target, but improvements in recent decades allow some optimism.

According to the UN Food and Agriculture Organization, there are currently about 805 million undernourished people, or 11 percent of the global population, down from about one billion, or 19 percent, in 1990-92. This progress has occurred despite growing population, significant food waste, inefficient distribution, and widespread poverty, all of which remain major challenges. Human-

induced climate changes, many of which involve changes to the water cycle, are another stress on agriculture and the broader food system. Global average temperature, which has already increased by almost 2 °F since 1900, is projected to go up another 2-4 °F by 2050 and 2-7 °F by 2100, accompanied by changes in precipitation timing and intensity, increased drought, altered stream and river flows, and rising sea levels. Can progress toward eliminating hunger be maintained in the face of these projected changes? Or does climate change threaten continued progress, or even reversal of gains already made?

These are the fundamental questions addressed in *Climate Change, Global Food Security, and the U.S. Food System*, which was released on December 2, 2015, at the global climate change meeting in Paris, France. This report, which has been downloaded more than 330,000 times since its release, is the product of a scientific assessment sponsored by the U.S. Department of Agriculture as part of the U.S. Global Change Research Program. I am one of the author team, which also included Dennis Ojima from CSU's Ecosystem Science and Sustainability Department and Natural Resource Ecology Lab and researchers from U.S. government agencies, inter-governmental organizations, and academic institutions in the U.S., England, Argentina, and Thailand. Our charge was to review the current scientific literature to identify potential impacts of climate change on food systems and global food security and to consider how these could affect the U.S.

We found that climate change is likely to diminish global food security by disrupting production, increasing prices, interrupting transport, increasing waste, and diminishing food safety. Fortunately, it appears that adaptation holds real promise for reducing climate change effects on food security, and the complexity of the food system offers multiple potential points of intervention. But effective adaptation is subject to highly localized conditions and socioeconomic factors. Technically feasible steps can be inhibited or prevented by high costs and lack of near-term benefit.

We also found that many factors aside from climate change influence future food systems and food security. Some amplify the effects of climate change and increase the risks to food security (e.g., population growth), while others appear likely to diminish risk and are likely to help offset damaging climate change impacts (e.g., increasing levels of wealth). The risks are greatest for the global poor and in tropical regions and increase as the magnitude and rate of climate change increases over time. Finally, this set of changes is likely to affect consumers and producers in the U.S. through increased food prices, changing availability of imports, and increased demand for U.S. exports, food aid, and other types of assistance. 

What are the implications for the United States?

The U.S. has many advantages: a large area of arable land, high agricultural yields, vast integrated transportation systems, and a high level of overall economic development. Nonetheless, changes in climate are expected to affect U.S. consumers and producers by altering the type and price of food imports from other regions of the world, as well as by changing the export demands placed on U.S. producers and the transportation, processing, and storage systems that enable global trade. Demand for food and development assistance may increase, as may demand for the technologies and information to manage changing conditions.



Solving the Climate Change Riddle Reasons for Optimism

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SYNOPSIS

Much of the popular discussion surrounding climate change can be pessimistic, but there are plenty of reasons, from technological improvements to public involvement, to frame the future of climate change with optimism.

On August 29, 1956, almost sixty years ago, CSU professor of Civil Engineering Ralph Parshall—the inventor of the Parshall flume used to measure water in thousands of irrigation ditches—gave a talk to the Fort Collins Rotary Club about water. At the very end of his talk he said, “Carbon dioxide gas in the atmosphere is at present a tremendous quantity, 235 billion tons. We are adding 10 billion tons per year. Every time you drive your car around the block you make a contribution of this gas to the atmosphere. This gas together with ozone, water vapor and other gases at high altitude retards the radiation of heat from the earth’s surface

which increases the temperature of the air somewhat in the nature of the glass roof on a greenhouse. The various natural effects have been known for a long time but since man has little or no control we can only bend our efforts in the direction of safe guarding ourselves in the best possible manner. At the moment there does not appear to be a solution to this problem.”

