APRIL–JUNE 2009 • VOLUME 63 NUMBER 2

California Agriculture

"Unequivocal"

How climate change will transform California

University of California | Peer-reviewed Research and News in Agricultural, Natural and Human Resources

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Cover: In its 2007 report, the Intergovernmental Panel on Climate Change concluded that climate change is “unequivocal.” Wildfires are expected to become more commonplace in California, consistent with the predictions of climate-change models. Twelve large wildfires — fueled by powerful Santa Ana winds that pushed flames through brush and grass dried from drought — raged in California on Oct. 23, 2007, clouding the air over the Pacific Ocean with dense plumes of smoke. *Photo: NASA image by Jeff Schmaltz, MODIS Rapid Response Team, Goddard Space Flight Center*

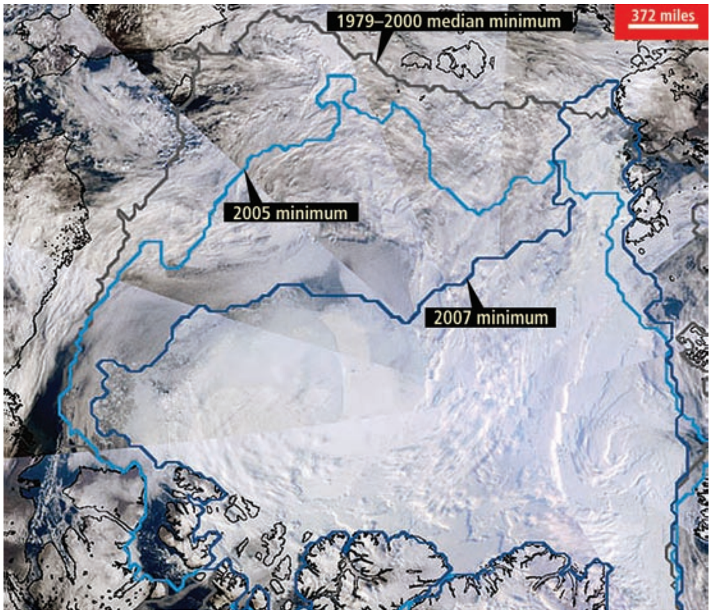
California Agriculture journal gratefully acknowledges UC Davis meteorologist Bryan Weare, faculty chair for this special issue. We also thank UC Davis plant physiologist David. R. Smart for his assistance and several *California Agriculture* associate editors for their contributions to these articles.

Climate change affects us all

Earth's temperature has risen 1°F in the last 100 years — a small number with a profound impact. California's warmer winters and springs have led to reduced snowpack, increasing the seasonality of water flows and directly affecting our ability to grow plants, produce food and support growing populations. Wildfires are increasing; crop pests are expanding their ranges. "Natural disasters" — such as droughts, Santa Ana winds, tornados, higher intensity rainfall events and fire — are more frequent and severe. Such changes are consistent with trends worldwide.

But climate change up to now is small compared to what is in store. We now know that once carbon dioxide is in the atmosphere, it is there for a long time, perhaps 1,000 years. Even if we reduce our current heat-trapping emissions, the amount of greenhouse gases will continue to accumulate for some time. According to low, medium and high emissions scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), our planet will heat up another 1°F to 2.3°F by 2034 — an accelerating change that will take place over the course of just 25 years, rather than 100.

After mid-century, the three scenarios diverge widely in their predictions (see figure, page 53). Depending on future heat-trapping emissions, there are huge differences in the predicted average heating, ranging from 3°F to 10.4°F by the end of this century — and leading to potentially catastrophic effects such as a sea-level rise of 6 to 30 inches.



On Sept. 15-16, 2007, NASA's Terra satellite observed sea ice and open ocean throughout the Arctic. Shown are the sea-ice minima of 2007, the previous record low in 2005, and the long-term average from 1979 to 2000. The 2007 minimum fell substantially below previous records. *Source: Image by Terry Haran, National Snow and Ice Data Center, Univ. of Colo., Boulder.*

The degree of heating and resulting climate impact depends largely on what we do now. It matters that we reduce our carbon footprint, use fewer fossil fuels and fertilizers, and learn how to change, manage and mitigate.

Barbara Allen-Diaz
Assistant Vice President,
UC Agriculture and
Natural Resources

Landmark initiatives have already begun in California. The state made history with passage of the Global Warming Solutions Act of 2006 (AB32), promising to reduce global warming pollution to 1990 levels by 2020. In partnership with the state, UC scientists have been leaders in climate-change research for a decade. UC Agriculture and Natural Resources (ANR) scientists are advancing our knowledge of global warming impacts on food production and natural resources. For example:

- They have found that the use of cover crops leads to increased carbon storage, by as much as 4,000 to 4,500 pounds per acre over standard farming practices.
- Others are examining how changing climates will modify wildfire activity, which could profoundly affect carbon sequestration as well as forest conservation.
- Researchers have developed technology that increases drought tolerance in plants, potentially helping farmers around the world to maintain crop productivity.

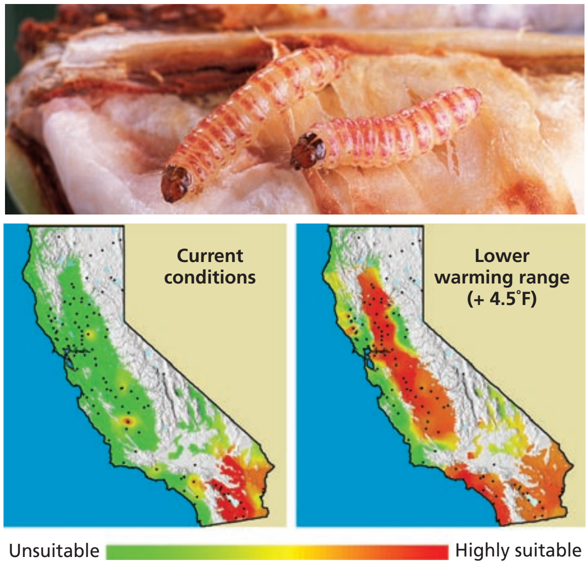
California's $37 billion agricultural industry will be severely affected by the coming changes. Recent and predicted increases in temperature will have major impacts on where plants can be grown. Changing temperatures will also likely shift the range of native plants, and even cause some to disappear altogether (see page 57).

In this special issue of *California Agriculture*, UC scientists advance our understanding of how climate change will affect California (see page 59). New research reported suggests a mechanism to explain why initial increases in crop production due to "CO_2 fertilization" decline rapidly, a finding with important implications for hunger and nutrition worldwide (see page 67). Additional findings have shown that crops will suffer greater pest losses (see page 73). The numbers and

Editor's note: Barbara Allen-Diaz was among 2,000 scientists recognized for their work on the Intergovernmental Panel on Climate Change (IPCC), when the Nobel Peace Prize was awarded jointly to the IPCC and Vice President Al Gore in 2007. Allen-Diaz's contributions focused on the effects of climate change on rangeland species and landscapes.

Peter Starman/Getty Images

Wildfires have become more frequent and widespread in California in recent decades. In July 2002, an 8,600-acre blaze burned near Topaz Lake in Mono County, near the Nevada border in the eastern Sierra Nevada.



USDA

Projected range expansion of the pink bollworm (top) in California. At present, the pink bollworm's range (above left) is limited by winter frosts that kill dormant larvae. Rising winter temperatures would allow this major cotton pest to expand northward.

kinds of invasive pests and diseases are increasing because of rising temperatures overall, and because pests consume more of the plant due to higher carbon and lower nitrogen content. In addition, the lack of winter chill periods will allow pests to breed throughout the year.

Scientists also describe mitigation options to reduce agriculture's impact on the climate system. For instance, California dairies, the valued producers of 21% of the nation's milk, can help decrease greenhouse-gas emissions and reduce their contributions to global warming (see page 79). UC investigations have shown that management practices can have a significant impact on the amounts of greenhouse gases emitted from cropped fields (see page 84). UC economists have identified sustainable fertilization practices and proposed incentives for farmers to incorporate them into their everyday practices (see page 91). In a review of carbon trading, scientists discuss evolving markets as tools to reduce greenhouse-gas emissions (see page 96).

Climate change will challenge California's natural ecosystems. For example, no Joshua trees will be able to grow in Joshua Tree National Monument in the Mojave Desert. Douglas and white fir forests will likely become dominated by oaks and madrone. These changes also will affect wildlife populations that depend on these ecosystems.

Such profound challenges require not only research — to develop new pest and disease strategies, new cropping systems and better understanding of the changes in timing of flowering and seed production — but also new commitments to education and public outreach. We must foster greater science literacy, enabling people to make informed choices, develop new options and take action at all levels. UC, and specifically ANR, have vital roles in this effort. No single research track or set of actions will be enough to curb the ongoing and complex changes to our climate system. Solutions will require partnerships and will involve tradeoffs — ecological, economic and social.

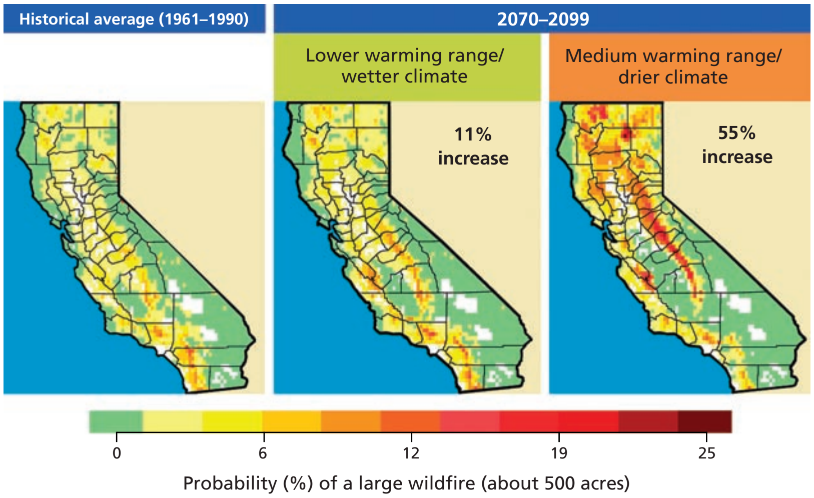
ANR, with its network of campus-based scientists, Cooperative Extension (CE) specialists and county-based CE advisors, is uniquely situated to identify, examine and deliver solutions. Our system includes a network of 10 Research and Extension Centers located throughout California's various crop production and climatic zones, from the high desert on California's northern border to the highly productive Imperial Valley desert on our Mexican border. These centers retain decades of records on climate, water, crop productivity and biodiversity, among other long-term data sets. All are now invaluable sources of information to project the local effects of changing climate, and to experimentally test new crop options, plant and animal production methods, ways to conserve biodiversity, and options to remain sustainable and viable in a global economy.

In a multipartner project, for example, the UC Berkeley Institute of the Environment has launched the Sustainable Neighborhood project. Funded by the Gordon and Betty Moore Foundation, the project is working in China to design, build and monitor a replicable, transit-oriented sustainable neighborhood that generates all of its energy from on-site renewables (such as wind, solar and biomass); processes all of its sewage, food and green wastes; and recycles all its water. If successful, this innovative project will lead to the first carbon-neutral community of its kind that can be replicated on a massive scale.

