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Authors

Carter, Colin
Santer, Benjamin
Auffhammer, Maxililian
et al.

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Climate Change: Challenges to California's Agriculture and Natural Resources

Special Issue

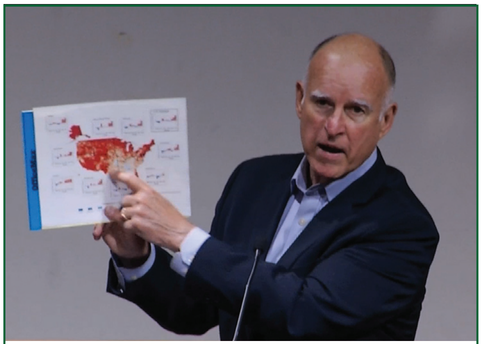
Forum Videos Are Available at bit.ly/1ugX8yk

California's ongoing drought is extraordinary and one of the worst in state history. Recently, Stanford University scientists reported that the drought may be linked to global climate change. This special issue of *ARE Update* summarizes a one-day Forum on climate change and associated challenges facing California's agriculture and natural resources, held in Sacramento in May 2014. California's Governor Jerry Brown addressed the Forum and he stressed the importance of both reducing carbon emissions, and at the same time devising ways to adapt to climate change.

The United Nations Intergovernmental Panel (IPCC) 5th assessment of the published literature on climate change concluded that some of the worst impacts of climate change will be in agriculture and these impacts are likely more serious than what was believed earlier. We all live downstream from agriculture and agriculture is truly the "canary in the coal mine" when it comes to climate change.

In this issue, one of the leading climate scientists in the nation, Benjamin Santer from Lawrence Livermore National Laboratory, distills the scientific evidence into layperson's terms and describes the most likely impacts of climate change on California.

Maximilian Auffhammer notes that climate change is a "slow-moving process" that offers the agricultural industry a window of opportunity in dealing with climatic uncertainties. Professor Auffhammer points out there are few studies that have measured the climate sensitivity of California's most important crops.



Governor Edmund G. Brown, Jr. addressed the Giannini Foundation Climate Change Forum on May 19, 2014.

Given the lack of global policies to reduce carbon emissions, adaptation may be necessary for agriculture. In a very interesting article, Professors Olmstead and Rhode explain the history of how U.S. agriculture has adapted to past disease and pest shocks. Some crops have also moved geographically, confronting a new climate.

One of California's most crucial challenges will be to maintain its water security. Richard Howitt emphasizes that moving forward, California must adjust its management of water to reflect the realities of climate change.

David Zilberman and Scott Kaplan discuss the broad economics of climate change on global food security and agricultural production and cropping systems. They stress that some agricultural regions will gain from climate change, and others will lose. On net, California agriculture may lose, especially in the coastal and delta areas, and the southern portion of the state.

The "Shape of Things to Come" for California's Climate and Agriculture

Benjamin Santer

Human-caused climate change is not some future hypothetical event, affecting only remote islands and Arctic villages. It is happening here and now, in our own state. The impacts of 21st-century climate change will be experienced by all Californians and are likely to be pervasive, affecting every sector of California's economy.

Human activities have changed the chemical composition of the atmosphere. Since the Industrial Revolution, atmospheric levels of carbon dioxide (CO_2), a potent heat-trapping greenhouse gas, increased by about 40%. Measurements of lighter and heavier isotopes of carbon reveal that at least three-quarters of this increase is due to human-caused burning of fossil fuels. According to the latest national and international scientific assessments (see "Further Reading"), the rise in atmospheric CO_2 levels has been the dominant cause of the 20th-century warming of the Earth's surface.

CO_2 and carbon isotope measurements are hard scientific facts—as is the link between increasing CO_2 and surface warming. Few climate scientists dispute these basic facts. While there is scientific discussion regarding the amount of warming caused by the 40% increase in CO_2, the existence of a human-caused warming signal is not the subject of serious scientific debate.

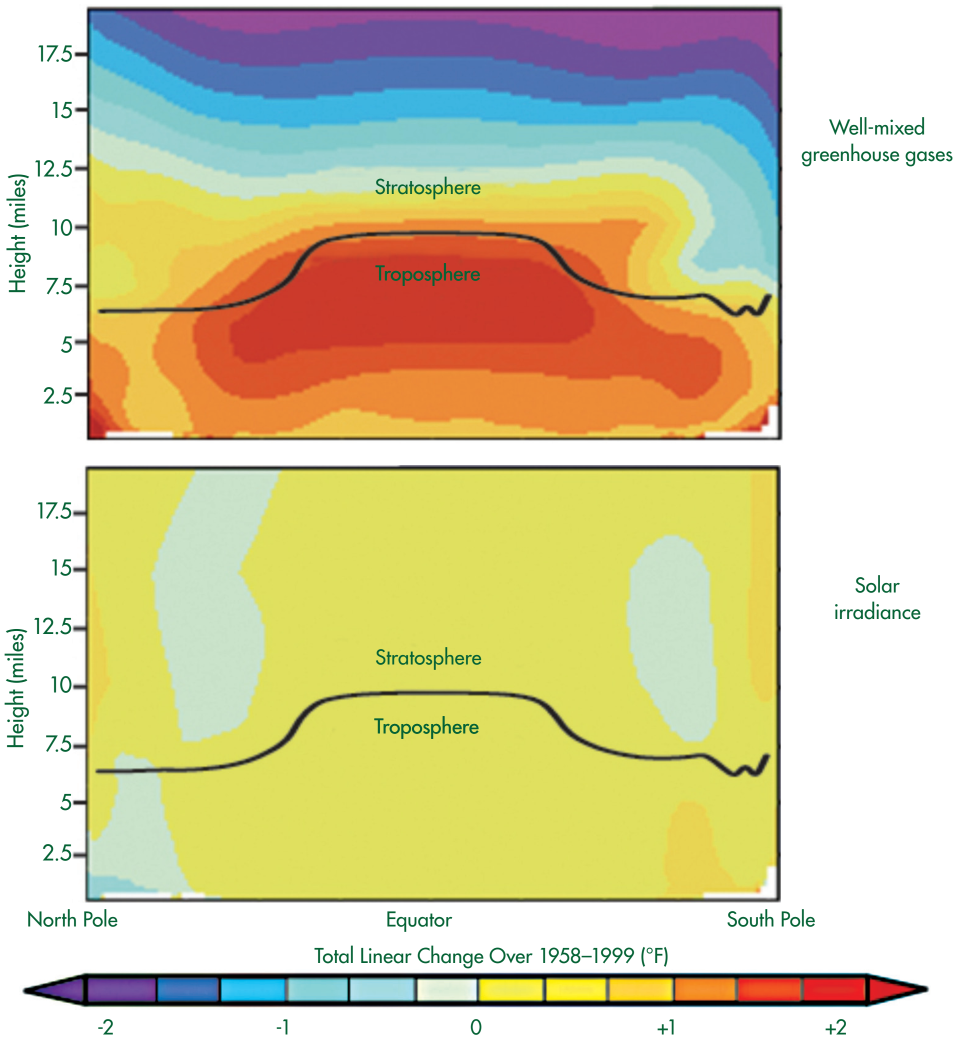
Climate Fingerprinting

The scientific search for this warming signal began in the late 1970s, with the publication of a paper by Klaus Hasselmann describing a statistical method for "fingerprinting" the climate system. Just as no two humans have identical fingerprints, so no two influences on the climate system have identical signatures in climate records. Unique identifiers of different causal factors become much more obvious when scientists probe beyond a single number—such as the global-average temperature of the Earth's surface—and look instead at complex *patterns* of climate change.

The insights that can be gained from studying climate change patterns are clear from Figure 1, which shows trends in atmospheric temperature over 1958 to 1999. Results are from two different simulations performed with a computer model of the climate system. In the first simulation, the model was driven by historical changes in greenhouse gas concentrations (upper panel). The second simulation used estimated 20th-century changes in the Sun's energy output (lower panel). The temperature trends from each simulation were averaged along bands of latitude, and then plotted at 17 different levels in the atmosphere, from close to the Earth's surface to an altitude of nearly 20 miles.

The greenhouse gas fingerprint in Figure 1 (upper panel) has a distinctive pattern of warming of the lower atmosphere and cooling of the upper atmosphere. A similar pattern of "warming

Figure 1. Different Factors That Influence Climate Have Different "Fingerprints"



Source: Modified from Global Climate Change Impacts in the United States, Karl et al., 2006 down low, cooling up high" is found in temperature observations made from satellites and weather balloons. In sharp contrast, the solar fingerprint warms through the full vertical extent of the atmosphere (lower panel of Figure 1) and does not look like the actual observations. The best explanation of the observed temperature changes requires a substantial contribution from human influences (see the 2013 Santer *et al*. paper in "Further Reading").

Fingerprint research was influential in shaping the bottom-line finding of the IPCC's Second Assessment Report in 1995: "the balance of evidence *suggests* a discernible human influence on global climate." This cautious but historic sentence generated strong reactions. One line of criticism was that the fingerprint research contributing to the "discernible human influence" finding relied heavily on studies of surface temperature change. Critics argued that if there really were a human-caused climate signal in observations, it should be identifiable in the oceans, atmosphere, water cycle, and in snow and ice—not just in surface temperature.