Since Parshall’s remarkable talk, scientists have extensively studied the greenhouse problem and now understand the threat it poses to human and natural systems. We now know, for example, that significant warming will occur in this century, often defined as warming in excess of 2°C (3.6°F), if we continue to emit greenhouse gases at our current rate of 50 billion tons per year. We know, also, that to prevent dangerous warming these emissions must be eliminated. Finally, contrary to Parshall’s pessimism, in just the last few years viable, cost-effective technologies and international political agreements to deal with the problem have appeared. Indeed, it even appears that the first signs of slowing emissions may be at hand.

It is worth discussing these developments in detail.

Cost-Effective, Scalable, Renewable Electrical Energy Technologies

The easiest way to reduce greenhouse gas emissions is to modify electrical energy generation which creates approximately 30 percent of U.S. emissions. The good news is that the revolution in renewable energy costs since 2008 is significant and is quickly changing how we generate our electrical energy (Figure 1). Solar modules have dropped in cost by a factor of about 10 since 2003 and now cost under \$0.50 per watt. Lazard puts unsubsidized utility-scale solar photovoltaic (PV) installations in the best locations at under the price of coal and natural gas generation: about \$45 to \$60 per megawatt-hour, which compares with \$52 to \$78 for natural gas combined cycle and \$65 to \$150 for coal.

Wind is also competitive with natural gas power plants with costs dropping by 25 percent since 2008. In states with good wind resources, wind is now the cheapest

option for new energy. Wind in the best locations is \$32 to \$77 per megawatt-hour, even cheaper than solar. Wind turbine technology has greatly advanced in the last 20 years with larger turbines (5 MW vs. 1 MW) utilizing longer blades to access stronger and more consistent winds located higher above the earth's surface.

Renewable energy in 2015 provided 13 percent of total U.S. energy production, up sharply from eight percent in 2007 (Figure 2). Solar has grown from less than 1 gigawatt (GW) in 2008 installed to almost 30 GW now. Wind went from 25 GW in 2008 to over 75 GW in 2015, one-fifth the installed capacity of coal. Total U.S. solar and wind renewables went from 26 GW in 2008 to over 103 GW in 2015. More than 50 percent of the newly installed generation in the last year was from renewables. This trend is being driven by the economics of renewables, not carbon reductions.

Both wind and solar have interesting cost aspects because once installed there are no fuel costs. No other form of energy has this benefit, and it means operators escape the fuel price risk inherent to fossil fuels. Both solar and wind have been helped by federal tax credits, but experts also believe these technologies will be fully competitive without tax credits in just a few years.

A Viable Path to Carbon-Free Energy for Electricity

Over the past five years a number of peer-reviewed studies have laid out economically viable paths using renewables to eliminate greenhouse gas emissions. Two recent peer-reviewed studies in reputable journals by accomplished scientists have looked at the costs, feasibility, and co-benefits of moving quickly to all renewable energy. The findings are exciting and encouraging. First, a January 2016 study by NOAA scientists in Boulder and CU concluded that carbon dioxide emissions from the electrical sector could be curtailed by up to 80 percent by 2030 without an increase in electricity costs. Further, they concluded that additional energy storage was not necessary for energy reliability to achieve this reduction if a new energy transmission grid is built to move energy around the nation—renewable energy is always

available somewhere in the nation at any given time (Figure 3).

A late 2015 study by a team from Stanford recently laid out state-by-state roadmaps to move to 100 percent

renewable energy by 2050. Interestingly, end-use power demand is reduced by 40 percent when moving to electricity, a benefit of the efficiencies implicit in electricity use (Figure 4). This study shows a large