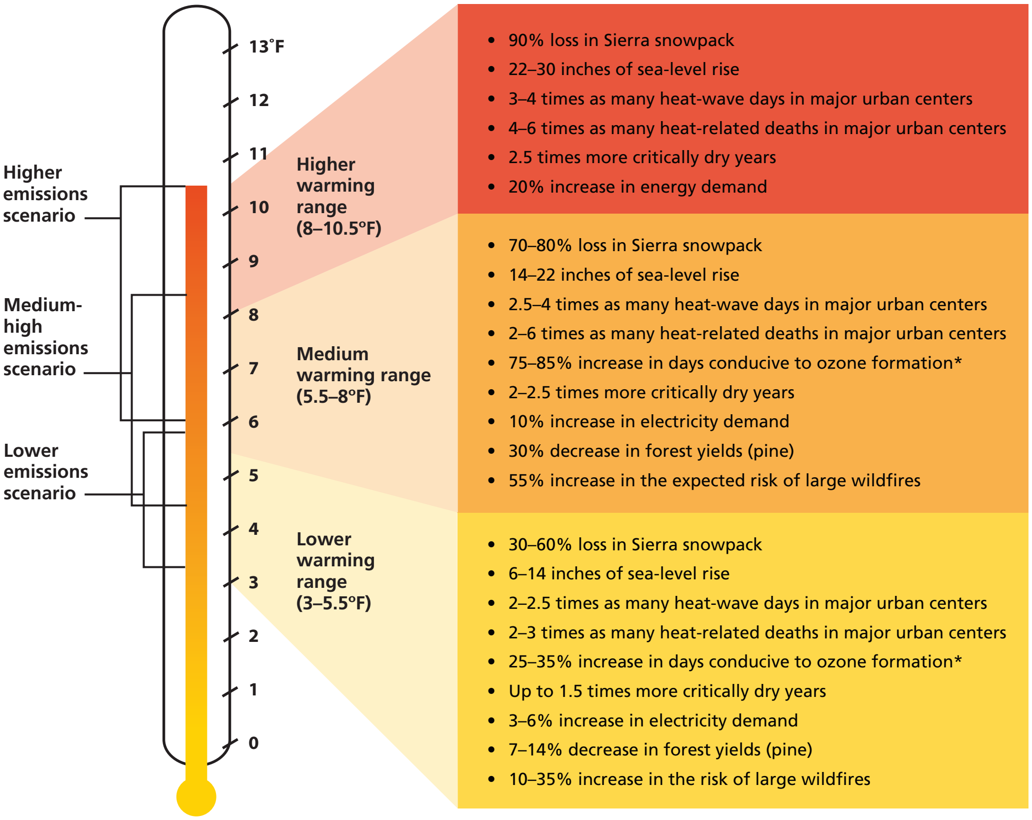
Closer to home, Sonoma County has joined America's Fund for Integrated Solutions, a national network of local governments, universities and private partners. In partnership with UC, local businesses and others, the county is integrating more-efficient energy use with retrofits of existing buildings, and seeking incentives for developing new sources of renewable energy from solar, wind and wave power — all coupled with attention to human needs and behaviors.

It will take both individual actions, and partnerships at all scales, to change behaviors, industries and the way we think about our place in the world. Perhaps the biggest challenge is making the paradigm shift from a fossil fuel–based economy to one driven by renewable sources of energy.

There is no time like the present for addressing climate change. The critical players are all at the table: politicians, scientists, technologists, city-county and regional planners, business people, nonprofits and government. We have an administration in Washington, D.C., that has signaled its readiness to make policy and behavior changes to decrease U.S. greenhouse-gas emissions, reduce our dependence on fossil fuels and build green industries with green jobs to help ensure a thriving future. Our planet, and our future, depend on it.



Predicted increase in the frequency of wildfires in California. If temperatures rise into the medium warming range, the risk of large wildfires could increase by as much as 55% over the reference period (1961–1990).



- 90% loss in Sierra snowpack
- 22–30 inches of sea-level rise
- 3–4 times as many heat-wave days in major urban centers
- 4–6 times as many heat-related deaths in major urban centers
- 2.5 times more critically dry years
- 20% increase in energy demand

- 70–80% loss in Sierra snowpack
- 14–22 inches of sea-level rise
- 2.5–4 times as many heat-wave days in major urban centers
- 2–6 times as many heat-related deaths in major urban centers
- 75–85% increase in days conducive to ozone formation*
- 2–2.5 times more critically dry years
- 10% increase in electricity demand
- 30% decrease in forest yields (pine)
- 55% increase in the expected risk of large wildfires

- 30–60% loss in Sierra snowpack
- 6–14 inches of sea-level rise
- 2–2.5 times as many heat-wave days in major urban centers
- 2–3 times as many heat-related deaths in major urban centers
- 25–35% increase in days conducive to ozone formation*
- Up to 1.5 times more critically dry years
- 3–6% increase in electricity demand
- 7–14% decrease in forest yields (pine)
- 10–35% increase in the risk of large wildfires

* For high ozone locations in Riverside and Visalia

◀ Projected global warming impacts in California, 2070–2099 (as compared with 1961–1990). Warming ranges represent averages predicted from three global climate models (representing different climate sensitivities) and three IPCC global emissions scenarios (see page 61).

Source of figures, pages 52 and 53: Our Changing Climate. California Energy Commission's Public Interest Energy Research (PIER) Program, July 2006. The CEC's second biennial climate-change science report will be posted in early April at: http://www.climatechange.ca.gov/

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Mission and audience. *California Agriculture*'s mission is to publish scientifically sound research in a form that is accessible to a well-educated audience. In the last readership survey, 33% worked in agriculture, 31% were faculty members at universities or research scientists, and 19% worked in government agencies or were elected office holders.

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UC researchers are estimating the "farm to fork" energy usage for rice — including cooking — as part of the Agricultural Sustainability Institute's low-carbon diet project.

"Low-carbon diet" research looks at total energy usage of foods

Is an organic tomato grown in Mexico better for the environment than a conventional one grown 150 miles away from your Bay Area home? Is it more sustainable to drive to a big-box store and buy lots of groceries to keep in the freezer, or to purchase ready-made meals or cook individual ingredients at home? These types of questions are at the heart of a UC Agricultural Sustainability Institute (ASI) project that is examining the food system's role in climate change.

"Changes in consumer food choices, as well as in our vast food-production system, could contribute substantially to meeting goals for reducing greenhouse gases," ASI director Thomas Tomich says. "Individual foods vary tremendously in their carbon footprints."

The low-carbon diet project uses life-cycle assessment methodology to tally the energy used to produce particular foods, then does computer modeling to estimate greenhouse-gas emissions. Researchers identify and collect data on farming practices, pest control, irrigation, harvesting, processing, transportation, refrigeration, storage and even cooking. "We're looking for all the inputs, from farm to fork," says Gail Feenstra, ASI food systems analyst.

The project has collected data on processing tomatoes, dairy and rice, and Sonja Brodt and Alissa Kendall of UC Davis are currently crunching numbers to find the "break-even" point for the energy usage of rice. A new effort in conjunction with Cornell University, funded by the Kellogg Foundation, will examine the carbon footprints of local foods in California and elsewhere in the United States. ASI is also launching the California Nitrogen Assessment, funded by the Packard Foundation, to further quantify the scope of the state's greenhouse-gas emissions.

An estimated 15% of U.S. energy usage and greenhouse-gas emissions is related to the food system. The major contributors are livestock-related methane and nitrous oxide emissions (see page 79); synthetic nitrogen fertilizers (see pages 84, 91); air freight; heated greenhouse production; post-retail consumer transport and food storage; and food waste at multiple points along the supply system.

"We are developing information so that major food suppliers, food service professionals and retailers, as well as consumers, can figure out where to focus to make the biggest impact on climate change," Feenstra says. — *Janet Byron*

For more information

UC Agricultural Sustainability Institute
http://asi.ucdavis.edu/research/energy_food_system.htm

Climate-change modeling finds many crop yields are likely to decline

Climate change would likely cause the yields of several major California crops to decline significantly by 2050, while others would not change. Scientists at Lawrence Livermore National Laboratory (LLNL), UC Merced and others recently modeled the effect of climate change for six of California's most valuable perennial crops: wine grapes, almonds, table grapes, oranges, walnuts and avocados (*Agricultural and Forest Meteorology* 141 [2–4]: 208–18).

"In California, 20 to 30 years is the productive lifespan for most of these plants," says David Lobell, who was agricultural ecologist at LLNL when he led the study. "If we can get a picture of how the climate will change during this interval, we can evaluate what that means in terms of projected crop yields." In addition, keeping the time frame relatively short limits modeling uncertainty.

The projections showed variable results. Winegrape yields, for instance, would change little over the next century, but the other crops exhibited moderate-to-substantial declines. The amount of uncertainty was considerable, but the overall trend was toward decreased yields.

"More than 95% of the simulations for almonds, table grapes, walnuts and avocados showed a negative response to warming by midcentury," Lobell says. "The current climate is either at or above the optimum temperatures for the crops we studied, and all climate models project at least some warming during this period."

Lobell is now senior research scholar at Stanford University. He and his colleagues have recently expanded their study to more crops in California; it will be released in coming months on the California Energy Commission Climate Action Team Web site. — *Editors and Ann Parker*

UC scientists help California prepare for climate change

For all the alarming signs of climate change — from earlier springs to melting polar ice — the overwhelming scientific consensus is that we haven't seen anything yet. Climate change is likely to accelerate greatly over the next century, with temperatures expected to climb faster than they have in the last 10,000 years.

California farmers face an uncertain future, where current crops may fail and water may be even more scarce. To help them adapt, UC researchers are finding ways to cut emissions of the greenhouse gases behind climate change, and to lessen their impacts on agriculture and wildlands (see box).

"There are no easy solutions," says UC Davis ecologist Louise Jackson. "Everything will be complicated by tradeoffs."

Globally, the average temperature is expected to rise another 2°F to 10°F on top of the 1°F increase since 1900, according to the Intergovernmental Panel on Climate Change (IPCC) (see page 59). While the world and the United States as a whole have gotten wetter, the Western states are likely to become drier. In addition to these broad changes, heat waves and rainstorms are likely to intensify.

Efforts to control climate change have focused on developed countries, which have contributed most of the carbon dioxide, methane, nitrous oxide and other greenhouse gases since the Industrial Revolution. But that is now shifting. China just became the world's largest greenhouse-gas contributor and is likely to increase its carbon emissions at least 11% from 2004 to 2010, which is twice as fast as previously predicted, according to a recent study by UC Berkeley environmental economist Maxmillian Auffhammer and UC San Diego economist Richard Carson.

This underscores the fact that climate change cannot be tackled unilaterally, despite California's AB32 mandate to bring carbon emissions back to 1990 levels by 2020. In addition, because it takes so long for plankton in the oceans to clear carbon dioxide from the atmosphere, temperatures will still be higher mid-century even if we cut emissions today. Rather, the greatest impacts will be in the second half of the century, when temperatures are projected to increase most rapidly.

As a relatively small greenhouse-gas contributor at 7% of the state's total emissions, agriculture is unlikely to be heavily regulated. In fact, farmers could benefit from regulation by selling credits for reduced emissions on the carbon market (see page 96). Moreover, many ways of controlling agricultural emissions — such as drip irrigation, conservation tillage and dairy methane digesters — will have the added benefit of making farming more sustainable (see pages 79, 84, 91).


Jim Nickles/USGS

In the Sacramento-San Joaquin River Delta, researchers are studying the potential of "carbon-capture" farming to trap atmospheric carbon dioxide and rebuild soils lost to subsidence. A pilot study on Twitchell Island (shown) raised soils 10 inches between 1997 and 2005, as cattails, tules and other plants grew, died and decomposed. The 3-year, $12.3 million project joins scientists from UC Davis and the U.S. Geological Survey.