Researchers in the relatively new field of climate change detection and attribution (D&A) took this criticism seriously and expanded the search for human effects on climate. D&A researchers demonstrated that human fingerprints on climate were pervasive, and could be identified in rainfall, atmospheric moisture, salinity, ocean heat content, and many other types of observational record. The internal consistency of the D&A evidence was both scientifically compelling and sobering—a wake-up call for humanity.

On the strength of this new evidence, the 2013 IPCC Fifth Assessment Report concluded that: "Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes... It is *extremely likely* that human influence has been the dominant cause of the observed warming since the mid-20th century." The words "extremely likely" had a very specific meaning: the likelihood of this finding being correct was assessed to be 95% or greater.

Fingerprint studies have successfully identified human effects on California's temperature, snowpack depth in mountainous areas of the western United States, and the timing of stream flow from major western river basins. In each one of these cases, the changes in climate are of great practical and economic concern.

In a mere 16 years, the climate science community moved from a cautious "something unusual is happening in the climate system" to "humans are playing a dominant role in the warming of planet Earth." This transition marked a growing awareness that humans are now active participants in the climate system, and no longer simply innocent bystanders.

Detecting Human Effects on California's Climate

While the identification of a human fingerprint in global climate is an important scientific milestone, our personal experience of a changing climate is at the regional and local level. Can we see human signals in the regional-scale climate changes in California? Do such regional signals exist in things that have real social and economic value?

The answer to both of these questions is clearly "yes." Fingerprint studies have successfully identified human effects on California's temperature, snowpack depth in mountainous areas of the western United States, and the timing of stream flow from major western river basins. In each one of these cases, the changes in climate are of great practical and economic concern.

A prime example is the shift towards declining snowpack in the Sierras, and towards earlier spring runoff. As the 2014 U.S. National Climate Assessment noted: "Winter snowpack, which slowly melts and releases water in spring and summer, when both natural ecosystems and people have the greatest needs for water, is key to the Southwest's hydrology and water supplies." The better we understand such changes, the better we can prepare for them.

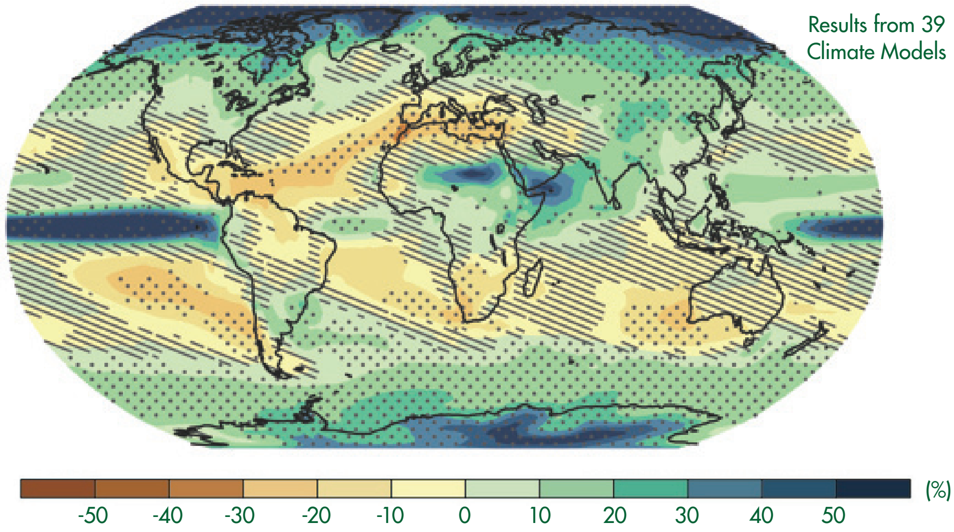
Implications of Detection Results for Future Climate Change

What does successful detection of human-caused fingerprints tell us about the expected future changes in California's climate? This question is difficult to answer. In almost all D&A studies, the fingerprints identified in observations are estimated with complex computer models of the climate system. Successful simulation of 20th-century climate change is a necessary condition for building confidence in computer model projections of 21st-century climate. But the past is not always prologue to the future, so scientists evaluate the credibility of model projections in many different ways—not just by comparison with historical climate records.

For example, D&A analysts ask whether projections of 21st-century climate change are robust across a range of different climate models. They consider whether the projected changes make physical sense. They evaluate how well the models used for making projections simulate key climate processes—particularly the processes responsible for "spread" in the 21st-century projections. They check whether climate forecasts made 20 to 30 years ago were accurate. Computer models of the climate system are constantly subjected to a variety of different reality checks. They are the best tools we have for attempting to understand 21st-century climate change.

Figure 2. Can We Reduce Scientific Uncertainties in Projected 21st-Century Rainfall Changes?

Change in Average Precipitation Between the End of the 20th and 21st Centuries



Source: Summary for Policymakers, IPCC Fifth Assessment Report, 2013

Robust Features of 21st-Century Changes in California's Climate

The current historic drought in California has prompted serious concern about 21st-century changes in rainfall, snowpack, runoff, and atmospheric circulation. What do current state-of-the-art climate models tell us about projected changes in these quantities?

Consider rainfall first. Figure 2, taken from the 2013 IPCC Report, shows the percentage change in annual-average rainfall between the end of the 20th and the 21st century. The results are based on simulations of historical and future climate change performed with 39 different computer models of the climate system. The stippling indicates areas where at least 90% of the models agree on the sign of the rainfall change and where the model average rainfall change is large compared to natural climate variability. Many areas of the globe are stippled. A prominent example is the Arctic, which becomes wetter over the 21st century.

In the diagonally shaded areas, however, the model average rainfall change is of comparable size to natural, decade-to-decade fluctuations in climate. Such is the case over much of California. The results in Figure 2 suggest that for decades to come, the "signal" of human-caused changes in California rainfall may be difficult to discriminate from the large background "noise" of natural climate variability.

Despite this uncertainty in California rainfall projections, there are many things we can be confident about. We know, for example, that the 21st century will be considerably warmer than the 20th century. According to the 2014 U.S. National Climate Assessment, annual-mean surface temperatures over the southwestern U.S. (including California) "are projected to rise by 2.5°F to 5.5°F by 2041–2070, and by 5.5°F to 9.5°F by 2070–2099, under a 'business as usual' emissions scenario."

Regional warming in response to continued human-caused increases in greenhouse gases is a very robust feature of model simulations. This warming signal drives a reduction in snowpack, which in turn means that more of the runoff from snow-fed river basins is likely to occur earlier in the year.

Another robust feature of model climate change projections relates to the temperature of the lower 4 to 11 miles of the atmosphere (the troposphere). Virtually all model simulations show larger tropospheric warming over the Arctic than at the equator. This preferential warming of the Arctic is also a prominent feature of satellite observations. It is largely due to so-called "feedbacks" involving the shrinking of Arctic snow and ice coverage.

The tropospheric temperature gradient between the equator and the North Pole has a major influence on Northern Hemisphere winds, storm tracks, and the jet stream. Precisely how these large-scale circulation features will respond is unclear, particularly in terms of their effects on regional climate. What is clear, however, is that the atmospheric circulation must react to major changes in its temperature structure. Such circulation responses may well have profound impacts on California's climate in the 21st century.

Human-caused Climate Signals in Agricultural Productivity

Today, D&A studies are not only being performed with changes in the climate itself—D&A analysts are also trying to link agricultural and ecosystem impacts to human-caused climate change. Such work is challenging. It requires accounting for confounding influences unrelated to climate. In agricultural D&A studies, these confounding factors include changes in land use and irrigation, and the development of crop varieties resistant to certain diseases and pests.

Despite these significant scientific challenges, the 2014 U.S. National Climate Assessment concluded that: "There have already been detectable impacts on (agricultural) production due to increasing temperatures." Intuitively, this makes sense. Scientists have successfully detected human-caused changes not only in the average climate, but also in the behavior of extreme temperature and rainfall. Agricultural productivity is very sensitive to the frequency, intensity, and duration of such extremes. It is highly likely, therefore, that agricultural productivity has already "felt" (and will continue to feel) the effects of human-caused changes in extreme events.

Final Words

In the absence of significant efforts to reduce emissions of CO_2 and other greenhouse gases, continuation of the 20th-century status quo—for California's climate, water resources, and agricultural productivity—is the least likely outcome for the 21st century. We are leaving known climate for an uncertain climatic future, and are relying on models, physical intuition, and past observations as our guides in this uncharted climatic territory. It will be a bumpy ride for all of us. But the ride will be a little smoother if we have better scientific understanding of human fingerprints on climate, and can identify robust features of the projected climate changes.

Suggested Citation:

Santer, Benjamin, 2014. "'The Shape of Things to Come' for California's Climate and Agriculture." *ARE Update* 18(1):2-5. University of California Giannini Foundation of Agricultural Economics.

Benjamin Santer is a research scientist with the Program for Climate Model Diagnosis and Intercomparison at the Lawrence Livermore National Laboratory in Livermore, California. He can be reached by email at santer1@llnl.gov.

Further Reading

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Estimating Impacts of Climate Change on California's Most Important Crops

Maximilian Auffhammer

> Understanding the historical and future impacts of climate change on California's specialty crops should be a research priority for the state.

California produces almost 50% of U.S.-grown fruits, nuts, and vegetables. Consumers across the United States regularly purchase crops produced solely in California. After milk, grapes and almonds have become the state's top-two valued commodities accounting for 4.5 and 4.3 billion dollars of output, respectively. Strawberries lettuce, walnuts, and tomatoes also make the top ten, jointly accounting for another 5.9 billion dollars of output.