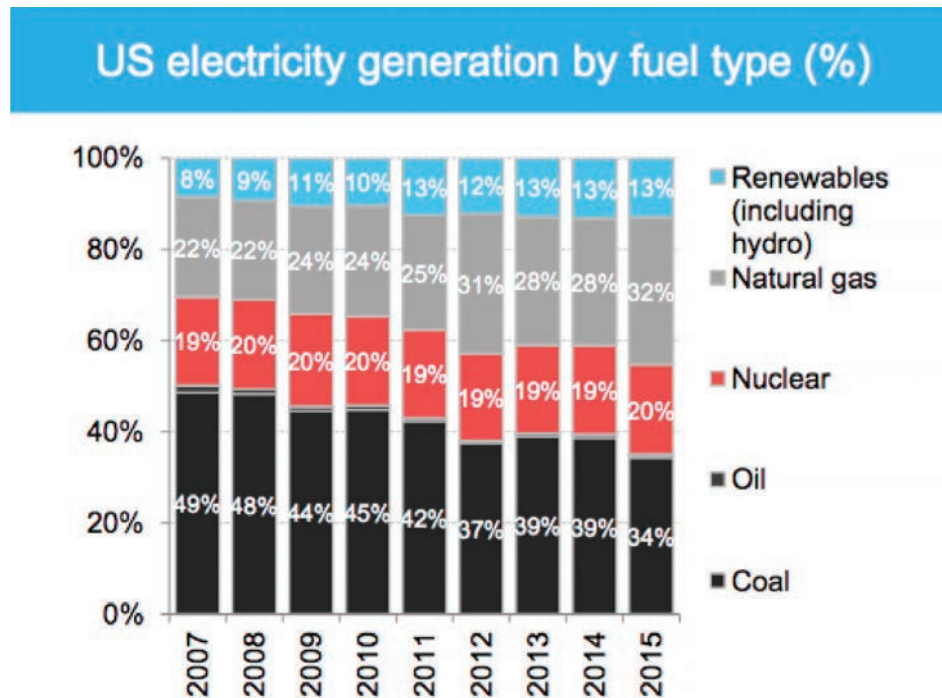


Figure 1. Since 2007, energy generation from coal has decreased, and generation from renewables and natural gas have increased. Reproduced by permission from 2016 Sustainable Energy in America Factbook by Bloomberg Finance L.P., and the Business Council for Sustainable Energy.

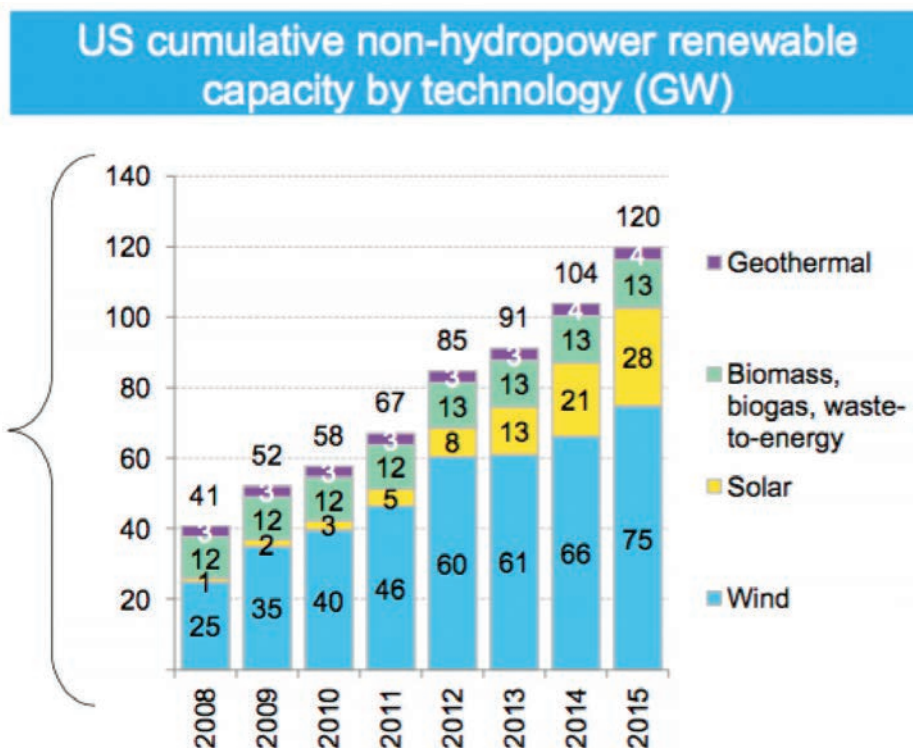
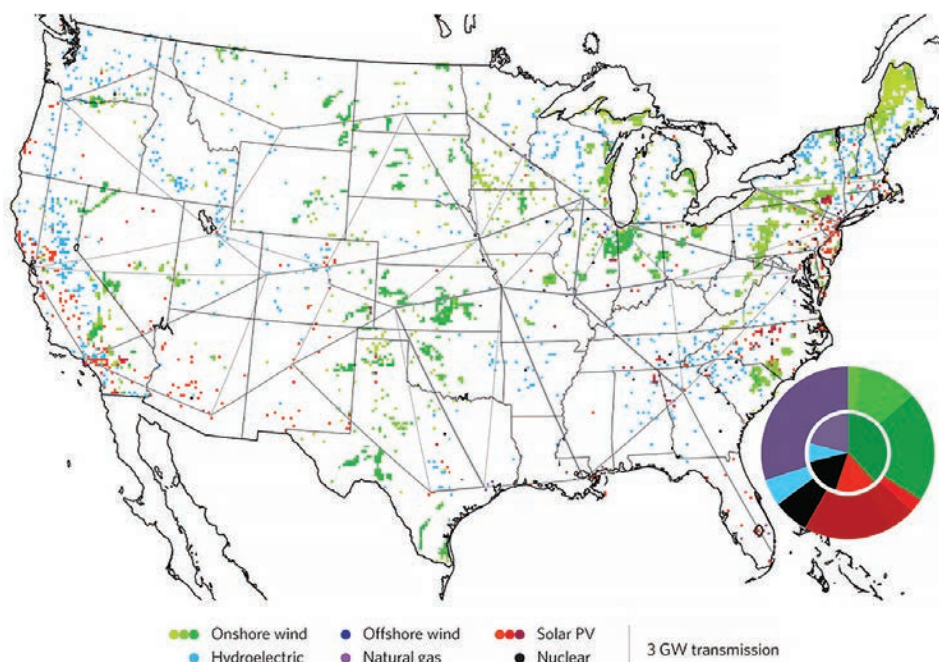