Curbing tractor emissions

One of the best ways of reducing greenhouse gases is to use less fossil fuel, the source of most carbon dioxide emissions. Studies during the 1990s showed that farmers can cut tractor fuel use from 6% to 20% by decreasing the tire pressure, says Shrini Upadhyaya, UC Davis agricultural and biological engineer. "Farmers often set tire pressure at 24 pounds per square inch (psi) but may be able to go down to 6 psi, depending on the load," he says, adding that while many farmers don't like to see the tires bulge, they can actually sit quite low. The biggest gains in fuel economy are in tilled fields during the spring, when the soil is a bit wet. Another benefit of lower pressure is that more of the tire surface touches the soil, reducing compaction (see *California Agriculture* 50[2]:28–31).

A drawback of lower tire pressure is that it is not optimal for all driving surfaces. "We knew it was good in the field but didn't know how well it would work on paved roads," Upadhyaya says. The recent increase in fuel prices prompted a follow-up study, which showed that tractors on roads are more fuel efficient at higher rather than lower tire pressures: increasing the pressure to 23 psi cuts fuel use by 12%. But farmers cannot be expected to adjust their tire pressure every time they switch from driving on a field to driving on a paved road, and vice versa. To circumvent this, Upadhyaya envisions designing tractors that automatically adjust their tire pressure to fit the driving surface, as some military vehicles already do.

Now, however, the project is on hold once more. "While interest went up with the recent high gas prices, it then went down again," says Upadhyaya. "But the technology is there."

Carbon-capture farming

In addition to reducing their emissions, farmers can help remove carbon dioxide from the air. A technique called "carbon-capture" farming capitalizes on plants' ability to absorb atmospheric carbon dioxide and then trap the carbon in soil upon decomposing. Soils grew 10 inches higher over 7 years in wetland test plots on a Sacramento-San Joaquin River Delta island, according to a recent pilot study by UC Davis and U.S. Geological Survey researchers.

"Wetlands can capture carbon at a tremendous rate," says UC Davis soil biogeochemist William Horwath. An acre can grow about 15 tons of plant material per year, which contains about 8 tons of

Climate change threatens California's native plants

Recent research shows that the next century of climate change could drastically shrink the ranges of California's endemic plants, nearly 2,400 species that are unique to the state and help make it a global biodiversity hotspot. In the worst-case scenario, two-thirds of these plants could lose more than 80% of their current ranges.

"Plants are very sensitive to climate," says UC Berkeley plant ecologist David Ackerly, part of the team that reported this work in a 2008 *Public Library of Science (PLoS) ONE* study called "Climate Change and the Future of California's Endemic Flora." "The rate of climate change is now 3 to 10 times faster than at the end of the last ice age." This is so fast that many plants just won't be able to keep up.


Jack Kelly Clark

The native California bay laurel, currently widespread in the coastal mountains and Sierra Nevada foothills, could see its range diminish dramatically.

Many of today's familiar landscapes could shift or even disappear in the future, the study predicts. As temperatures rise and rainfall becomes more variable, California's plants will generally move north and coastward to cooler areas. More specifically, coast redwoods could grow farther north, Sonoran desert plants could move into the Central Valley, and oaks could die out in the middle of the state.

Plants on mountain slopes may fare best, Ackerly says. If their current habitat gets too hot, they could easily reach cooler sites by moving a bit higher upslope. In contrast, plants growing on mountaintops would have nowhere to go, and those growing in flat areas would have to move tremendous — and unrealistic — distances.

"California's ruggedness may turn out to be one of its greatest buffers against climate change," Ackerly says. Conservation planners could apply this finding to mountainous areas such as the coast ranges, the Sierra Nevada foothills and the San Gabriel Mountains east of Los Angeles. One approach entails establishing a network of protected areas at various elevations, connected by corridors to let plants move up as the temperature rises.

Another approach is for us to help the plants move. "It's cost-prohibitive for animals but not so crazy to think about for plants," Ackerly says. "We do restoration ecology all the time." Called managed relocation, this approach is hotly debated among conservationists, who prize preserving species in their natural habitats. Still, it may be time to turn traditional conservation on its head and "ask what will live on a reserve in the future versus where a given species can live," Ackerly says. Forestry could benefit from this approach without sparking controversy, since timberlands are managed plantations of native trees. To plan for harvests in 30 to 40 years, foresters could move seeds now in accord with expected climate changes.

Dire as the projections are, there is still hope for California's plants. "While most seeds drop right by the parent, jays can move acorns a third of a mile and wind-dispersed seeds can move many miles," Ackerly says. "It only takes a few long distance migrants to jump-start a new population."

— Robin Meadows

carbon. Of that, 90% is lost to bacterial decomposition and the rest is captured in soil. The Delta is particularly well suited to carbon-capture farming. "It's one of the most productive ecosystems on the planet," says Horwath, who is also the UC Sustainable Agriculture Farming Systems (SAFS) project leader. "There are lots of nutrients and the climate is ideal."

Besides removing carbon from the air, rebuilding the Delta island soils would help protect the levees that route drinking water to two-thirds of Californians. The levees are in danger of caving in because after years of draining and tilling the fragile peat soils, most of the islands lie 20 feet below the surrounding water. "We have created monsters in these islands," Horwath says. "It would be a catastrophe if the levees broke during an earthquake."

Because much of this land is privately owned, it cannot simply be flooded to protect the levees. Instead, the researchers hope to give Delta farmers another option. Instead of vegetable crops, Horwath envisions the farmers planting cattails, tule rushes and other wetland vegetation, and then selling the carbon credits. "They would be land stewards, growing carbon," he says. To assess the feasibility of carbon-capture farming, the researchers are scaling their study up to 400 acres. Possible pitfalls include the fact that wetlands emit methane, potentially outweighing the benefits of the carbon dioxide they remove from the air.

For more information

AB32 Fact Sheet
http://www.arb.ca.gov/cc/factsheets/ab32factsheet.pdf

California Climate Change Portal
http://www.climatechange.ca.gov

UC Davis: Climate Change Terms and Definitions
http://climatechange.ucdavis.edu/terms.html

UC Davis John Muir Institute of the Environment, climate change science
http://climatechange.ucdavis.edu/index.html

Yolo County case study

While many studies focus on specific ways to combat or cope with climate change, a UC Davis team took a comprehensive look at what Yolo County can expect — and what to do about it — in the coming decades. Led by ecologist Louise Jackson, the 13-member interdisciplinary team included agricultural and natural resources researchers as well as social scientists. Sponsored by the California Energy Commission, the study benefited from a steering committee that included farmers, county and state representatives, and farm advisors.

"Overall, the single most important thing for growers is how to deal with specific crops that may be affected by heat waves, droughts and higher temperatures," Jackson says.

For example, over the next 50 years, Yolo County will likely get too hot for the warm-season crops that thrive there today, such as tomatoes, cucumbers, sweet corn and peppers. Instead, the future climate will suit melon, sweet potatoes and other hot-season crops during the summer, and lettuce, broccoli and other cool-season crops during the winter. Ways of helping farmers prepare include fostering markets for new crops, and breeding crops that tolerate longer, hotter heat waves and other climate extremes.

Farmers can also help themselves by growing more kinds of crops, which should make their operations more resilient to climate change. The current trend in Yolo County is toward less crop diversity, with seven types accounting for 85% of farmed land (see pages 84, 91). Crop choices are driven by factors including how lucrative they are, the availability of local processors and economies of scale. However, "farmers also need to think about diversification and trying new crops," Jackson says.

The study also showed that as snow melts earlier in the Sierra Nevada and coincides with spring rains, marginal farmlands near the Sacramento River will be more likely to flood. "Marginal lands are present on every farm, along edges and riparian areas," Jackson says. "We can put these lands to work for increasing habitat, biodiversity and water quality." For example, rather than abandoning land that floods to weeds, farmers could create wetlands that store carbons and sell the resulting credits.

But while such restoration would capture carbon, this might be offset by the natural wetland emissions. Similarly, there are trade-offs with many of the other ways farmers can reduce their greenhouse-gas emissions. Two practices with clear-cut benefits are using less fuel and less nitrogen fertilizer, which is overapplied by as much as 50% and can contribute to nitrous oxide emissions. Nitrous oxide is a powerful greenhouse gas, with about 300 times the impact of carbon dioxide. Besides being good for the environment, reducing fuel and fertilizer use is "good for the bottom line," Jackson says.

One practice that is not so clear-cut is drip irrigation, the study found. By keeping much of the soil dry, drip irrigation decreases carbon dioxide and nitrous oxide emissions from soil microorganisms. But partly because this practice requires fuel for pressurization, it also increases carbon emissions. Conversely, conservation tillage decreases fuel use but can also increase soil moisture and thus microorganism emissions. Likewise, cover cropping can capture carbon and decrease fertilizer use, but the plant residue also emits carbon dioxide during decomposition.

Farmers will have to weigh the various approaches for adapting to climate change. "Rather than giving one solution, we explain the costs and benefits and let people choose what works for them," Jackson says. *— Robin Meadows*

REVIEW ARTICLE

How will changes in global climate influence California?

by Bryan C. Weare

In 2007, the Intergovernmental Panel on Climate Change (IPCC) published its fourth assessment reports summarizing recent global climate change and projections for the next century. This article reviews the basics of climate science and modeling, highlights the conclusions of the IPCC report, and identifies the well-understood aspects of climate change that will be important for California agriculture and society as a whole. Predicted impacts to California include increased flooding and reduced water availability, higher sea levels, worse air pollution and fewer chilling hours for important crops.


U.S. Bureau of Reclamation

In a warmer world, the availability of water is likely to be the most important issue that Californians face. Reservoirs such as Shasta in Northern California, shown in fall 2008 at nearly 60% of its capacity, will likely be fuller in winter, and lower in spring and summer when crops are irrigated.

Important consequences of observed and future global warming are as diverse as decreases in winter chilling hours (a necessity for many fruit and nut crops), more extreme air pollution episodes and more frequent coastal flooding. Most important are past and future reductions in winter snowpack, which increase the likelihood of winter flooding, and reduce the water available from reservoirs for irrigation and other uses in late spring and summer.

During the past decade, the most controversial subject in atmospheric science has been the question of whether humans are having a significant impact on climate. The Intergovernmental Panel on Climate Change (IPCC) recently evaluated many aspects of global climate change in a set of extensive reports. These reports are compiled by panels of hundreds of scientists and social scientists from around the world under the umbrella of the United Nations. They describe comprehensive evaluations of the published literature concerning global climate change. The *Physical Science Basis* report alone is nearly 1,000 pages, and establishes the basis of climate science and the most recent climate observations and model results (IPCC 2007). This review of the IPCC report and other recent scientific literature focuses on the most important factors that influence agriculture in the western United States.

The science of climate

We put the IPCC conclusions into context using the basics of climate change science (fig. 1). In general, the temperature of Earth's atmosphere is determined by a balance between the amount of trapped sunlight and the nearly equal loss of heat into deep space. The distribution of sunlight means that the equatorial regions are warmer than the poles, and that summer is warmer than winter. Atmospheric winds and ocean currents further influence the mean climate. For instance, the U.S. West Coast is relatively mild in winter because warm ocean air flows from west to east. However, in summer that oceanic flow is relatively cool partly because the Alaska current cools coastal waters.

For Earth, the amount of trapped sunlight during a year is closely offset by a nearly equal amount of heat being lost into deep space. However, global climate change will occur if, over years or decades, either the amount of absorbed sunlight or emitted heat changes. The amount of absorbed sunlight varies for a number of reasons, including slight fluctuations in solar output, changes in cloud cover and variations in snow cover. The two latter factors alter what is known as Earth's "albedo," the fraction of sunlight that is reflected back into space. In addition to natural factors, the amount of absorbed sunlight may be altered by human activities. For instance, we may increase the surface albedo by replacing black asphalt with more reflective, light-colored concrete, or the top-of-atmosphere albedo through introduction into the atmosphere of reflective aerosols (dust particles), primarily as a result of burning fossil fuels. Both of these factors will lead to decreased absorption of solar radiation at the surface and lowered surface temperatures.