California's 80,500 farms sold their output for $42.6 billion, which comes out to about 2% of gross state product. Exports accounted for 43% of that output. A look at the historical statistics on yields for a sample of important California agricultural products shows an incredible record of yield growth over the past 70 years.

As shown in Figure 1, strawberry yields today are ten times higher than they were in 1940. Almond yields are 8.5 times higher, and tomatoes are 7.3 times higher. Not all crops have experienced similarly steady and rapid yield growth, but even broccoli and lettuce experienced a three-fold increase in yields over this period.

Agronomists and agricultural economists have empirically documented factors, which can explain this growth in yields: irrigation, fertilizers, pesticides, high-yielding varieties and better farming practices, to name but a few. Further, California's farmers have pushed the frontier in terms of technological innovation for decades and in turn helped increase incomes of rural communities throughout the state.

The agricultural sector in California faces a number of old and some new challenges. There is increasing competition from abroad for a number of California's key crops, irrigation water is scarce due the ongoing drought and state legislation, input prices (e.g., labor, fuel, fertilizers, and pesticides) are on the rise, and there is the permanent threat of pest damage. The most recent addition to this list of threats to California's agricultural sector is climate change.

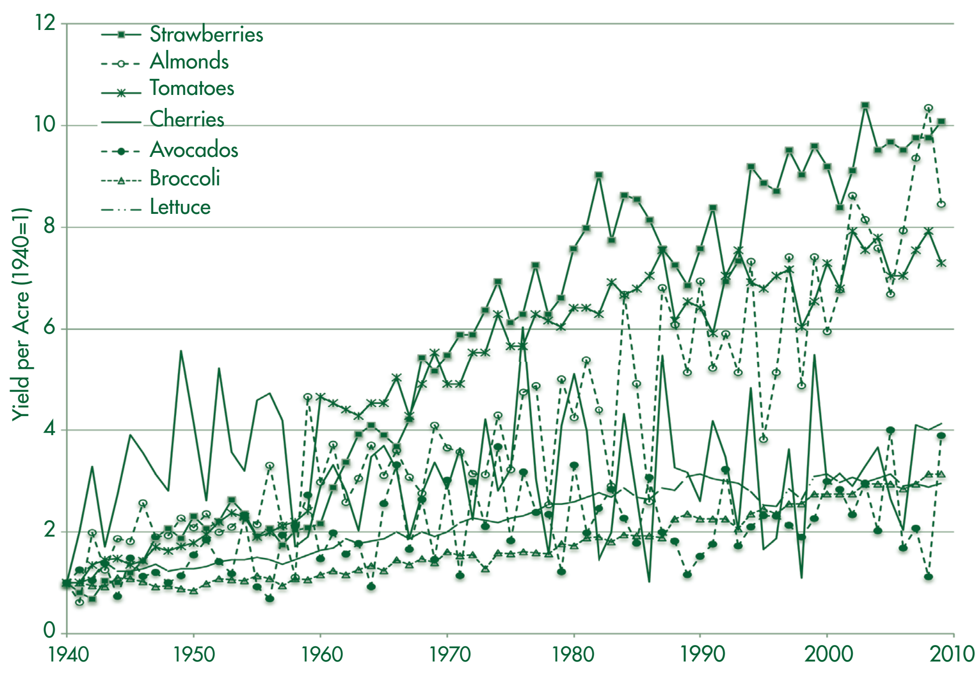
California's relatively mild climate is partially responsible for the high quality and quantity of output of the major crops grown here. Further, there are many microclimates, such as the Napa Valley, which have enabled the birth and continued success of California's agricultural commodities and differentiated products on the world market.

Challenges in Estimating Impacts of Climate Change on Crops

The major concern arising from anticipated climate change is that the "new" climate will negatively affect the quality and overall output of these important commodities. There are a number of ways in which a change in climate regime might affect the sector. Warming will lead to an upwards shift of the distribution of temperatures experienced on the ground. This shift will lead to fewer cold days and more extreme heat days. A warmer climate will also negatively affect our ability to store irrigation water naturally in the snowpack.

Shifting fog patterns might affect the suitability of certain areas for growing crops, which rely on this fog and affect the quality of the product. Changing precipitation might affect water availability for irrigation. All

Figure 1. Yields per Acre for Seven Commodities

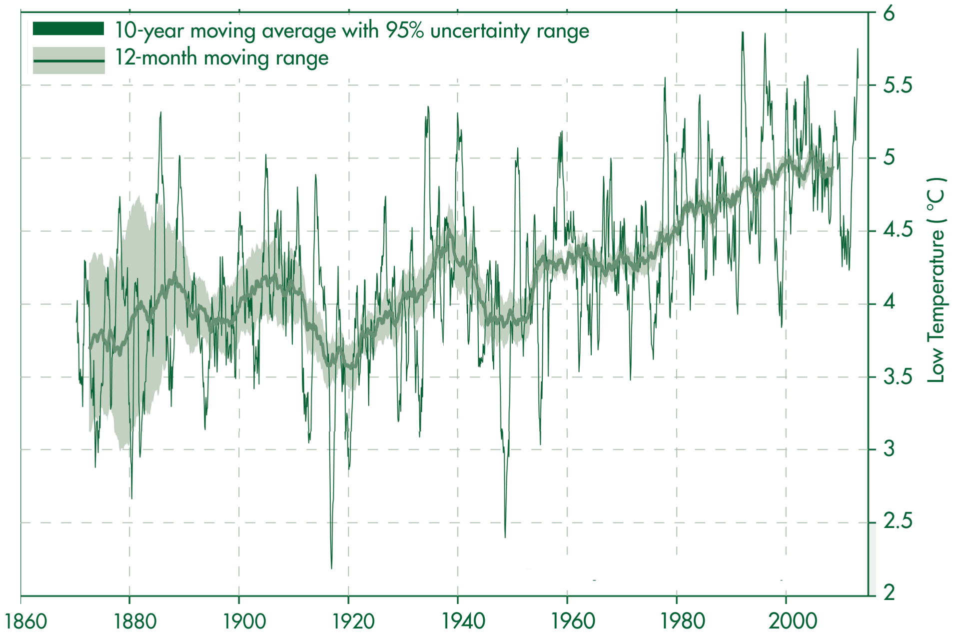


Source: United States Department of Agriculture, National Agricultural Statistics Service of these statements are conjecture, which need to be backed up by careful analysis. The so-called "perfect experiment" to study these impacts would be to randomize different concentrations of greenhouse gases across a few hundred otherwise identical planets and observe what happens to crop yields on planets with higher concentrations. This is clearly not an experiment that can be run. So how does one estimate impacts in practice?

In order to estimate impacts of climate change on agriculture, a researcher needs to understand two factors. The first ingredient is a "counterfactual" climate under past or future climate change. If one looks into the past, one could look for trends in measured climate that are consistent with climate change.

A truly "nonpartisan" dataset of observed temperatures was assembled by formerly confessed climate skeptic Professor Richard Muller at UC Berkeley. The Berkeley Earth Project assembled maybe the most extensive public database of global weather data records and analyzed them using a transparent and consistent set of rules. The data show an undisputable trend in global surface temperatures, which cannot be explained by any other factor than anthropogenic emissions of greenhouse gases. Figure 2 above shows the recorded minimum temperatures for Modesto from this dataset.

Figure 2. Minimum Temperatures for Modesto, California



Reference Location: 37.78N, 120.00W; Nearby Cities: Modesto, Merced, Turlock
Source: Berkeley Earth Project

This figure displays a clear trend, which accelerates in the early 1960s. The calculated change in *average* temperatures for this location is roughly 1.6 degrees Fahrenheit since 1960, which is significant. It is important to note that there is and always will be significant year-to-year variability in weather. However, there is a clear detectable trend in temperatures, which is more pronounced in nighttime temperatures than in daily maximum temperatures.

The warming trend in Modesto is slightly slower than the global average trend or the trend for North America. Further, it is important to note that the observed trends in temperature cannot account for which part is from anthropogenic emissions of greenhouse gases versus which part might be due to changes in land use patterns. So the record shows that there has been warming, which is consistent with what we would expect from climate change.

If we are interested in projections of future climate, Ben Santer's piece in this issue discusses how global climate models can be used to project future climate with and without human-caused climate change. These models can be used to construct a counterfactual future climate with and without anthropogenic emissions of greenhouse gases.