Figure 2. Renewable energy capacity has increased in recent years. Reproduced by permission from 2016 Sustainable Energy in America Factbook by Bloomberg Finance L.P., and the Business Council for Sustainable Energy.



Cost-optimized locations of renewable energy installations by type (deeper colors indicate higher quality) along with new transmission grid to ensure reliability to meet 80% of US demand by renewables. Outer pie is installed capacity and inner pie is total demand met by each technology. Reprinted by permission from Macmillan Publishers Ltd: Nature Climate Change, MacDonald et al, 2016.

number of co-benefits including more jobs gained than lost by the conversion, more than 50,000 premature deaths avoided per year from air pollution associated with current dirty energy generation, and savings in energy costs. Importantly, the additional land needed for renewables is minimal.

Nuclear energy has also been proposed as a viable solution, including new, safer reactor designs and fuels without the potential for misuse in weapons. Nuclear power, unlike renewables, can provide consistent baseload power without new transmission grids and thus has a form of reliability not currently possible with renewables. Nuclear power also has high energy-density, meaning much energy is produced from a relatively small area or volume. Unfortunately, the Fukushima disaster renewed public concerns about nuclear safety. In the early 2000s, a number of reactors were proposed but after the 2011 event were abandoned. Currently, there are only four nuclear reactors under construction in the U.S. The costs are also higher than many forms of renewables. Some scientists say that even were nuclear acceptable, the long permitting and construction time lags would make it difficult to build enough new plants in the timeline

needed. Nuclear power may yet have a role to play, but meanwhile renewables are cost-effective and are being installed quickly throughout the nation.

Transportation

Fossil-fuels, mostly petroleum, currently power our transportation sector and this sector is responsible for approximately 28 percent of U.S. greenhouse gas emissions. Experts have said for years that in order to move away from greenhouse gas emissions we must electrify this sector. In just the last few years, electric vehicles have shown the potential to become viable replacements for conventional fossil-fueled vehicles in many circumstances. Chevrolet, BMW, Ford, Tesla and Nissan have sold electric vehicles for the last few years and these cars represent about one percent of vehicles sold today in the U.S. Affordable models with 200-mile range by Chevrolet, Tesla, Ford will be entering the market as soon as 2017. One recent study suggests that the crossover point where, considering all costs, EVs' would cost less than conventional fueled is fast approaching. Even at \$2 per gallon gas, existing EV's have one-quarter the per mile fuel cost as a conventional vehicle that gets 20 mpg.