Greenhouse effect. Changes in the greenhouse effect are the primary ways that humans can influence climate.

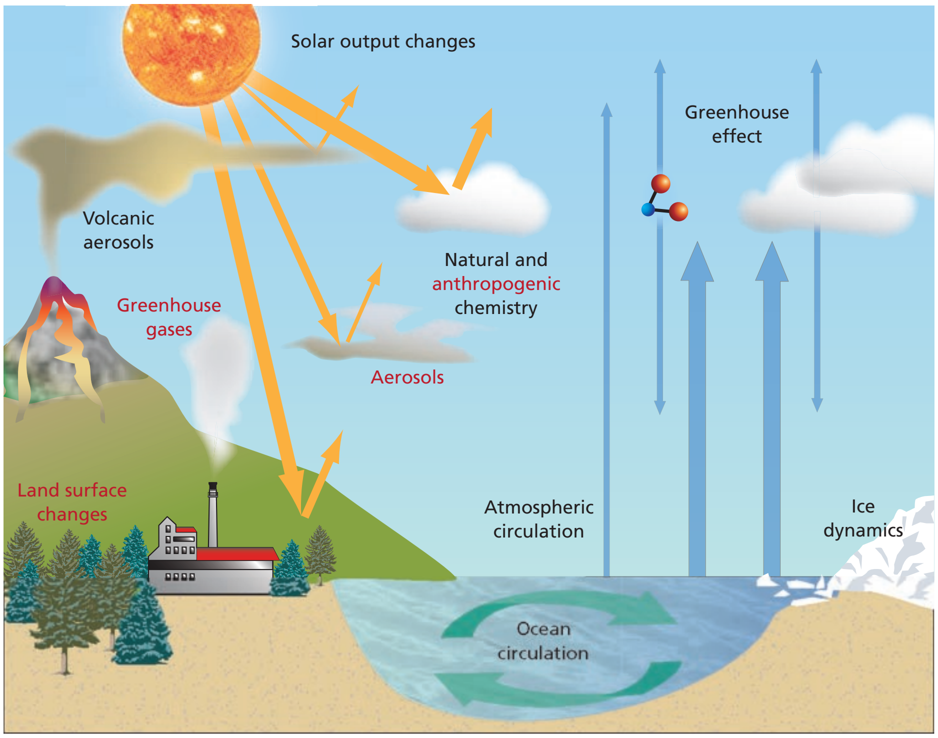

Fig. 1. Schematic of factors and processes controlling global climate; the primary controls are changes in solar radiation (yellow arrows) and outgoing heat (blue arrows). Adapted from IPCC 2007, fig. 1.2.

Each greenhouse-gas molecule can absorb a tiny portion of upward-traveling heat (fig. 1), which it must release almost immediately. This release occurs in all directions, so that part of the heat, which was originally leaving the atmosphere, is redirected back down to the ground. This means that less heat escapes to outer space and more heat heads toward Earth, increasing surface temperatures.

The major constituents of the atmosphere, nitrogen and oxygen, absorb almost no heat or sunlight. Their concentrations have little direct effect on climate change. The main naturally occurring greenhouse gases are water vapor and carbon dioxide. Without these gases the average surface temperature of Earth would be about 32°F (18°C) cooler than today — not a very pleasant place. Humans can add to the greenhouse effect by emitting carbon dioxide, mostly from the burning of fossil fuels, and other greenhouse gases such as chlorofluorocarbons, methane and nitrous oxide.

Feedbacks. An initial temperature change due to radiative factors may be amplified or diminished by positive and negative feedbacks (fig. 1). An example of a positive feedback is the snow-albedo feedback mechanism, in which an initial increase in temperature leads to less snow and ice at higher latitudes. Since both ice and snow easily reflect sunlight back to space, this decrease will lead to more sunlight being absorbed by Earth's climate system, tending to increase the temperature even more. Another well-understood positive feedback is related to water vapor, the most important greenhouse gas. As Earth warms, the ability of the atmosphere to hold water vapor generally increases. The additional water vapor absorbs more heat and causes Earth to warm further.

Negative feedbacks may also occur, which tend to reduce the magnitude of the overall temperature change but not its direction. For example, in the moister atmosphere associated with higher temperatures, thicker clouds are likely to form. Increased cloud thickness will lead to lower surface temperatures, primarily because clouds effectively reflect sunlight. The initial temperature increase may therefore be reduced.

2007 IPCC Report

The recent IPCC report concludes that warming of the climate system is "unequivocal," that this warming is "very likely" due to increased anthropogenic greenhouse-gas concentrations, and that continued greenhouse-gas emissions and climate changes are "very likely" to be larger in the next century. Some important details of the IPCC report are discussed below; quotations from the report are shown in *italics*.

Climate-forcing factors. *Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed preindustrial values determined from ice cores spanning many thousands of years . . . The primary source of the increased atmospheric concentration of carbon dioxide since the preindustrial period results from fossil-fuel use, with land-use change providing another significant but smaller contribution. The atmospheric concentration of methane in 2005 exceeds by far the natural range of the last 650,000 years (320 to 790 parts per billion [ppb]) as determined from ice cores. The global atmospheric nitrous oxide concentration increased from a preindustrial value of about 270 ppb to 319 ppb in 2005.*

Although atmospheric carbon dioxide concentrations have increased steadily, only about half of the fossil-fuel-related carbon dioxide released into the atmosphere over the past century has remained there. The other half has been deposited primarily into the deep oceans and terrestrial biomass — forests and soil humus. The increasing concentrations of methane are believed to be largely related to natural-gas drilling and distribution, feedlot emissions and decomposition in landfills and rice fields. Increases in nitrous oxides are primarily related to air pollution and livestock waste management (see page 79).

Increases in these and other anthropogenic and natural climate-forcing factors result in changes, which can be related to an equivalent change in the solar heating of Earth. Figure 2 (page 62) illustrates the current values of most of these factors and uncertainties in the estimates. The most important forcing factors, having the lowest relative uncertainties, are positive and lead to global warming. However, other anthropogenic climate-forcing factors, which have estimated influences that are relatively uncertain, are leading to a smaller amount of cooling. Natural variability of the sun currently is also

The rate of these projected changes will challenge our scientific, economic and social ability to effectively cope.

inducing slight heating (fig. 2). Another possibly relevant natural cooling factor, not shown in figure 2, is the unpredictable but important effect of strong volcanoes, which put large amounts of aerosols (reflective dust particles) in the stratosphere, resulting in less solar heating and leading to a cooling of Earth's surface for up to a few years.

Magnitude of warming. *Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.* The overall temperature increase has been about 1°F (0.5°C) over the past century. The warming is largest over the highest latitudes and the centers of continents and smallest over the tropics and the oceans.

Sea level. *Global average sea level rose at an average rate of 1.8 millimeters (0.07 inch) per year from 1961 to 2003. There is high confidence that the rate of observed sea-level rise increased from the 19th to the 20th century. The total 20th-century rise is estimated to be about 0.17 meter (6.6 inches).* Most of this increase in sea level is thought to be due to the expansion of water in the oceans as they warm. Another fraction, whose magnitude is subject to considerable debate, is due to the increased melting of mountain glaciers and of small fractions of the massive ice of Greenland and Antarctica.

Role of greenhouse gases. *Palaeoclimatic information supports the interpretation that the warmth of the last half-century is unusual in at least the previous 1,300 years. Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse-gas concentrations.* This is a stronger, more conclusive statement than was made in the previous IPCC report, which was released in 2001. In fact, the current report concludes:

The observed widespread warming of the atmosphere and ocean, together with ice mass loss, support the conclusion that it is extremely unlikely that global climate change of the past 50 years can be explained without external forcing, and very likely that it is not due to known natural causes alone.

For the next two decades, a warming of about 0.2°C (0.4°F) per decade is projected for a range of SRES (Special Report on Emissions Scenarios) (Nakićenović and Swart [2000]) emissions scenarios (discussed below). *Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C (0.2°F) per decade would be expected. Continued greenhouse-gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century.*

The overall conclusion of this IPCC report is that there will likely be a steady increase in global, hemispheric and regional temperatures in the next century due to human influences. The magnitude of the changes will largely depend upon future increases in greenhouse-gas emissions and, perhaps, changes in anthropogenic aerosol concentrations resulting from a broad variety of human activities.

Global climate models

Global climate models are the most important, and probably the most widely misunderstood, tools used by climate scientists to understand past climate changes and estimate

Glossary

Albedo: Fraction of sunlight at the top of the atmosphere that is reflected back into space.

Albedo, surface: Fraction of sunlight hitting a surface (such as a polar icecap, cropland or resurfaced parking lot) that is reflected upward.

Emissions scenarios (A2, B1): The A2 (high emissions) economic scenario assumes relatively rapid global population and economic growth with few controls on fossil-fuel emissions. The B1 (lower emissions) scenario assumes extensive emissions controls such that atmospheric carbon-dioxide concentrations do not exceed 550 parts per million (ppm), less than 50% higher than the current value of about 380 ppm.

Feedback, positive and negative: A sequence of processes, which will either amplify (positive) or reduce (negative) the size of an initial change, such as a surface temperature increase. Generally, a negative feedback will not alter the sign of the change.

Forcing factors: Factors external to the natural ocean-atmosphere climate system that greatly influence climate. Natural forcing factors include output of the sun (radiant energy) and volcanic aerosol (dust) concentrations. Human (anthropogenic) forcing factors include concentrations of greenhouse gases such as carbon dioxide and methane.

UN Photo/Eskinder Debebe

In November 2007 in Valencia, Spain, United Nations Secretary-General Ban Ki-moon (center), flanked by Renate Christ (left), secretary of the Intergovernmental Panel on Climate Change (IPCC), and Rajendra Kumar Panchauri (right), IPCC chair, displayed the fourth IPCC assessment report, which concluded that warming of the climate is "unequivocal."

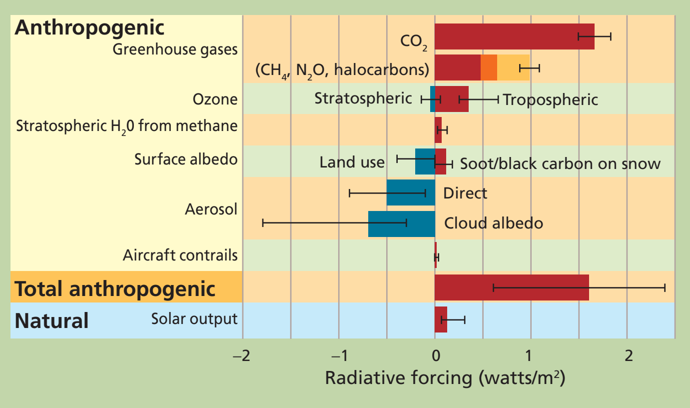

Fig. 2. Primary forcing factors for global climate change. Magnitudes are expressed in terms of the equivalent change of incoming sunlight at the top of the atmosphere. The temporary cooling effect of unpredictable, massive volcanoes is not shown. Adapted from IPCC 2007, fig. SPM.2.