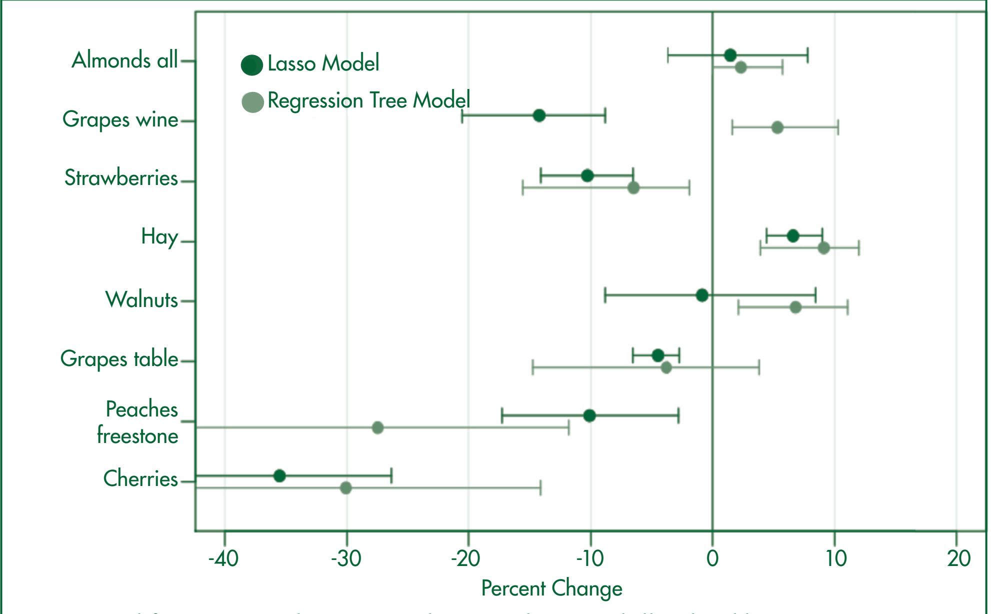
Climate Sensitivity of Crops

The second ingredient required for an impact study is a reliable estimate of how individual crop yields respond to variation in weather or climate. We call this a *climate sensitivity*. This is not an easy challenge. As discussed above, the researcher needs to statistically separate the contribution of climate/weather to yields from that of irrigation water, fertilizer, pesticides, labor, prices and soil quality, to name but a few. In order to conduct such an exercise, the optimal data one would want will cover a large spatial area, preferably at the field level, over many growing seasons. This can easily be done for corn, soy, cotton and wheat, as there hundreds of counties growing these commodities. The data for specialty crops are more limited.

Due to the data availability, the literature has focused largely on the climate sensitivity of cotton, soy, wheat and corn. There is strong evidence showing that these field crops suffer very badly from just a few days above 30 degrees Celsius, so-called extreme heat days. While we do grow some of these row crops in California, these are by no means the economically most important crops in the state. Grapes, almonds, strawberries, lettuce, walnuts, and tomatoes are economically much more significant here.

In order to arrive at estimates of impacts of climate change on the crops of economic significance to California, you combine the climate sensitivity of a crop with observed or

Figure 3. Estimated Impact of 2°C Warming on Crop Yields



Source: California Perennial Crops in a Changing Climate, Lobell and Field, PIER Program, 2009

projected changes in climate. This is where the trouble begins. There are very few studies that have looked at the climate sensitivity of the economically significant crops in California.

One of the first studies was conducted for the California Public Interest Energy Research (PIER) program by David Lobell and Chris Field. They use data for the crops of interest, estimate climate sensitivities, and project impacts for a two-degree warming scenario. Figure 3 shows the estimates of the impact of two degrees of warming on yields for the crops analyzed. The model predicts large negative impacts on cherries; negative, but uncertain, impacts on peaches; and a slight negative yield impact for berries.

If we take a step back and assess whether we have the necessary information to plan for the decades of warming ahead, I would argue that we are ill-prepared. We simply do not have a good understanding of the climate/temperature sensitivities of California's most important crops. While there are lots of aggregate studies that look at the sensitivity of the total value of crops—or the area planted—to temperature and rainfall, these are only of limited use. We need to understand how individual crops (e.g., avocados, tomatoes, almonds, walnuts, etc.) respond to changes in the aspects of climate important to their yields.

While we have access to county-level crop reports, there is a need for academics with extensive statistical toolkits to collaborate with the agricultural organizations of the state in order to once again push the frontier of what is known. What we lack are good sources of data for the crops that are the backbone of California's agricultural sector and that are not being researched by national agricultural services due to their mostly local importance.

Further, the yield studies cited above do not do a satisfactory job at incorporating the potential for adaptation. If summers are hotter, one might shift the planting calendar forward. If climate zones shift northward, so might some agricultural production. Further, if farmers have a good understanding of the changes they will be facing in this new world, they will likely do what they have always done—innovate and meet the climate challenge head-on.

The California Department of Food and Agriculture recently convened a Climate Change Consortium for Specialty Crops, whose report outlines both impacts and strategies for resilience. This forum brought together academics, representatives from the agricultural sector, and policy makers to chart a path forward in our understanding of the challenges ahead.

While climate change is by no means the only risk California's agricultural sector faces, it is a slow-moving process, which we can anticipate to a certain degree and jointly develop adaptation strategies.

Suggested Citation:

Auffhammer, Maximilian, 2014. "Estimating Impacts of Climate Change on California's Most Important Crops." *ARE Update* 18(1):6-8. University of California Giannini Foundation of Agricultural Economics.

Maximilian Auffhammer is the George Pardee Jr. Professor of Sustainable Development in the Department of Agricultural and Resource Economics at UC Berkeley and a lead author of the recent IPCC 5th assessment report. He can be reached by email at auffhammer@berkeley.edu.

For additional information, the author recommends:

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Can We Adapt to Climate Change? Lessons from Past Agricultural Challenges

Alan L. Olmstead and Paul W. Rhode

Evidence mounts that farmers will face enormous challenges to adapt to climate change and to the accompanying increase in pest and disease problems. California farmers have faced many serious crises in the past. This paper highlights a few of those past episodes and some of the lessons garnered from those experiences.

Evidence from the North and South Poles and many points in between signals the enormity of the climatic change underway. Climate models forecast over the next century significant increases in temperatures, a rising sea level (with accompanying salinity problems for coastal water supplies), and changing precipitation patterns—some areas will receive more precipitation and others less. Moreover, the timing of the precipitation over the course of the year may change; California will likely receive less snow—making water storage more of a problem. In addition, changing climatic conditions will likely bring a significant worsening in the pest and disease environments beyond what would otherwise have happened. These changes will present significant challenges to agriculturalists.

There have been no experiences with climate change affecting agriculture in the past equivalent to what we expect to confront in the next 50 to 100 years. Nevertheless, history offers valuable insights into the ability of farmers (aided by scientists) to adjust to different climatic conditions and to pests and diseases.

A key lesson of general importance is California farmers are not alone in facing new and more variable conditions and shocks. Climate change will also affect the state's competitors in the United States and around the world. Some competitors may benefit, but many will suffer deteriorating conditions. Thus, the outcome in California will depend crucially on how climate change affects the *comparative advantage* of California farmers. This, in turn depends not just on the physical elements, but also on how the state's farmers adapt to the new challenges relative to how others adapt.

Farmers live and work in a complex physical, economic and political environment, and the quality of markets, transportation networks, legal institutions, research infrastructures and so on govern their ability to adapt. Successful adaptation on farms will depend on substantial advances in policy off the farm.

This principle of comparative advantage has often favored California farmers during past weather shocks and pest invasions. As examples, the spread of the boll weevil in the American South gave impetus for the spread of cotton production in California in the early 20th century. In addition, California citrus growers were major beneficiaries of the "Great Florida Freeze" of 1894/1895.

California farmers have repeatedly benefited from the state's relatively progressive research infrastructure to adapt successfully to environmental shocks. One of the most destructive threats, cottony cushion scale, was first observed in the Golden State in 1868 during the infancy of the citrus industry. By the 1880s, the damage was so extensive that the entire industry appeared doomed. Growers burned thousands of trees and helplessly watched their property values fall. Farmers tried all manner of remedies, including alkalis, oil soaps, arsenic-based chemicals and other substances, but the pest continued to multiply. Many experimented with fungicides. The preferred approach was to cover the trees with giant tarps or tents and pump in cyanide solutions, which was both costly and environmentally hazardous.

> *The record suggests that farmers and scientist have adjusted production in the past to meet enormous challenges; whether they can adapt to the new conditions remains to be seen, but the past record should give us hope.*

In 1888 the USDA entomologist, Albert Koebele, discovered that a ladybird beetle in Australia consumed the scale. Within a couple of years, another entomologist had conducted experiments in Southern California, distributing the beetles in large numbers to growers. A year after the general release, the voracious beetle had reduced cottony cushion scale to an insignificant troublemaker, thereby contributing to a three-fold increase in orange shipments from Los Angeles County in a single year. Figure 1 (on page 10) shows a patented fumigating tent made redundant by ladybird beetles.

There are many other examples of signature California industries being saved by research. One of the more significant was the early struggle with phylloxera, which threatened the grape (and wine) industry. The pest gained

Figure 1. The Culver Fumigator

The introduction of the ladybird (vedalia) beetle reduced the need to fumigate to kill cottony cushion scale.

Source: Olmstead and Rhode, Creating Abundance, 2008

notice in California in the mid-1870s. It was already inflicting great damage in Europe to the benefit of California growers. The infestation affected most California grape-growing regions by 1880. By this date, farmers in Sonoma County alone had already dug up over 400,000 vines. By 1890 the future of viticulture in California looked bleak.

Researchers experimented with hundreds of biological, chemical, and cultural cures (including applying toad venom) without success. Salvation only came after researchers (in Missouri, California, and France) hit on and perfected the idea of grafting European vines onto resistant native-American rootstocks. This research began in the 1860s, but adoption of this technique was slow because of the enormous investment required. By 1915 about 250,000 acres of vines had been destroyed in California, and little land had been replanted with resistant stock. The process of replacing vines continues today.

At the time when cottony cushion scale and phylloxera were on the march, the future probably looked as dire as it does today for many observers. Predicting the future and anticipating new technologies that may be over the horizon was as difficult in the past as it is today. In some cases, shocks just brought hardship—researchers were not always able to help ward off pests and diseases.