To be sure we don't have all the answers or the technologies for transportation. This sector is inherently difficult to reduce emissions because the extremely high energy-density and transportability of carbon-based fuels is challenging to replace. For the foreseeable future, for example, aircraft will have to rely on energy-dense carbon-based fuels. Airlines have, however, successfully experimented with carbon-neutral biofuels as one viable solution for the interim while we await technology breakthroughs.

Agriculture

There are a number of efforts underway to reduce agricultural greenhouse gases which are approximately nine percent of U.S. emissions. Internationally, The Global Alliance for Climate-Smart Agriculture, a group of 120 nations, universities, NGOs, and companies is working to help agriculture "sustainably intensify" its operations, adapt to change, and reduce greenhouse gases (See Longchamps and Kholsa Article).

The USDA is pursuing 10 building blocks to reduce agricultural greenhouse gas emissions. These blocks include improving soil health and nitrogen stewardship, deploying anaerobic digesters for manure, conserving sensitive land, promoting grazing management, protecting forests, promoting long-lived wood products, increasing urban forests, and promoting renewable energy and energy efficiency (See "USDA Building Blocks"). Also, the 100-member U.S. the Coalition for Agricultural Greenhouse Gases (C-AGG) is working to find effective voluntary incentives for agriculture to reduce greenhouse gases.

International Commitments to Reduce Emissions

Last year in Paris, on December 12, 2015, 195 nations signed an unprecedented climate agreement to reduce greenhouse gas emissions with the goal of completely eliminating greenhouse gas emissions sometime between 2050 and 2100. The agreement set a target of keeping future temperature increases to below 2°C with 1.5°C being an aspirational target. Each nation has made a self-determined future commitment to greenhouse gas reductions known as an

Individually Determined National Contribution (INDC). These commitments will be revisited and progress measured every five years with the goal of increasing the commitments over time.

While there is no formal enforcement mechanism other than ‘name and shame’, and while most experts see the current INDC commitments as not enough to stop warming at 2°C, the fact that after twenty years of negotiation we have a binding international agreement is an enormously important psychological as well as practical goal. No longer can some make the claim that some nations are not doing their part to solve the problem. And the fact that 195 nations signed the agreement is the strongest possible statement that current climate change science is actionable, contrary to claims that we don’t know enough.

Additional bilateral agreements have been reached. In 2014 the U.S. and China reached a separate agreement whereby the U.S. agreed to reduce its emissions to 26 to 28 percent below 2005 levels by 2025 and China agreed to peak its emissions by 2030 if not sooner and to reach 20 percent renewables by that date. China is well on its way to meeting its commitment.

Worldwide Emission Trends

The rapid growth in worldwide greenhouse gas emissions since 2000, averaging 2.4 percent per year, slowed unexpectedly to zero percent in 2014-2015. This is the first time that emissions have slowed in a non-recessionary economic environment. Much of the drop in 2014-2015 was due to declining coal use in China. A switch to non-fossil-fuels in that country is already well underway.

Other developed nations have consistently shown emissions declines since 2005. The European Union emissions dropped by 2.4 percent per year from 2005 to 2014. U.S. emissions dropped an average of 1.4 percent per year since 2005, mostly due to coal-fired power plant closures. Since 2009, long planned and more stringent Clean Air Act rules have led to the retirement of over 200 coal plants in the U.S providing significant emissions reductions. The shuttered plants, grandfathered under the original Clean Air Act,

were years beyond their design life, infrequently used and could not meet modern pollution requirements for sulfur dioxide, mercury, soot, and nitrogen oxides in addition producing twice the carbon dioxide emissions of state-of-the-art natural gas plants.