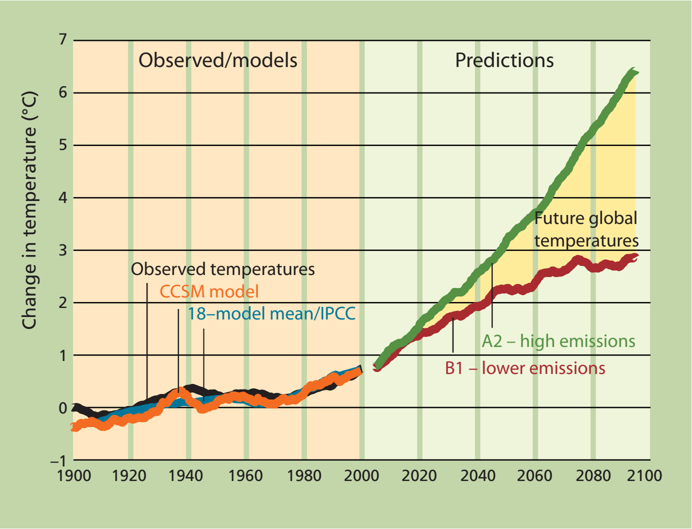

Fig. 3. Observed and predicted changes in average surface temperatures in the Northern Hemisphere. Observed/models (left) shows: observed temperatures between 1900 and 2000 (Mitchell and Jones 2005); 18-model mean sample of IPCC global ocean-atmosphere predictions starting about 1850, for 1900 to 2000; and Community Climate System Model (CCSM) prediction for 1900 to 2000. CCSM predictions (right) for 2000 to 2100 are based on the A2 (high emissions) and moderate B1 (lower emissions) economic scenarios. The likely range of global temperatures in the future is between the green and red lines.

those of the future. State-of-the-art, physics-based computer models are an outgrowth of weather models, which are used to make forecasts 1 to 10 days into the future. Although we all sometimes make fun of weather forecasts, it is now possible to forecast 4 days with the same accuracy as it was possible to forecast 3 days a decade ago.

Modeling climate processes. The processes simulated by these climate models (fig. 1) involve the physics not only of the atmosphere, but also oceans, ice masses and land surfaces. To emulate these processes in the atmosphere, the models calculate the temperature, pressure, winds and humidity at points between 50 and 150 miles apart in the horizontal direction and as much as a few thousand feet in elevation. At each point, the models mathematically solve the basic laws of physics, including Newton's laws of motion, the conservation of energy and the conservation of total mass and water. Comparable calculations are made for the oceans to predict area-averaged currents, temperature and salinity.

These large-scale processes are coupled to carefully tested approximations of subgrid-scale processes, which occur in regions that are smaller than the spacing of most model grids. An example is the interaction of atmospheric temperature and winds with clouds, which individually occur over regions of a few hundred yards to a few miles, but which also as a group are vitally important for determining the global climate. Other subgrid-scale processes include turbulence near the ground, the growth of cloud drop to rain drops, land-surface interactions, and in some climate models, atmospheric and oceanic chemistry, and plant growth.

How models work. To use a climate model one starts with the observed conditions for one time in the past, then all of the relevant equations are projected into the future in intervals of a few minutes. The primary controls on climate are basic physics and forcing factors such as solar output and greenhouse-gas concentrations. This process creates descriptions of day-to-day weather a year or decades into the future. After many thousands of time steps, estimates of nearly any climatic variable for some future time, such as 50 years from now, can be obtained from averages of the appropriate output. The development of a climate model that simulates future weather is somewhat like making homemade ice cream in a churning ice cream maker. The ice cream ingredients correspond to the composition and structure of the atmosphere/ocean/ice system. The stirring rate of the ice cream maker corresponds to Newton's laws of motion, and the temperature corresponds to the climate-forcing functions, such as sunlight received at the top of the atmosphere. The hardness and consistency of the ice cream at any time is equivalent to Earth's weather. As the ice cream maker turns, the cream mixture evolves by becoming harder and smoother. As a climate model evolves, that is, moves forward in model time, it makes predictions of temperature, precipitation and other variables further and further into the future. Just as in the ice cream maker, where the final product is primarily a function of the ingredients and mixing of the maker, in a climate model the final climate is primarily a function of the forcing variables and the basic laws of physics. Most importantly, the output of these models is not adjusted in any way by weather or climate observations after the initial step.

Uncertainties of climate predictions. The uncertainties associated with climate predictions fall largely into two categories. First, there are complex positive and negative climate feedbacks. Second, relatively large uncertainties surround future greenhouse-gas and aerosol emissions, and thus the magnitude of forcing on the model. These uncertainties are primarily related to economic and social projections of the future global economy and human activities.

Evaluating models. The IPCC models have been used to simulate the 20th-century climate starting at a date before 1900 and controlled by both known natural and anthropogenic factors, such as solar output, volcanic and anthropogenic aerosols, and greenhouse-gas concentrations. The averaged outputs of (1) 18 of these model runs and (2) the representative Community Climate System Model (CCSM) produced at the National Center for Atmospheric Research in Boulder, Colo., emulate very well the observed changes in Northern Hemisphere temperature (fig. 3). The agreement with actual climate data includes the total change over the past century and the fact that heating was slow for the first third, nearly zero in the middle third and relatively fast for the final third (fig. 3).

In the western United States, both the 18-run model mean and the CCSM output perform quite well in emulating the changes throughout the 20th century for surface temperature (figs. 4A-C). Observed temperatures generally increase between 1.8°F and 3.6°F (1°C and 2°C) for every degree Centigrade increase in Northern Hemisphere temperature, with the smallest changes over the ocean. Mean temperature changes in the 18 IPCC models and the CCSM both have slightly smaller values than those observed but a similar geographic pattern.

When modeling local changes in precipitation over the western United States that are associated with the observed rise in Northern Hemisphere temperature (figs. 4D-F), the situation is more complex than for temperature. The observed changes indicate both wetter and drier conditions associated with recent global warming (fig. 4D). In contrast, the 18-model IPCC mean precipitation pattern indicates a broad reduction in precipitation over much of the West (fig. 4E). The CCSM results are different again, showing larger changes and a more varied pattern (fig. 4F). This disparity is not unexpected, since short-term weather forecasts of precipitation are less skillful than those of temperature. This is because precipitation processes are complex and have spatial scales much, much smaller than model grid spacing. These results suggest that models do not yet reliably simulate local patterns of precipitation change.

Loss of Arctic sea ice. The loss of Arctic sea ice, an important aspect of climate change, has received special attention in the last few years (Serreze et al. 2007). There has been a dramatic, well-documented decline in sea ice such that the coverage in September 2007 was only about 60% of the mean for the preceding 30 years. Reports for September 2008 suggest a slightly smaller decline than in the prior year. Nevertheless, rapid decreases in Arctic ice clearly have important consequences for the positive ice albedo feedback mechanisms. More distressing is the fact that the melting of Greenland and Antarctica seem to have accelerated in a manner not well explained by most models (Min et al. 2008).

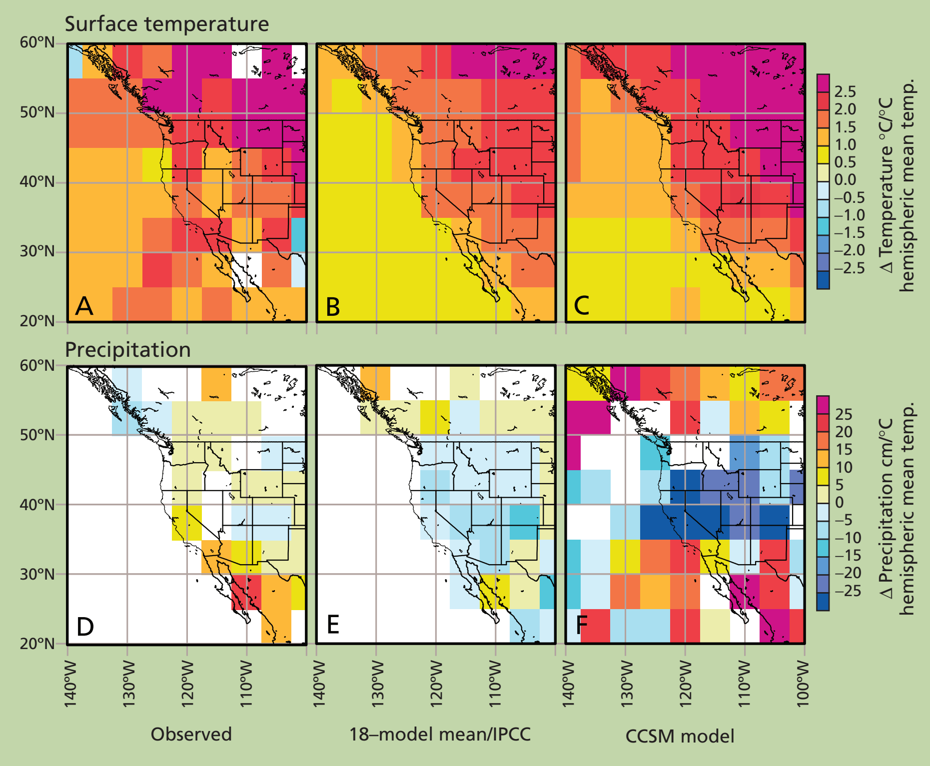

Fig. 4. Sensitivity of (A-C) local surface temperature and (D-F) precipitation to changes in Northern Hemisphere average surface temperature (see fig. 3) in the western United States, under observed and model conditions. Blank areas show statistically insignificant changes.

Future climate predictions

High and lower emissions scenarios. The main scientific controversies regarding global climate change concern predictions for the future. These predictions combine socioeconomic scenarios of fossil-fuel usage, farming practices and pollution control with global climate models (fig. 3). The right side of figure 3 illustrates predicted average temperatures in the Northern Hemisphere using the CCSM, utilizing the so-called A2 and B1 socioeconomic scenarios. The A2 (high emissions) scenario assumes relatively rapid global population and economic growth with few controls on fossil-fuel emissions. The B1 (lower emissions) scenario assumes extensive emissions controls such that atmospheric carbon-dioxide concentrations do not exceed 550 parts per million (ppm), about 50% higher than the current value of about 385 ppm. The true value of future greenhouse-gas forcing factors is expected to be somewhere between these two scenarios. The CCSM model produces average Northern Hemisphere temperature changes that are within the range of all 18 models in the IPCC evaluation (fig. 3). Average surface temperatures in the Northern Hemisphere are likely to rise between 3.6°F (2°C) and 5.4°F (3°C) by 2050 and as much as 12°F (6.5°C) by the end of the 21st century.

Regional temperature. When the CCSM is used to predict changes in surface temperature over the western United States for 2050 and 2095 — using the more-sensitive, high-emissions A2 scenario — the temperature changes are largest over the Rocky Mountains and higher latitudes, and smallest over the southern Pacific Ocean (figs. 5A, 5B). Over California, predicted temperature increases are between 1.8°F and 3.6°F (1°C and 2°C) for 2050 and around 7°F (4°C) for 2095. A good deal of confi-

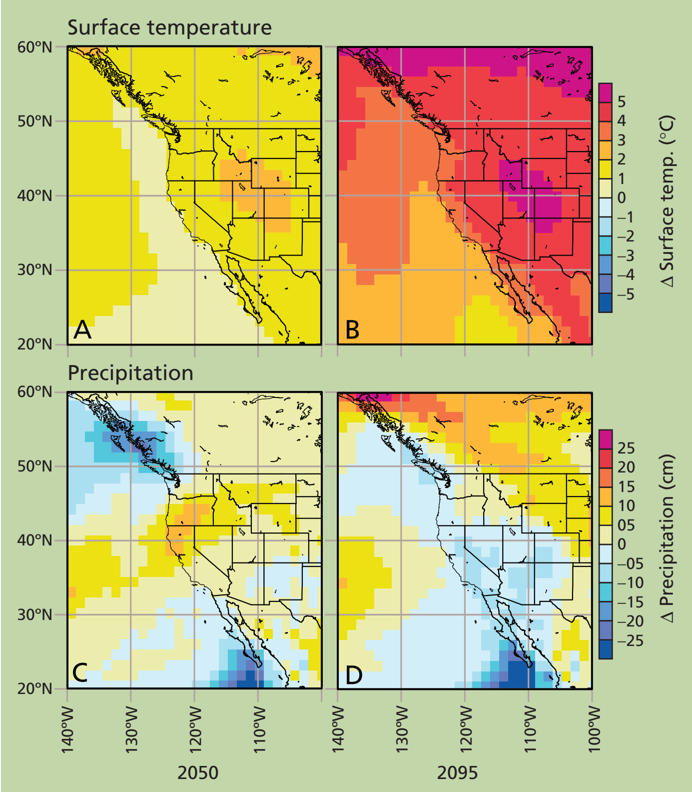

Fig. 5. Changes in (A, B) surface temperature and (C, D) precipitation for 5 years centered on (A, C) 2050 and (B, D) 2095, relative to 2003 values, based on CCMS model and A2 (high emissions) scenario.