The inability to protect against Pierce's disease in the 1880s and 1890s offers a prominent example of a failure. This bacterial disease wiped out the thriving grape/wine industry first in the Anaheim area and then in most of Southern California. As a postscript, the disease now plagues the industry in Northern California and short of attacking the sharpshooter vector that carries the malady, there is still no effective control. One consequence of the 19th-century disaster in Southern California was a greater expansion of the citrus industry in the region—this was a major adjustment.

There are other cases—such as the collapse of the Golden State's bonanza wheat sector—where research did not ride to the rescue in time. By 1890 California ranked second in the nation as a wheat producer. As Figure 2 highlights, a rapid collapse occurred in the first decade of the 20th century. California's transition out of wheat is generally attributed to other higher value crops enticing farmers to change their cropping patterns.

However, there was another side to the story. California grain farmers had focused their innovative efforts on mechanization and evidently did little to introduce new wheat varieties, improve cultural practices, or even maintain the quality of their planting seed. Decades of mono-cropping mined the soil of nutrients and promoted the spread of weeds. By the 1890s, there were widespread complaints that the land no longer yielded a paying crop. In addition, the grain deteriorated in quality and value, becoming starchy and less glutinous.

The mono-cropping and soil-mining methods may have made economic sense given the high interest rates at the time, but this cannot explain the inattention to seeds by both farmers and researchers. Our study of the research conducted at the California State Experiment Station shows that there was little wheat-breeding work until after 1905, which was much later than what was the norm in other major wheat-producing states.

History offers many other examples of agricultural adaptation to challenges and shocks—some of the most sensational deal with the underlying forces allowing for the settlement of the North American continent. The story of settlement as usually told focuses on the perseverance of rugged pioneers, hacking out the wilderness to make farms, the railroad, the displacement of Native American populations, and the like.

But the spread of agriculture onto new lands in new regions was first and foremost a gigantic and difficult exercise in biological learning and adaptation. Without crops that could survive in the new environments, the history of the West would have been far different.

Focusing on wheat will illustrate the difficulties that farmers had to overcome and how this ties to possible adjustments to global warming. One widely reproduced map offers predictions of where wheat is apt to be produced in 2050—just 36 years from now. It shows the region suitable for wheat stretching into Alaska with a northern frontier several hundred miles north of the current frontier in Canada. The southern frontier of suitable land barely dips into the northern United States. By this account the great producing areas in Kansas, the Dakotas, the Palouse, Alberta, Saskatchewan, and Manitoba will be unsuitable for wheat.

A check of the actual research paper cited suggests that the popularized account exaggerates the shift and that many wheat growing areas in the United States and Canada will still be in production at mid-century. How do these predicted changes compare to past changes? The surprising answer is that even the most extreme predictions about the changing location of production probably do not surpass the changes that occurred in the past.

Wheat was brought to North America by early European settlers, but we pick up the story of its geographic evolution in 1839 when county-level data first became available. At that time, the geographic center of wheat production in North America (the United States and Canada) was in eastern Ohio, near what is now the West Virginia border. New York and Ohio accounted for the greatest concentration of wheat cultivation and little was produced west of Illinois. By 2007 the center of production had moved to west-central South Dakota, or about 1,100 miles.

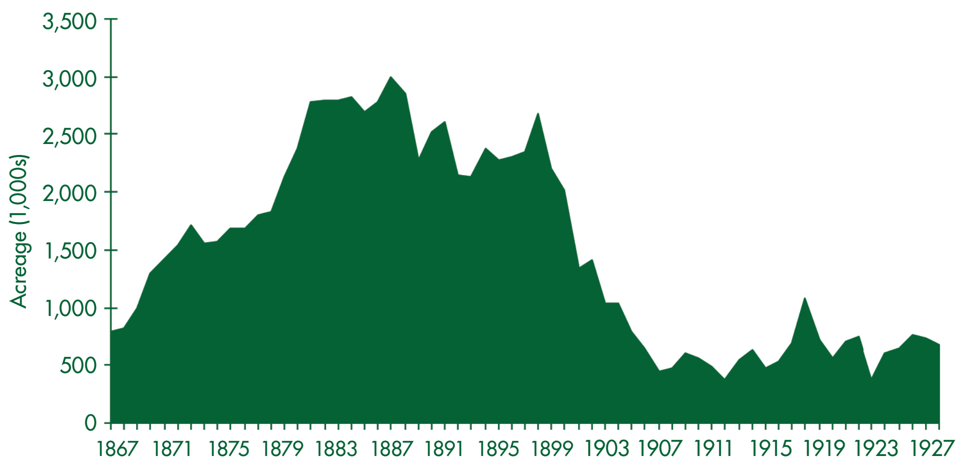
The movement of the fringes of production was also impressive. In 2007, 10% of the wheat grown in North America was grown west of 115 degrees longitude (roughly a north-south line running from Calgary, Alberta through Las Vegas, Nevada and into northern Mexico). Another 10% was grown north of 52 degrees latitude (an east-west line about 200 miles north of the U.S.-Canadian border west of Minnesota). Given the increase in total wheat output, 10% of production in 2007 represented more wheat than was grown in North America in 1839. In addition, by 2007 considerable wheat was also grown in northern Mexico. What is more remarkable, most of these changes in the location of production had occurred by 1910—well before the era of modern plant breeding guided by an understanding of advanced genetic engineering.

Granted, wheat production moved over vast distances but what does this have to do with global climate change? A lot! The many generations of farmers who moved wheat onto the moving frontier typically had little knowledge of the different climatic conditions that they would face. Farmers generally brought wheat seed with them from the already settled areas of the United States and Canada. These varieties typically failed in the harsher and more variable climates encountered in the West. Only after a long period of experimentation and adaptation—sometimes through careful observation, sometimes as a result of serendipity, and sometimes with the help of plant breeders—did farmers hit on new varieties suitable for the different conditions they faced.

The climatic differences were enormous and rivaled the changes predicted over the next century. In 1839 the average wheat grown in North America occurred in places that typically received 39.4 inches of precipitation, and places receiving less than 31 inches grew almost no wheat. In 1929 one-half of North American wheat was grown in places that received 20 inches or less of precipitation, and more wheat was grown at that later date in areas with 14 inches or less of precipitation than was grown in all of North American in 1839. If anyone had told farmers in Ohio in 1839 that people would be growing wheat with only 40% of the rainfall they were accustomed to, they would have thought the idea was daffy.

Wheat production also moved into much colder and hotter regions. In 1839 the median wheat produced in North America thrived in a zone where the average annual temperature was 52 degrees. In 1929 median wheat production occurred with an average of about 44 degrees. Given the concern with hotter temperature in the future, let's look at the differences in conditions confronted in moving

Figure 2. California Wheat Acreage, 1867–1929



Source: Paul W. Rhode, 1995

production from Columbus, Ohio to Ciudad Obregon in Senora, Mexico.

In 1839 wheat farmers around Columbus probably received over 38 inches of precipitation and experienced an average annual temperature of about 52 degrees Fahrenheit. The average conditions in the years 1981–1990 (before considerable global warming affected measurements) in Ciudad Obregon were 13.1 inches of precipitation and 74.5 degrees. These *differences* in conditions are much greater than the *changes* predicted by most models for the next century for wheat growing regions in North America. These findings do not mean that there will not be serious challenges in the future—there will be. The record does suggest that farmers and scientists have adjusted production in the past to meet enormous challenges; whether they can adapt to the new conditions remains to be seen, but the past record should give us hope.

The historical record offers several lessons. To adapt appropriately, farmers need the right incentives—this means that they must face prices that reflect the real cost of the resources they use and the products they produce. Subsidies of various forms might be politically convenient and ease some short-run burdens of adjustment, but they will also likely slow adjustments creating longer-run competitive disadvantages. Once in place, subsidies will be hard to terminate.

In the past, scientists played an important role in helping farmers adjust to challenges. Research contributed to increased productivity, but the movement into less hospitable environments, or the damage caused by pests and pathogens, offset some of the potential increases in efficiency. There is much research and adaptation that just allows farmers to maintain their productivity.

The expectation of more adverse conditions and unexpected negative shocks in the future because of global warming suggests that there might be an even greater need for "maintenance research." If so, society should allocate more (public and private) funding for scientific research than would otherwise have been the case. Given the long time lag between the commencement of research and the payoffs, it would be wise to invest more in research now instead of waiting for the crisis to hit.

Many issues such as pests and disease control, making more efficient use of water supplies, more public research, and the like will probably necessitate collective action, which will require more, not less, government involvement. As resources become scarcer—especially resources for which there are not good markets (water) or which have a large common-property element (clean air)—we can expect more distributional disputes and calls to change historic, but perhaps increasingly inefficient, legal systems. Farmers residing in states and nations that make adjustments to their institutions will fare better in a profoundly changed climatic environment.

Suggested Citation:

Olmstead, Alan L., and Paul W. Rhode, 2014. "Lessons from Past Agricultural Crises." *ARE Update* 18(1):9–12. University of California Giannini Foundation of Agricultural Economics.

Alan L. Olmstead is Distinguished Research Professor of Economics at UC Davis and a member of the Giannini Foundation of Agricultural Economics. He can be contacted by email at alolmstead@ucdavis.edu. Paul W. Rhode is professor of economics at the University of Michigan and a research associate of the National Bureau of Economic Research.