Almost all of this lost power has been replaced with natural gas and renewables; indeed during the last 12 years, gas and renewables have provided 93 percent of all new power brought on line due to cost advantages. The boom in fracking for natural gas has assisted with this transition by making cheap, plentiful gas available to power our most efficient power generating stations, natural gas combined cycle plants. There is reason to believe that these reductions will continue and even accelerate. The recently announced U.S. Clean Power Plan, for example, will reduce emissions from electricity by 32 percent in 2030.

Most scientists expect global greenhouse gas emissions to continue upward despite the recent slowing. India, and other developing countries are expected to increase their emissions in the near term as they modernize. It is nevertheless encouraging that many nations have begun the transition to carbon-free energy.

Conclusion

Ralph Parshall’s prescient 1956 talk noted the greenhouse effect and lamented our inability to stop the inevitable impacts. Sixty years later it is readily apparent that climate

change is happening quickly and that the impacts will be serious. In 2015, the Earth topped 400 ppm in CO₂ concentrations for the first time in at least the last 800,000 years, long before modern humans existed. Fourteen of the fifteen hottest years on record have occurred since 2000. Sea levels from melting glaciers and thermal expansion of seawater are rising at the fastest rates in the last 2,700 years threatening major cities. Hot and dry droughts, heavy downpours, earlier runoff, more rain and less snow, and hotter and longer heatwaves—all long predicted by scientists—are now appearing with disturbing frequency.

The good news is that after extensive scientific studies and much technology development we are now poised to solve this pressing problem. Clean, affordable carbon-free electrical energy that powers all aspects of society is no longer a nice sounding but impossible goal. Using current technology, we can now see most of the way to a world without carbon pollution and serious, damaging climate change. Indeed, it is already happening under our very eyes.

The challenge is that there is still much to be done, and current commitments to reduce greenhouse gas emissions do not go far enough. Climate change is, and will continue to be, disruptive for humans throughout the 21st century. Clever and crafty humans have the motivation, international agreements, and the technology to do what it takes to solve this very difficult and pressing problem. 🌀

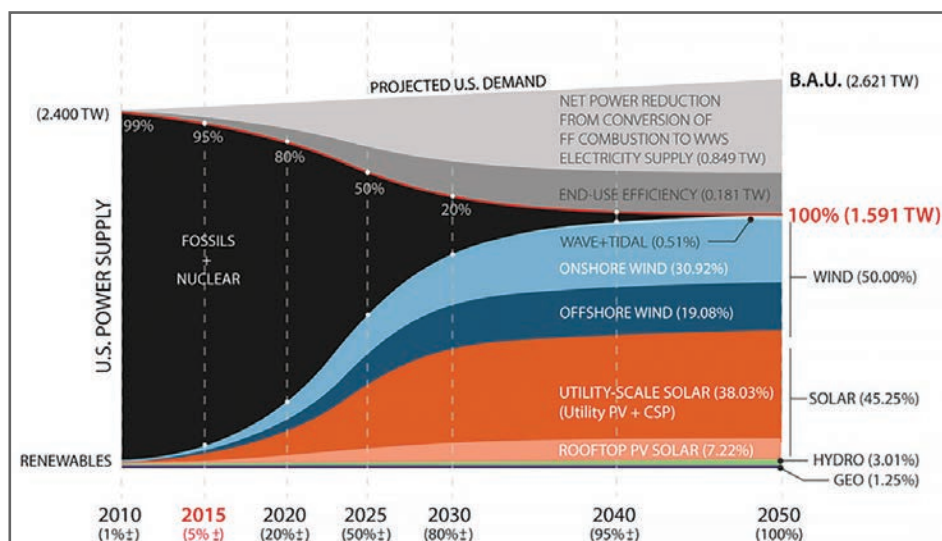


Figure 4. One path to zero fossil fuels by 2050 involves 45% solar, 50% wind, and a 40% decrease in demand because of the implicit efficiency in electricity. Reproduced from Jacobson et al., 2015 with permission of The Royal Society of Chemistry.