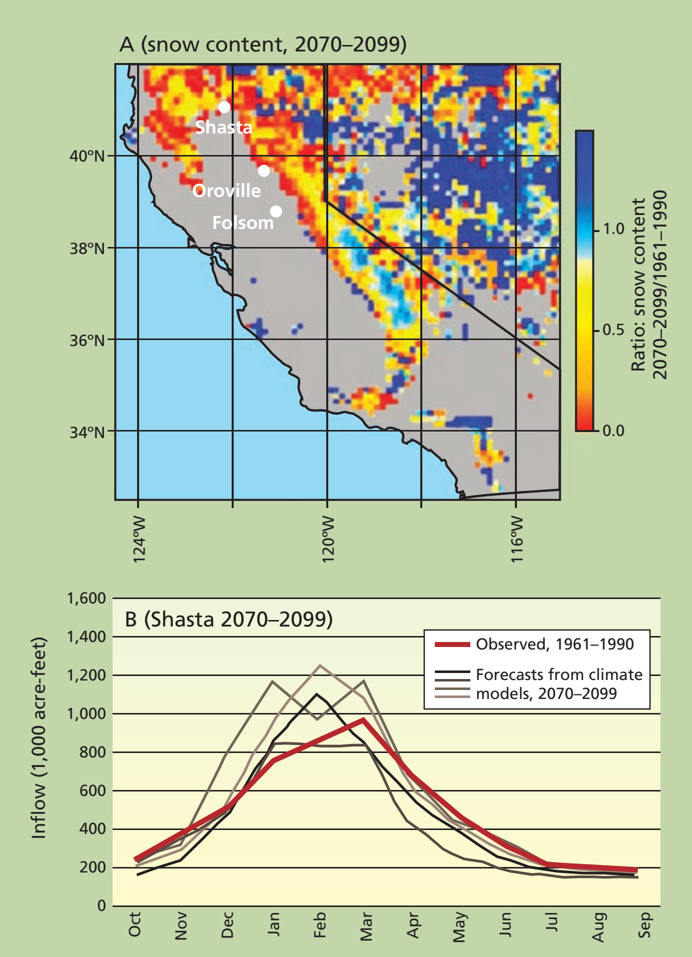

Fig. 6. (A) Ratio of predicted average 2070–2099 April snow water equivalent relative to that observed for 1961–1990. Prediction is based upon a hydrological model driven by the output of a climate model using the B1 (lower emission) scenario. Adapted from Cayan, Mauer, et al. 2008, fig. 14. (B) Monthly mean inflows into Shasta Reservoir for historic period (red line), and output of two climate models each using A2 and B1 emissions scenarios (gray/black lines). Adapted from Purkey et al. 2008, fig. 2.

dence may be given to these results because the CCSM model has a sensitivity similar to the mean of the IPCC models, because of the good agreement between the CCSM with observations over the past century (fig. 4), and because of the similar patterns of change for the two future times.

Precipitation. When the CCSM is used to predict changes in annual precipitation over the western United States for 2050 and 2095, also using the A2 high emissions scenario, both maps suggest lower precipitation at the lowest latitudes, which is in agreement with other models used in the IPCC evaluation (figs. 5C, 5D). However, the patterns of change over much of the remainder of the region differ from each other and from that of the 20th-century simulations (fig. 4). Unfortunately, little confidence can be placed on local precipitation-change patterns from the CCSM and, perhaps, any current climate model. Because of this uncertainty and because the IPCC climate models generally put the western United States between a broad band of future precipitation increases to the north and decreases to the south, the most reasonable expectation is that total precipitation over the West is unlikely to change substantially from that of today.

Forecasts and California agriculture

Growing conditions. A number of scientific articles have begun to address what these forecasts mean for California agriculture (see page 55). In addition to the research reported and reviewed in this issue of *California Agriculture*, a group of articles was compiled in a special edition of the journal *Climatic Change* (Cayan, Luers, et al. 2008). An earlier summary is given in Hayhoe et al. (2004), with extensive online supplements. Annual mean surface temperatures for California and the western United States are likely to increase substantially in the next century. However, more important to agriculture and society as a whole are variables such as minimum winter temperatures or other extremes. Tebaldi et al. (2006) describe global climate model results for four important temperature statistics: number of days of frost, number of days of the growing season, number of days of heat waves, and percentage of days of warm nights. Their results suggest California will have fewer frost days, longer growing seasons, more heat waves and more warm nights in the future.

Water availability. Perhaps the most important issues associated with global

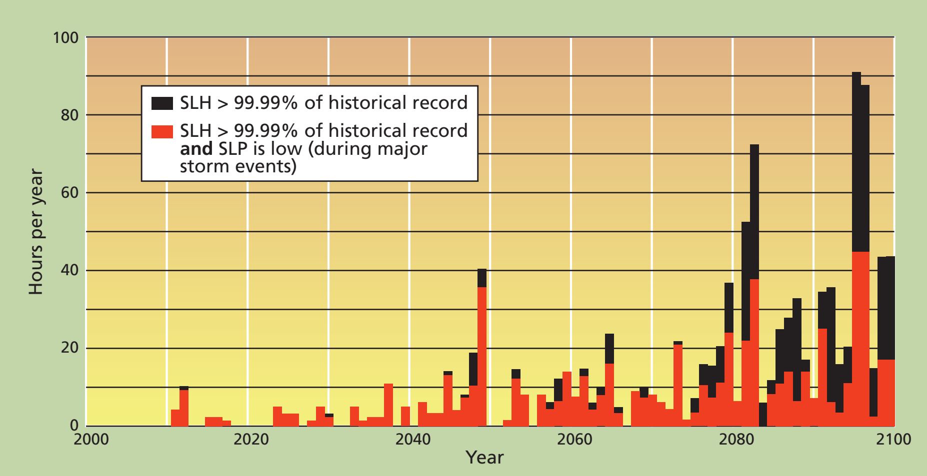

Fig. 7. Hours in which sea-level height (SLH) is expected to exceed 99.99% of the historical record for San Francisco Bay. Black bars are for all times and red bars are for when sea-level pressure (SLP) is low (during major storm events). Data is based on weather simulations of an ocean/atmosphere model, adding the influence of a 12-inch sea-level increase. Adapted from Cayan, Bromirski, et al. 2008, fig. 6.

warming for California are related to water availability. As the western United States warms, mountainous regions will receive rain rather than snow more often and be subject to earlier snowmelt, leading to reduced snow depth and less stored snow water in spring. As a result, there will likely be more flooding, and increased pressure will be placed on the state's reservoir systems.

Cayan, Maurer, et al. (2008) predicted the change in April 1 snow content from 2070 to 2099, relative to observed values between 1961 and 1990 (fig. 6). This prediction is based on a snow hydrology model, which is driven by temperature and precipitation values and predicts current snow measurements well. From 2070 to 2099, the precipitation and temperature data are averages from two climate models driven by the moderate B1 (lower emissions) scenario. These models predict increases in surface temperature, but little change in total precipitation (fig. 6A). By 2085 the prediction is the nearly complete loss of April snow at lower elevations of the mountains, substantial losses at middle levels and relatively small losses at the coldest, highest elevations.

Water storage. Because mountains tend to be conical, losses of low- and mid-elevation snow areas are more important to changes in snow water storage than changes at higher elevations (fig. 6A). For example, flows in Shasta Reservoir are likely to increase in winter, but decrease in spring and summer (fig. 6B). Comparable changes are expected for Oroville and Folsom, which also receive water from mountain regions that are expected to have large decreases in springtime snow (fig. 6A). These changes will tend to raise reservoir inflows and heighten the chances of winter flooding. To offset greater chances of flooding, dam operators will have to reduce reservoir levels. The combined effects of less snowpack and reduced reservoir storage will lead to much less water availability in summer for agricultural and other uses.

Sea level. Global warming will lead to important increases in sea level, which may influence coastal California. The IPCC report predicts global average sea-level increases by 2060 of 10 to 20 inches (25 to 50 centimeters), leading to increased periods of flooding over the next 100 years (fig. 7). Flooding, which is essentially unheard of in the California of today, may become almost commonplace in the coming century.

Chilling hours. Baldocchi and Wong (2008) studied hours of chilling, which is important for many fruit and nut crops. Yearly chill-hour accumulation is the number of hours below 50°F (7.22°C). They found that observed chill-hour accumulations over the past 60 years have been variable, but they clearly drop around 1990 (fig. 8). Based on the moderate B1 (lower emissions) scenario, future estimates have realistic year-to-year variability, but also show a clear and substantial downward trend. The number of chilling hours at the end of this century is expected to be half or less than during the 1980s. In this scenario, many crops, such as pears and pistachios, will not be commercially viable in large areas of California where they are currently grown.

Pollution. Another aspect of warmer temperatures that is likely to affect Californians and agriculture is a projected change in air pollution. The speeds of air-pollution chemistry reactions are often sensitive to temperature and humidity. For example, Kleeman (2008) studied peak concentrations of ozone and small atmospheric particles in the San Joaquin Valley for a period in January 1996, based on a sophisticated air-quality model driven by observed meteorological conditions. When surface temperatures were assumed to increase by 9°F (5°C),

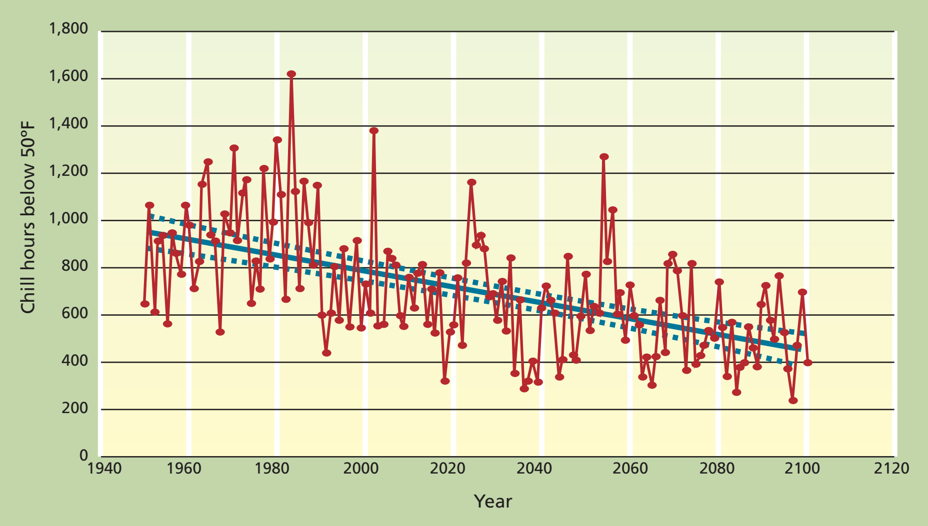

Fig. 8. Past and projected annual total chill hours for Davis, Calif. Values through 2003 are observations; values after are based upon average projections of two climate models driven by moderate B1 (lower emissions) scenario. Adapted from Baldocchi and Wong 2008, fig. 7.

peak ozone pollution concentrations were expected to nearly double.