For additional information, the authors recommend:

Alston, J.M., J.M. Beddow, and P.G. Pardey, 2009. "Agricultural Research, Productivity, and Food Prices in the Long Run," *Science* 325: 1209–1210. This offers a sense of the need for more agricultural research and the time lags between starting new projects and the diffusion of useful results.

Olmstead, A.L. and P.W. Rhode, 2008. *Creating Abundance: Biological Innovation and American Agricultural Development*. New York: Cambridge University Press. Pages 223-261 deal with environmental adaptation and pest problems in California.

Olmstead, A.L. and P.W. Rhode, 2011. "Adapting North American Wheat Production to Climatic Challenges, 1839-2009," *Proceedings of the National Academy of Sciences*, 108(2): 480-85. This deals with the adaptation of wheat to varying conditions in North America.

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Water, Climate Change, and California Agriculture

Richard Howitt

Climate change may modify the current California water supply system. Analysis of a 2050 climate change scenario shows that despite reductions in irrigated area and net water use, California agriculture can continue to grow in revenue value and employment.

California agriculture is shaped by water supplies that depend on its current climate, but future projections based on global climate circulation models show an increase in average temperature. This change will have a significant impact on California's water resources and the industries that they depend on, none greater than irrigated agriculture that uses over 80% of the developed water in California. It is no exaggeration to say that California agriculture runs on water delivered in the right quantity, quality, and location.

The characteristics of a Mediterranean climate—cool, wet winters and warm, dry summers—and the geographic distribution of California's water supply require a water storage and distribution system that covers the entire state. The current storage and transport system, which delivers California's water from the relatively lush northern half of the state to the San Joaquin Valley and arid southern coastal regions, is essential to supplying water to the right place at the right time.

Increases in the ambient temperature of California will change water supply in three ways. First, water runoff in the wet areas will be reduced. Second, the amount of water stored in the snow and ice pack in the mountains will be significantly depleted. Third, the increased temperatures and CO_2 will result in an increase in the evapotranspiration rate of many crops.

Climate Change Impacts

Predicted changes in California precipitation from climate change are much less dramatic and also less certain than temperature changes. The best consensus is that the mean precipitation will not change greatly, but the distribution of precipitation will shift backwards in the year by at least one month and precipitation will probably be more volatile. This means that the spring runoff will come warmer and earlier, which in turn means that dams will have to allow a greater empty reserve for flood control to achieve the same degree of reduction in flood risk that currently exists.

In addition, the warmer air temperature will mean that there is less storage, and the snowpack will melt faster and earlier. Combining these factors results in a significant reduction in the inflows into the California water storage system.

The analytic results in this article are drawn from a multidisciplinary study by Medellin-Azuara et al., 2012. The study used 35-year projections of climate change results to 2050, based on a climate model from the Geophysical Fluid Dynamics Laboratory. Under a high-emissions scenario (GFDL A2), the model predicted an average 2°C temperature increase by 2050, and a 4.5°C increase by the end of the century. This climate scenario predicts a significantly higher rise in temperature than many other global climate models; accordingly, these results should be regarded as an upper bound on the impact of water resources.

The effect of earlier and reduced runoff can be partially mitigated by reoperation of the California storage and water transport system. Table 1 shows the percent reduction in water deliveries by sector and region. The effect on deliveries varies by sector and region, but combining climate change and water operation models, the estimate is that there will be a 21% reduction in water deliveries by the year 2050. It is important to note that these cuts are after reoperation and potential water market trades between regions and sectors have been optimized.

The climate change-induced increases in CO_2, temperature, and heat stress will have different effects on yields of California crops, depending on the type of crop and the region. Generally, crop yields are predicted to decrease, particularly those in

Table 1. Percent Reduction in California Water Supplies by 2050

	Percent Reduction		
Region	Agriculture	Urban	Total
Sacramento	24.3	0.1	19.1
San Joaquin	22.5	0.0	17.6
Tulare	15.9	0.0	13.5
Southern California	25.9	1.12	8.9
Total	21.0	0.7	14.0

Source: Medellin-Azuara et al., 2012

The three columns are percentages with respect to different quantities for each sector, they are completely different and should not sum up since agriculture and urban have very different supply quantities. They are designed to show the percent reduction by region, sector, and total—nothing else.

Table 2. Climate-Induced Yield Change (%) by 2050

Crop Groups	Sacramento	San Joaquin
Alfalfa	4.9	7.5
Citrus	1.77	-18.4
Corn	-2.7	-2.5
Cotton	0.0	-5.5
Field Crops	-1.9	-3.7
Grain	-4.8	-1.4
Orchard	-9.0	-9.0
Pasture	5.0	5.0
Grapes	-6.0	-6.0
Rice	0.8	-2.8
Tomatoes	2.4	1.1
Truck Crops	-11.0	-11.0

Source: Medellin-Azuara et al., 2012

Southern California. The exceptions are alfalfa, pasture, and tomatoes whose yields are predicted to increase. Table 2 shows the expected effect on crop yields due to climate-induced changes in the growing environment.

Modeling California Agriculture in 2050

Three different scenarios were used to estimate the effects of climate change: a base model for 2005, a model with historical climate in 2050 (no climate change), and a model with warm-dry climate change (GFDL A2) in 2050. The base model is calibrated to 2005 conditions and is used as a reference point and a basis for extrapolation to later years.

The historical 2050 model represents California agriculture in 2050 in the absence of climate change, but incorporates shifts in market demand for California crops due to changed population and incomes, and technical changes in crop production. The warm-dry model represents agriculture in 2050 with the effects of climate change. The model results measure changes that occur with or without climate change, and those that only occur under climate change.

California agriculture will be changed significantly by 2050, with or without climate change, due to several driving forces. First, reduced water availability due to increases in urban water demand and currently unsustainable levels of groundwater pumping. Second, the expansion of urban land use in agricultural regions will divert both land and water from agriculture. Third, the current rate of technical improvement in crops yields will very likely slow down, but will still be significant.

> *Water shortages are the key variable by which climate change will reduce the growth of California agriculture.*

Changes in urban land use, which affects the potential footprint for agriculture in the future, are derived from land use projections by Landis and Reilly for the year 2050. Technological improvements, as represented by yield increases, have been an important driving force for the recent trends in agricultural production. Based on Brunke et al., these effects incorporate yield changes as a result of technological improvement. Finally, tastes and preferences are held constant, but increasing population and income are translated into shifts in the demand for crops, which differ greatly between California specialty crops and "global" commodity crops.

In addition to the effect of changes in production technology, crop yields are expected to change in response to climate change. The estimates in Table 2 are based on a review of literature, and project expected changes in yield that are based on the climate-change scenario (see "Further Reading"). The second important modification caused by climate change is changing water supply and availability. The study by Medellin-Azuara et al. used the CALVIN water policy model to estimate changes in water deliveries for agriculture. These estimates are then incorporated into the agricultural economic SWAP model to estimate resulting changes in regional cropping areas, revenues, and returns to land and management. (Howitt et al., 2012).

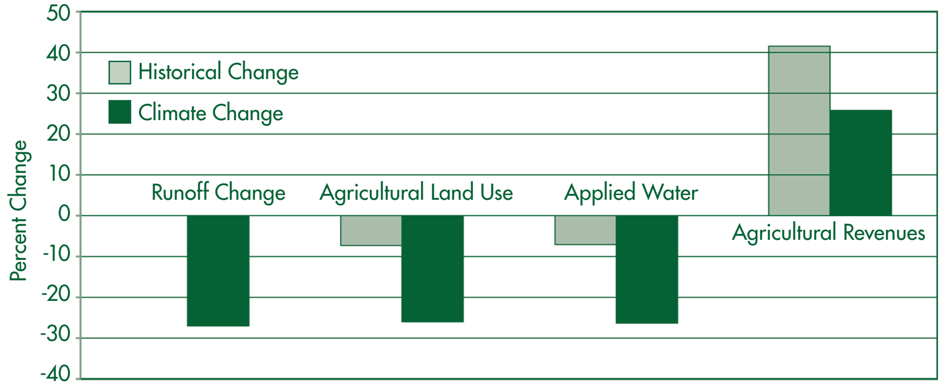
The SWAP model includes the shifts in the demand for crops projected to 2050, as discussed earlier. When combined with results from the biophysical models (which measure the effect of climate change on yields), the results show the importance of integrating and modeling the extent of adaptations of bio-economic systems to climate change. Since agricultural production systems are primarily driven by economic incentives, they can be expected to adjust and adapt by changing irrigation methods at the field level, though better systems or stress irrigation, and also by changing the crop mix on the farm to maximize returns from the available water. The results show such adaptations for irrigated agriculture in California.

Model Results

The model results show that irrigated land area in California will diminish, with or without climate change. The estimated reductions in irrigated agricultural area between 2005 and 2050 are 7.3% without climate change, and 26% under the climate-change scenario. Water runoff to agriculture is significantly reduced by 27%; however, after optimal reoperation of California's network dams and canals, coupled with a hypothetical open market for water between regions and sectors, the reduction in agricultural water deliveries is 7% without climate change, and 21% under the climate change scenario.

Despite this reduction in both land area and applied water, California's irrigated agricultural industry shows substantial growth in productivity and revenue, both with and without climate change. Without curtailments of the water supply and yield reductions, the model predicts that agricultural revenue

Figure 1. Percent Change in Agricultural Land Area, Water, and Revenue



Source: Medellin-Azuara et al., 2012

will grow in real terms by 40% by 2050. Climate change certainly reduces the rate of growth of the industry, but it will still grow in terms of revenue, profitability, and employment by 28% by 2050.