Further Reading

U.S. Department of Agriculture

USDA Climate Change

usda.gov/wps/portal/usda/usdahome?navid=climate-change

USDA Climate Hubs

climatehubs.oce.usda.gov

USDA Northern Plains Climate Hub

climatehubs.oce.usda.gov/northernplains

USDA Northern Plains Regional Climate Hub Assessment of Climate Change Vulnerability and Adaptation and Mitigation Strategies (PDF) by Derner, Joyce, Guerrero, and Steele (2015)
climatehubs.oce.usda.gov/sites/default/files/Northern%20Plains%20Vulnerability%20Assessment%205_1_2015_Compressed.pdf

Research and Outreach Organizations

Colorado Climate Center

climate.colostate.edu

Department of Interior North Central Climate Science Center

revampclimate.colostate.edu/

DOI Southwest Climate Science Center

www.doi.gov/csc/southwest

Western Water Assessment

www.colorado.edu

Colorado State Documents

Colorado Climate Plan (PDF)

codot.gov/programs/environmental/Sustainability/colorado-climate-plan-2015

Colorado Climate Change Vulnerability Study (PDF)

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Colorado Climate Preparedness Project (PDF) by Averyt, Cody, Gordon, Klein, Lukas, Smith, Travis, Udall, and Vogel (2011)

www.colorado.edu/publications/reports/WWA_ColoClimatePreparednessProject_Report_2011.pdf

Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation, 1st ed. (PDF) by Ray, Barsugli, and Averyt (2008)

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Colorado Water Conservation Board Climate Change Website

cwcb.state.co.us/environment/climate-change/Pages/main.aspx

Colorado Department of Public Health and the Environment Climate Change Website

colorado.gov/pacific/cdphe/categories/services-and-information/environment/air-quality/climate-change

Other Assessments

Nebraska Climate Change Assessment (PDF) by Bathke, Oglesby, Rowe, Wilhite (2014)

snr.unl.edu/download/research/projects/climateimpacts/2014ClimateChange.pdf

Intergovernmental Panel on Climate Change 2014 Synthesis Report (PDF) – The Core Writing Team, Pachauri, and Meyer, eds.

ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf

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nca2014.globalchange.gov/report

NOAA State of the Climate

ncdc.noaa.gov/sotc

U.S. Southwest Climate Assessment

swcarr.arizona.edu

USDA, Climate Change: Global Food Security and the U.S. Food System (PDF) by Brown, Antle, Backlund, Carr, Easterling, Walsh, Ammann, Attavanich, Barrett, Bellemare, Dancheck, Funk, Grace, Ingram, Jiang, Maletta, Mata, Murray, Ngugi, Ojima, O'Neill, and C. Tebaldi (2015)

usda.gov/oce/climate_change/FoodSecurity2015Assessment/FullAssessment.pdf

International Efforts

FAO Climate-Smart Agriculture

fao.org/climate-smart-agriculture/en

Global Alliance for Climate-Smart Agriculture

fao.org/gacsa/about/en



Basic Science and Background

EPA Climate Information

<https://www3.epa.gov/climatechange/>

NOAA Climate Information

www.climate.gov

Skeptical Science

skepticalscience.com

Books

The Discovery of Global Warming

by Spencer Weart

The Two-Mile Time Machine

by Richard Alley

The Thinking Person's Guide to Climate Change

by Robert Henson

Climate Tools

COMET-Farm: Whole Farm and Ranch Carbon and Greenhouse Gas Accounting System

cometfarm.nrel.colostate.edu/Home

Western Water Assessment Dashboard

wwa.colorado.edu/climate/dashboard.html

from www.colorado.edu

USDA Climate Hubs Tools

climatehubs.oce.usda.gov/content/tools-and-data

U.S. Climate Resilience Toolkit—Water Resources

toolkit.climate.gov/topics/water-resources/water-resources-dashboard from climate.gov

Greenhouse Gas Tools and Inventories

U.S. EPA Greenhouse Gas Inventory

www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html

State of Colorado Greenhouse Gas Inventory (PDF) by Arnold, Dileo, and Takushi (2014)

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Coalition on Agricultural Greenhouse Gases

c-agg.org



Colorado Water Online

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Longmont, Colorado
Photo by Sam Cox