The situation for small particle pollution (PM2.5) is somewhat more complex. Using a similar set of assumptions concerning changes in temperature and humidity, Kleeman (2008) showed substantial increases at the lower elevations of California and decreases in the foothill regions. Even if the emissions rates of pollutants and their precursors remain as today, in a warmer world pollution levels are likely to rise substantially over much of California. These increases could have important detrimental consequences for both natural and managed ecosystems as well as human health.

Human activity and climate change

We now know that relatively large global and regional climate changes have occurred over the past century. Our best scientific evidence strongly suggests that an important component of these changes is due to human activity. Furthermore, persuasive evidence indicates that the changes will continue at an increasing pace well into the next century. Important consequences of observed and future global warming are as diverse as decreases in winter chilling hours, more extreme air-pollution episodes and more frequent coastal flooding. Most important are past and future reductions in winter snowpack, which enhance the likelihood of winter flooding and reduce the water available from reservoirs for irrigation and other uses in late spring and summer.

These changes are likely to have profound influences on all aspects of California's economy and society. Furthermore, the rate of these projected changes will challenge our scientific, economic and social ability to effectively cope. It is important for all Californians to understand the causes of these changes, their likely implications and the nature of possible remediation.

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Robyn Carliss/Sustainable Conservation

The IPCC found that global sea levels rose 0.07 inch per year between 1961 and 2003, due to warmer oceans and melting of glaciers and polar ice. *Above*, the glacier Skaftafellsjökull, a spur of the Vatnajökull ice cap, is receding. An August 2008 report by the Icelandic government predicted that Iceland's glaciers will disappear by the middle of the 22nd century.

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As carbon dioxide rises, food quality will decline without careful nitrogen management

by Arnold J. Bloom

Rising atmospheric concentrations of carbon dioxide could dramatically influence the performance of crops, but experimental results to date have been highly variable. For example, when C_3 plants are grown under carbon dioxide enrichment, productivity increases dramatically at first. But over time, organic nitrogen in the plants decreases and productivity diminishes in soils where nitrate is an important source of this nutrient. We have discovered a phenomenon that provides a relatively simple explanation for the latter responses: in C_3 plants, elevated carbon dioxide concentrations inhibit photorespiration, which in turn inhibits shoot nitrate assimilation. Agriculture would benefit from the careful management of nitrogen fertilizers, particularly those that are ammonium based.

Atmospheric carbon dioxide (CO_2) has increased about 35% since 1800 (from 280 to 380 parts per million [ppm]), and computer models predict that it will reach between 530 and 970 ppm by the end of the century (IPCC 2007). This rise in carbon dioxide could potentially be mitigated by crop plants, in which photosynthesis converts atmospheric carbon dioxide into carbohydrates and other organic compounds. The extent of this mitigation remains uncertain, however, due to the complex relationship between carbon and nitrogen metabolism in plants (Finzi et al. 2007; Johnson 2006; Reich et al. 2006).

Carbon metabolism provides the energy and carbon molecules to synthesize organic nitrogen compounds in plants, whereas nitrogen metabolism provides the amino groups for all proteins (fig. 1). Proteins include all enzymes that catalyze (facilitate) biochemical reactions in plants, including

The rise in atmospheric carbon-dioxide levels — about 35% since 1800 — changes how plants metabolize important nutrients, which in turn alters food quality and nutrition, influences where plants and crops can grow, and affects pest management and other cultivation practices. Lesley Randall of the UC Davis Department of Plant Sciences attends to plants growing in hydroponic culture under elevated carbon-dioxide atmospheres, in environmental chambers at the UC Davis Controlled Environment Facility.

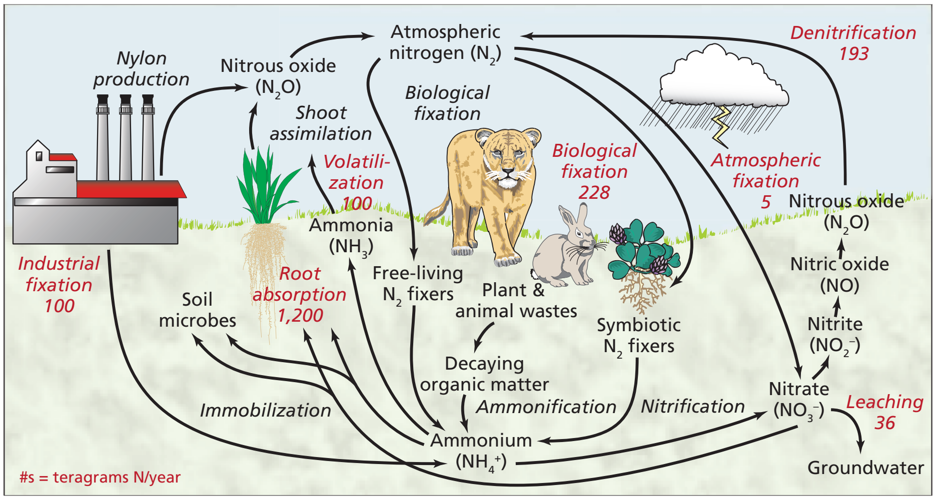


Fig. 1. Major processes of the biogeochemical nitrogen cycle. Fluxes (red numbers) are in teragrams (Tg = 10^{12} g) N/year. Terrestrial organisms and soils contain organic nitrogen that is active in the cycle. Assuming that the amount of atmospheric molecular nitrogen remains constant (inputs = outputs), the mean residence time of nitrogen in organic forms is about 370 years. Source: Bloom 2009.

At elevated carbon dioxide concentrations, C_3 plants that rely on nitrate as a nitrogen source suffer severe deprivation of organic nitrogen.

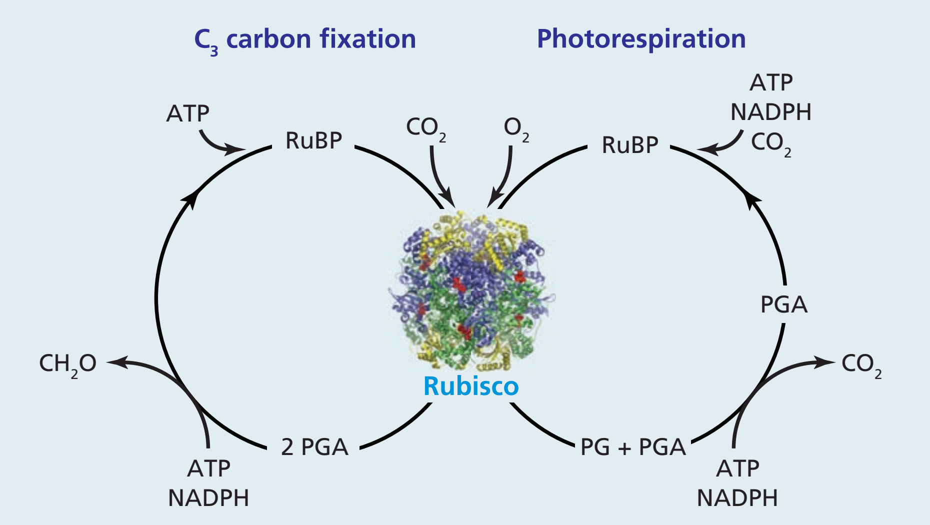
carbon metabolism. Any environmental perturbation that interferes with nitrogen metabolism sooner or later inhibits carbon metabolism.

Carbon dioxide acclimation

The focal point of crop responses to rising carbon dioxide levels is the enzyme rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase). Rubisco is the most prevalent protein on Earth and contains as much as half of the nitrogen in plant leaves. It catalyzes two different chemical reactions: one reaction combines a 5-carbon sugar RuBP (ribulose-1,5-bisphosphate) with carbon dioxide, and the other reaction combines this same sugar with oxygen.

The reaction of RuBP with carbon dioxide produces a 6-carbon compound that immediately divides into two molecules of a 3-carbon compound (3-phosphoglycerate), hence the name C_3 carbon fixation (fig. 2). These products pass through an elaborate biochemical cycle (Calvin-Benson cycle) that eventually forms one molecule of a 6-carbon sugar (fructose-6-phosphate) and regenerates RuBP.

The reaction of RuBP with oxygen oxidizes the RuBP, splits it into one molecule of a 3-carbon compound (3-phosphoglycerate) and one molecule of a



Molecule: Inger Andersson

Fig. 2. C_3 carbon fixation and photorespiration pathways in which the enzyme rubisco (ribbon model in center) catalyzes reactions between a 5-carbon sugar, RuBP (ribulose-1,5-biphosphate) and either CO_2 or O_2. The first stable products of C_3 carbon fixation are two molecules of PGA (a 3-carbon compound, 3-phosphoglycerate); the first stable products of photorespiration are one molecule of PGA and one molecule of PG (a 2-carbon compound, 2-phosphoglycolate). High-energy compounds ATP and NADPH, generated from photosynthesis, drive these reactions. As atmospheric CO_2 increases, there is an initial increase in C_3 carbon fixation (and sugar productivity), while photorespiration is inhibited. We have shown that inhibiting photorespiration diminishes nitrate assimilation. In plants that depend on nitrate as a nitrogen source, this eventually inhibits plant productivity and lowers protein content. Nitrogen is part of the amino groups essential to all proteins, and proteins include the enzymes that facilitate biochemical reactions. Source: Bloom 2009.

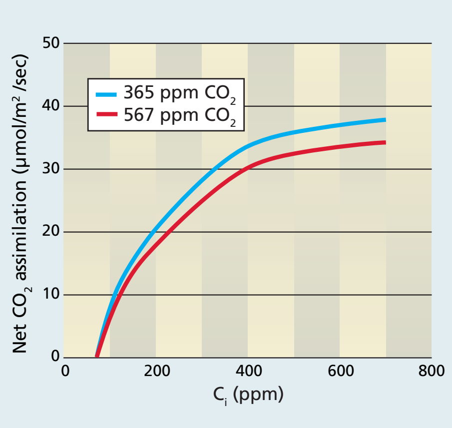


Fig. 3. Net carbon dioxide assimilation (photosynthesis) as a function of carbon dioxide concentrations within a leaf (C_i) for C_3 plants grown at either ambient (365 parts per million [ppm]) or elevated (567 ppm) atmospheric carbon dioxide concentrations, in free air CO_2 enrichment (FACE) plots, where plants growing in soil under the open sky are exposed to elevated carbon dioxide. Mean of 285 studies (Ainsworth and Rogers 2007).

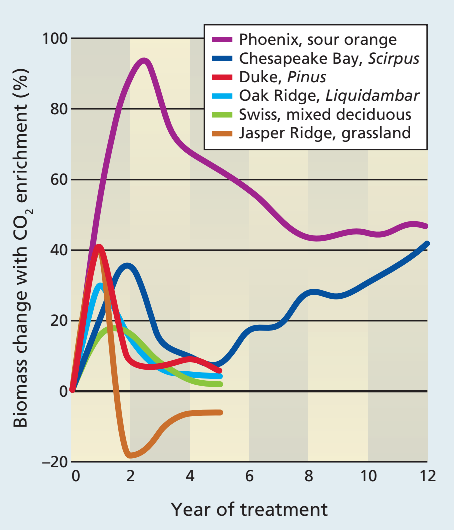


Fig. 4. Each line shows change in biomass over time for specific plants grown at elevated (567 ppm) and ambient (365 ppm) carbon dioxide atmospheres, in free air CO_2 enrichment (FACE) plots (Dukes et al. 2005; Korner 2006) and open-top chambers (Rasse et al. 2005; Kimball et al. 2007).