Figure 1 illustrates this sequential adjustment process of biotechnological and economic change within the industry. The systematic adjustments made throughout productive and economic parts of bio-economic systems show the ability of California agriculture to grow, despite a 27% reduction in water runoff. The growth in revenue is slower than the projections based on historical conditions but with climate change, the industry is still able to grow by 12% in real terms over the next 35 years.

Conclusions

The impacts of climate change on California water supplies and growing seasonal temperature mean that yields will be reduced in both perennial and annual crops—with the exception of fodder crops, which will show small increases in yields. Water shortages are the key variable by which climate change will reduce the growth of California agriculture. Adaptation to climate change by improved production technology and resource management can partially offset the economic impacts of resource reductions. The models that underlie this study show that the industry will continue to grow in both revenue and employment, despite significant reductions in land area and water use. This result is predicated on the assumptions that the demand for California specialty fruit and vegetable crops will continue to grow in a similar manner as it has in the past.

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Richard Howitt is professor emeritus of agricultural and resource economics at UC Davis. He can be contacted by email at howitt@primal.ucdavis.edu.

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An Overview of California's Agricultural Adaptation to Climate Change

David Zilberman and Scott Kaplan

While the overall impact of climate change will be moderate, the impacts will vary by regions—with big losers and gainers. Overcoming painful costs requires the development of adaptive capacity that can take advantage of advanced tools of science, including biotechnology, markets, and construction of dams and reservoirs. In California, climate change will increase the risk of flooding, disrupt water supply, and reduce productivity—especially in the Delta, coastal counties, and inland, southern regions.

The concentration of CO_2 in the atmosphere is on the rise, and there is concrete evidence that it can be attributed to human activities. Higher CO_2 levels are contributing to climatic changes that are likely to be enhanced in the future. Agriculture is dependent on the climate; thus, it is important to understand how climate change will affect agriculture, how agriculture will adapt to climatic changes, and what the impact will be on California—all of which will be addressed here. Our analysis is based on a growing literature of conceptual and empirical research on this topic, undertaken by both economists and scientists.

Implications of Climate Change for Agriculture

The impact of climate change will have several manifestations. It is quite common to refer to climate change as global warming because, on average, temperatures are rising. However, climate change will cause precipitation patterns to change, and weather conditions are likely to be much less stable with a higher likelihood of extreme natural disasters like hurricanes and monsoons. Moreover, climate change may result in rising sea levels, leading to a loss of agricultural land as well as seawater intrusion into coastal aquifers.

Since agricultural production depends on a combination of temperature, soil conditions, and precipitation, changes in climatic conditions may affect the relative productivity of crops across locations. With temperature increases, climate "migrates" from the equator towards the poles. For example, it is expected that a 1 degree Celsius warming (about 2 degrees Fahrenheit) will shift the climate zone 200-300 km towards the poles.

In addition to changes in temperature, there will be accompanying changes in rainfall and increased snowmelt. Thus, some areas close to the equator will become quite warm and will face agricultural productivity losses. On the other hand, some areas closer to the North and South poles will become warmer and witness agricultural productivity gains.

In addition to temperature and rainfall changes, the buildup of carbon in the atmosphere will affect agriculture through other means. This "fertilization effect" will lead to increased yields, since higher carbon levels enhance photosynthesis of plants. Another effect of global warming is the "daylight effect," resulting from the movement of agriculture away from the equator and a resulting reduction in exposure to the sun—thus, reducing yields. A third effect is the "pest effect," where changes in climate will lead to pest migration, primarily towards warmer regions away from the equator. Since pests are mobile and trees are not, this effect may result in significant increases in pest damage and yield losses.

In the case of California, significant warming (3 degrees Celsius) will shift the temperature of Los Angeles towards the Bay Area and the temperature of Fresno to Napa Valley. Nationally, the climate in Oklahoma is likely to shift north to Nebraska while the climate of Nebraska will migrate to North Dakota and parts of Southern Canada.

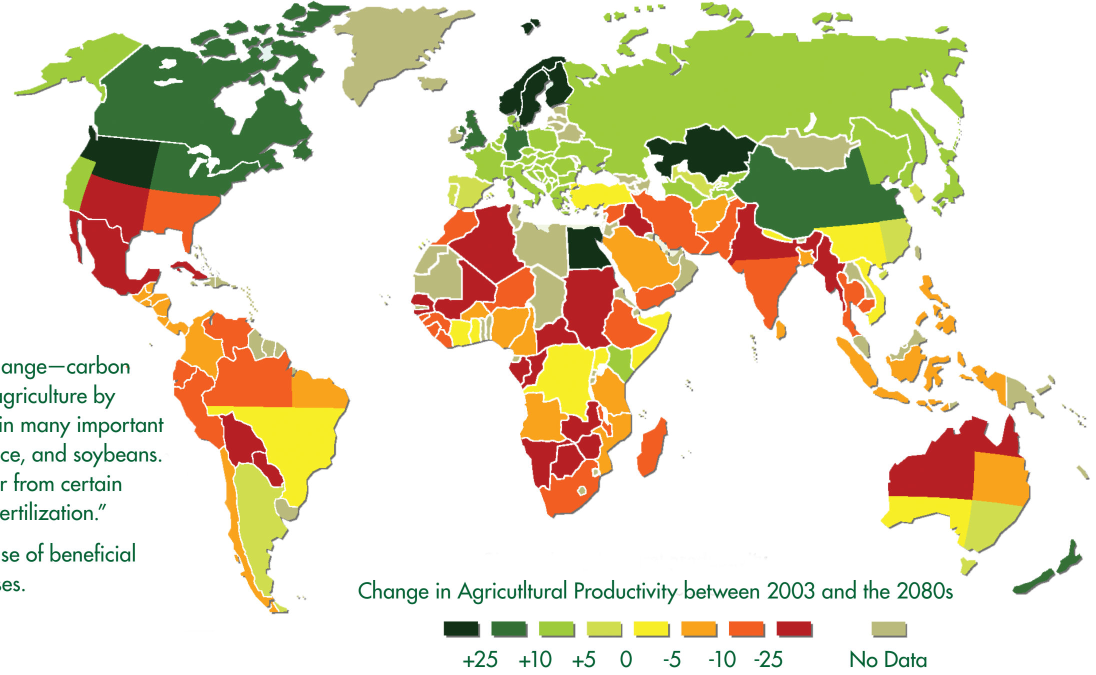
Figure 1 presents a map that illustrates how some regions across the world will fare under these changes. As one can see, the southern part of the United States will tend to lose while the northern parts of the United States, as well as Canada, will gain. Likewise, most of Africa and Latin America will lose; Russia, most of Europe, and Northern China will gain; and India and most of Australia will lose.

Farmers are not likely to take changes in climate lying down; they will change aspects of crop production they can control. There will likely be more corn production in North Dakota and Canada, and crops like sugarcane will grow in areas of Argentina. The capacity to adapt to climate change will determine its impacts to a large extent.

There is significant literature assessing the impact of climate change on agriculture. Under reasonable scenarios where the temperature does not rise above 3 degrees Celsius, most studies predict that aggregate impacts on agriculture after a period of adjustment are likely to be moderate. These predictions range from minimal impact to a 15% reduction in productivity.

However, the main concern is not over the aggregate climate effects, but about their distributional effects and the process of adjustment. Climate change may cause hundreds of millions

Figure 1. Projected Impact of Climate Change on Agricultural Yields



"A key culprit in climate change—carbon emissions—can also help agriculture by enhancing photosynthesis in many important (...) crops such as wheat, rice, and soybeans. The science, however, is far from certain on the benefits of carbon fertilization."

This map represents the case of beneficial carbon fertilzation processes.

Source: Cline, William R., 2007. "Global Warming and Agriculture: Impact Estimates by Country." Peterson Institute Press: All Books.

in Mexico, Africa, and India to lose their livelihoods. They are unlikely to be able to take advantage of new production opportunities available in Russia, Canada, and Europe. Thus, climate change may cause substantial pressure for population migration, which may be a main trigger for major international instability.

History suggests that periods of climate change resulted in politically destabilizing population movements. For example, during a mini-ice age period, Rome was destroyed when tribes from Northern Europe migrated south to warmer regions. Likewise, the incursion of Islam into the Indian sub-peninsula was associated with periods of inhospitable climate in the Middle East.

Secondly, climate change is evolving in an unpredictable and uncertain manner. Decision makers tend to be risk averse, and as such, their level of activity tends to decline as uncertainty increases. Thus, the uncertainty surrounding climate change may lead to underinvestment in adaptation and protection mechanisms for some aspects of climate change.

Finally, the delay in adaptation to climate change may cause a short-term crisis. Periods of rapid changes in climate may result in significant reductions in productivity in regions close to the equator, without a compensating increase in productivity in regions closer to the poles—as investment in agricultural development in these regions may not have occurred or "borne fruit."

During periods of rapid climate change, aggregate supply of food will decline, food prices will increase, and the food situation will worsen. While it is likely that aggregate adjustment to climate change will occur in the long run, short-term adaptation is of critical importance and development of capacity for such adaptation is a major priority.

On the Development of Adaptive Capacity

The risks and the costs of climate change can be reduced through adaptation activities. One key element of adaptation is mitigation—activities that will reduce the likelihood and severity of climate change. These activities include reduction in carbon emissions, carbon sequestration, and geo-engineering.

However, in this article we address adaptation in the narrower sense, which includes several sub-categories of activities:

(i) ***innovation and adoption of new technologies:*** new varieties that allow crops to withstand changes in weather, as well as resist increased pest infestation due to climate change,

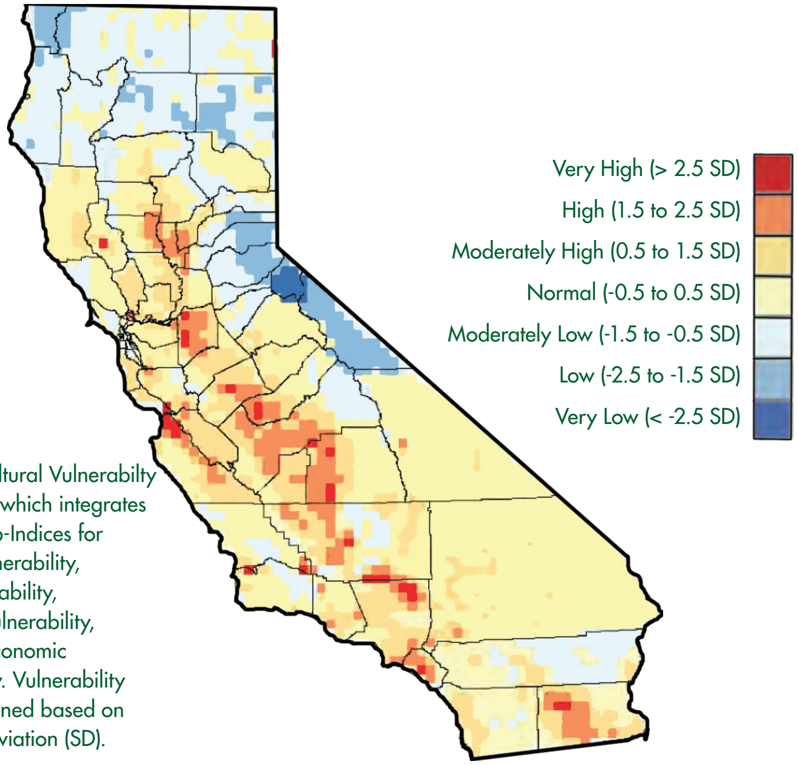
(ii) ***adoption and adaptation of existing technologies from different regions:*** as climate migrates, technologies migrate with it,

(iii) ***changes in land use of agricultural activities***: for example, switching from wheat to corn in northern regions,

(iv) ***migration:*** both away from regions that suffer from climate change and to regions that benefit from it, and

(v) ***investment in protective infrastructure:*** such as walls and dams to protect against rising sea levels and unstable weather.

Figure 2. Total Agricultural Vulnerability Index



Total Agricultural Vulnerabilty Index (AVI), which integrates the Four Sub-Indices for Climate Vulnerability, Crop Vulnerability, Land Use Vulnerability, and Socioeconomic Vulnerability. Vulnerability level is assigned based on standard deviation (SD).

Source: A white paper from the California Energy Commission's California Climate Center. University of California, Davis California Energy Commission, 2012.

A key to effective adaptation is investment in basic and applied research to develop new technologies that will help society cope with a new climate reality, and removal of unnecessary barriers for their commercialization and diffusion. One of the major challenges is to overcome attitudes that oppose the adoption of innovations to adapt to climate change. Some of the environmental groups that are very concerned about climate change are the people most vehemently opposed to the use of genetic modification in agriculture.

Genetic modification takes advantage of new knowledge in molecular and cell biology to develop crop varieties and other species that can accelerate the speed and reduce the cost of adaptation to climate change. Environmental groups tend to emphasize conservation and defense of current environmental conditions, and therefore promote mitigation over adaptation. The reality is that we need both as climate change progresses, and they may be complementary. Genetic modification has already increased the productivity of agriculture, thus reducing the environmental footprint associated with it, and it also enhances carbon sequestration by enabling the adoption of technologies like no-tillage. Combatting climate change requires an open mind about technologies and the utilization of innovations in an economically efficient and environmentally sustainable manner.

Implications for California Agriculture

California has the nation's most productive agriculture, producing more than 400 different commodities, and is a major producer of many high-value fruits and vegetables. The lion's share of the value of California agriculture comes from the approximately eight million acres of irrigated cropland. Climate change is likely to affect California agriculture through its impact on water resources, as well as agroclimatic conditions in different regions.

The snowpack in the Sierras has served as a natural regulator and water storage mechanism, and will face up to 80% depletion by 2100. Even if precipitation is slightly reduced, the acceleration in snowmelt will increase the risk of flooding and result in a loss of dry-season water availability. Dams in California have played an important role in adaptation to fluctuating weather and rainfall conditions, but they are costly both in monetary and environmental terms.

Furthermore, increased weather instability associated with climate change will require expansion of conveyance facilities and the introduction of trading mechanisms that allow effective allocation of water during shortages. The reduction in water supply and the increased demand for water, as a result of further warming, will increase the value of investment in new facilities. It will also lead to the design of institutions promoting increased use of recycled wastewater for agricultural and urban uses.

One of the major consequences of climate change is rising water levels. Under plausible scenarios, seawater is expected to rise 1.4 meters by 2100. These rising water levels are likely to be accompanied by a much higher likelihood and severity of seawater intrusion, which may lead to losses of coastal aquifers. Altogether, these rising sea-levels will significantly reduce the productivity of much of the coastal regions of California, including the Monterey Peninsula and Santa Maria region.

Rising water levels are likely to lead to a massive intrusion of salinity into the San Francisco and Sacramento Delta and threaten agricultural production in the already vulnerable delta islands. Thus, seawater intrusion may lead to reductions in the production of high-value crops in some coastal areas and the delta islands.

Production practices and irrigation regimes in other parts of these regions must be modified to address changes in water quality and availability.

California agriculture's capacity to flourish and withstand severe droughts in the recent past can be attributed to the extensive system of dams, reservoirs and canals, varied utilization of groundwater, continuous improvement in irrigation systems, and gradual expansion of the capacity to trade water. But much of California's water infrastructure is aging, and the risks of climate change challenge the existing system. It took close to 50 years from the initiation of the State Water Project to actually complete it.

Adaptation to climate change will require quicker redesign of facilities and institutions, balancing the net social benefits from economic activities and environmental conservation. Adaptation may lead to construction of new dams, reservoirs and canals, as well as more intensive use of water pricing and trading mechanisms.

Studies on the impact of climate change on California agriculture assess impacts on crop yields resulting primarily from temperature increases and changes in precipitation. The impact estimates are subject to a high degree of uncertainty, yet they suggest that with a 2 degree Celsius increase in temperature, reduction in the yields of fruits like walnuts, avocados, and table grapes will be greater than 5% in all of the current growing regions in California, and in many areas it will be much larger.

A 4 degree Celsius increase in temperature will reduce yields by more than 5% for most other fruit crops; in some important regions, the yield losses may reach up to 40%. While the yield effect on wine grapes may not be very high, the high quality in premier regions may suffer because of temperature increases.

Figure 2 presents the results of a recent study undertaken by the University of California, Davis that identifies some of the most vulnerable agricultural regions to climate change from multiple perspectives. The Salinas Valley (the "salad bowl" of the United States), as well as the San Joaquin Valley, were identified by the California Energy Commission as two of the most vulnerable agricultural regions to climate change effects—including seawater intrusion and temperature increases. Agriculture in the Imperial Valley and the corridor between Fresno and Merced are identified by this study as very vulnerable to climate change. Yet at the same time, the potential for rice production is increasing, and new opportunities may open up for some of the northern regions of the state, which may provide hospitable environments for fruits (wine grapes) and vegetables.

The estimates of climate change impacts are uncertain but two elements are clear. First, the aggregate impact of climate change will depend on our capacity to adapt existing crops to rising temperatures and new pest pressures. Second, climate change will require identification of new opportunities and investment in building new infrastructure for agricultural production and processing in newly suitable areas.

Conclusion

The impacts of climate change are uncertain, and research to better understand the process and potential for adaptive capacity are major priorities. Research suggests that in general, climate change is likely to lead to modest reductions in overall agricultural productivity in the long run and its impacts will vary across regions, with major losers and gainers.

In the case of California, climate change may reduce water supply and increase the risk of floods. Agricultural production in California's coastal region, the San Francisco-Sacramento Delta, and the southern region of the state are also likely to experience substantial losses.

The adjustment to such a change may be painful; it will require costly relocations of businesses and farms as well as development of new technologies and infrastructure. The capacity to adapt to climate change can be enhanced if it takes advantage of a full arsenal of science- and technology-based tools, including advanced tools of biotechnology, markets, and construction of dams and reservoirs.

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David Zilberman is a professor and the Robinson Chair in the Department of Agricultural and Resource Economics at UC Berkeley. He is a member of the Giannini Foundation of Agricultural Economics and can be reached by email at zilber11@berkeley.edu. Scott Kaplan is a research assistant in the ARE department at UC Berkeley.

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Julie McNamara, Outreach Coordinator
Giannini Foundation of Agricultural Economics
Department of Agricultural and Resource Economics
University of California
One Shields Avenue, Davis, CA 95616
E-mail: julie@primal.ucdavis.edu
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