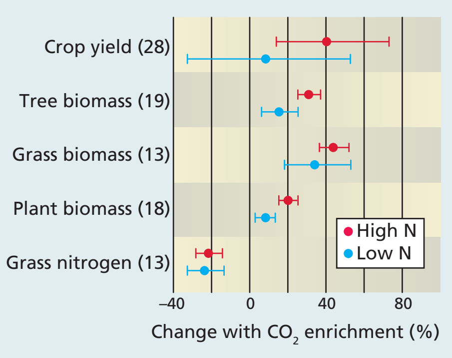


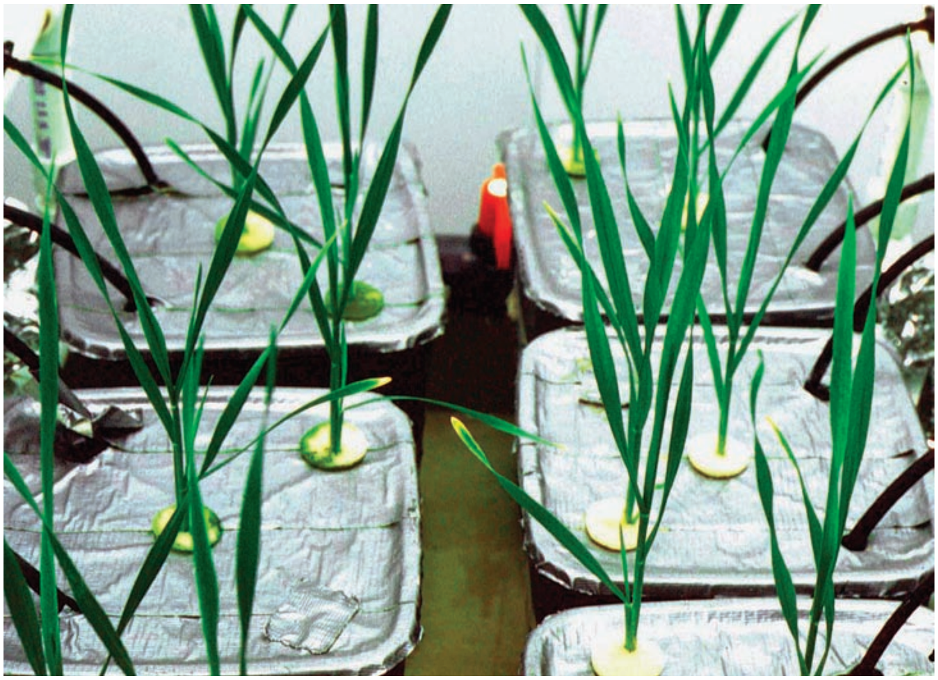
Fig. 5. Differences in yield, aboveground biomass, leaf nitrogen (N) concentrations and grain protein concentrations between C_3 plants grown at elevated (567 ppm) and ambient (366 ppm) carbon dioxide concentrations under heavy (high N) and normal N fertilization (low N). Symbols and error bars designate means ± 95% confidence interval for crops (Ainsworth and Long 2005), trees (Curtis and Wang 1998), grasses (Wand et al. 1999), all plant species (de Graaff et al. 2006) and grain protein (Taub et al. 2008). Parentheses contain number of studies included in the meta-analysis.

2-carbon compound (2-phosphoglycolate), and subsequently releases carbon dioxide, hence the names C_2 pathway or, more commonly, photorespiration. In total, photorespiration consumes biochemical energy, but does not result in any net production of sugar (Foyer et al. 2009). Thus, photorespiration has been viewed as a wasteful process, a vestige of the high carbon dioxide atmospheres (over 1,000 ppm) under which plants evolved (Wingler et al. 2000).

The balance between C_3 carbon fixation and photorespiration depends on the relative amounts of carbon dioxide and oxygen entering the active site of rubisco (i.e., portion of the enzyme involved in the primary chemical reactions) and the affinity of the enzyme for each gas (i.e., degree to which it attracts carbon dioxide or oxygen). At current atmospheric levels of carbon dioxide and oxygen (about 380 and 209,700 ppm, respectively), photorespiration in most crops (C_3 plants including wheat, rice, barley, oats, legumes, vegetables, and fruit and nut trees) dissipates over a quarter of the organic carbon produced during carbon dioxide assimilation (conversion from inorganic to organic form) (Sharkey 1988).

In contrast, C_4 crops (such as corn, sorghum and sugar cane), which have a metabolic carbon dioxide pump that increases the concentration of this compound at the catalytic site of rubisco, minimize photorespiration at the expense of the additional energy required for pumping.

Elevated levels of atmospheric carbon dioxide inhibit photorespiration in C_3 plants, making photosynthesis more efficient. Initially, this accelerates both their photosynthetic carbon dioxide assimilation and their growth by about a third. After a few days or weeks, however, carbon dioxide assimilation and growth both slow down until they are accelerated in the long term by only about 12% and 8%, respectively (figs. 3 and 4). Moreover, leaf nitrogen and protein concentrations ultimately decrease more than 12% under carbon dioxide enrichment (fig. 5). Such a loss of nitrogen and protein significantly diminishes the value of this plant material as food for animals and humans.



Wheat was grown in a controlled environmental chamber at elevated carbon dioxide (700 ppm). Plants in the three containers on the left received ammonium (NH_4^+) as the sole nitrogen source, whereas those on the right received nitrate (NO_3^-). Plants grown at ambient carbon dioxide under ammonium and nitrate nutrition were indistinguishable (not shown).

Together these trends are known as carbon dioxide acclimation.

CO_2 acclimation hypotheses

Several hypotheses have been put forward to explain carbon dioxide acclimation.

Carbohydrate sink limitation. According to this hypothesis, plants under carbon dioxide enrichment initially assimilate more carbon dioxide into carbohydrates than they can incorporate into their growing tissues. In response, they diminish carbon dioxide assimilation by decreasing their rubisco levels (Long et al. 2004). This change in rubisco levels, however, is not necessarily selective; the decrease may instead just be part of the overall decline in protein and nitrogen concentrations (Ainsworth and Long 2005; Makino and Mae 1999).

Progressive nitrogen limitation. Another hypothesis for carbon dioxide acclimation is that shoots accumulate carbohydrates faster than roots can absorb nitrogen from soils, making leaf nitrogen concentrations decrease (Hungate et al. 2003; Luo et al. 2004; Norby et al. 2001; Reich et al. 2006). As these leaves senesce and drop to the ground, (1) plant litter quality declines, (2) microbial immobilization of soil nitrogen increases because of the high carbon-to-nitrogen ratios in the litter, (3) soil nitrogen availability to plants further diminishes because more soil nitrogen is tied up in microorganisms, (4) plants become even more nitrogen limited, (5) plant protein levels decline

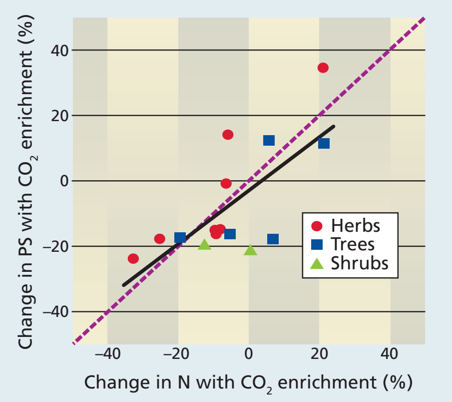


Fig. 6. Differences in leaf carbon fixation capacity (photosynthesis [PS]) versus total nitrogen concentration (N) between C_3 plants grown at elevated (567 ppm) and ambient (366 ppm) carbon dioxide concentrations. Each symbol designates the mean ratio for a species. Shown are the regression line (solid, slope = 0.815, $r = 0.71$) and 1:1 line (dotted). This data suggests that changes in photosynthesis from carbon dioxide enrichment derive from changes in plant nitrogen levels under carbon dioxide enrichment (Ellsworth et al. 2004).

and (6) plant processes including photosynthesis slow down (fig. 6). This hypothesis, however, has difficulty in explaining the variation in carbon dioxide acclimation among sites (Finzi et al. 2007) and among methods of carbon dioxide enrichment (Ainsworth and Long 2005).

Role of photorespiration

We have discovered another explanation for carbon dioxide acclimation: in C_3 plants, shoot assimilation of nitrate into organic nitrogen compounds depends on photorespiration, so any condition that inhibits photorespiration (elevated carbon dioxide or low oxygen concentrations) also inhibits shoot nitrate assimilation (figs. 7 and 8). Thus, at elevated carbon dioxide concentrations, C_3 plants that rely on nitrate as a nitrogen source suffer severe deprivation of organic nitrogen compounds such as proteins. The resulting decline in organic nitrogen compounds reduces the plants' yield and biomass production. While high applications of nitrogen fertilizer may partially compensate for this, the plants' nitrogen and protein concentrations still diminish (fig. 5).

Ammonium and nitrate are the two main sources of nitrogen that are accessible to plants from the soil. Plants show a wide range of responses to carbon dioxide enrichment because the balance between nitrate and ammonium availability varies over seasons, years, locations and plant species. In an annual California grassland where nitrate was the predominant nitrogen source, net primary productivity diminished under carbon dioxide enrichment (fig. 4) (Dukes et al. 2005). This was presumably because elevated carbon dioxide inhibited plant nitrate assimilation (by both shoots and roots), and the grasses became deprived of organic nitrogen. In contrast, ammonium is the major form of nitrogen available to plants in marshes because wet, anaerobic soils promote denitrification (the conversion of nitrate into nitrous oxide and dinitrogen gas) and nitrate leaching (the removal of dissolved nitrate into deep groundwater or surface water). For example, the dominant C_3 plant in the Chesapeake Bay marsh (*Scirpus olneyi*) showed little carbon dioxide acclimation (fig. 4); even after a decade of treatment, photosynthesis and growth remained about 35% greater under carbon dioxide enrichment (Rasse et al. 2005), with little change in nitrogen concentrations (Erickson et al. 2007). In wheat, another C_3 plant, elevated carbon dioxide atmospheres stimulated less growth under nitrate than under ammonium nutrition (fig. 9; see photo, page 69).

Physiological mechanisms

Several physiological mechanisms appear to be responsible for the dependency of nitrate assimilation on photorespiration.

First, the initial biochemical step of nitrate assimilation is the conversion of nitrate to nitrite in leaves. This step is powered by the high-energy compound NADH (reduced nicotinamide adenine dinucleotide), and photorespi-

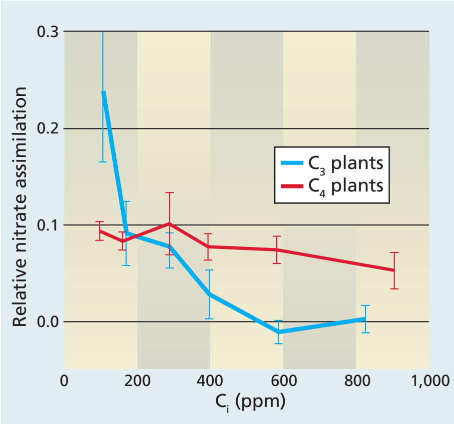


Fig. 7. Response of nitrate (NO_3^-) assimilation in C_3 and C_4 plants as a function of carbon dioxide concentrations inside a leaf (C_i). Relative NO_3^- assimilation was assessed from changes in CO_2-O_2 fluxes with a shift from NH_4^+ to NO_3^- nutrition (ΔAQ). The C_3 species included barley (Bloom et al. 1989), wheat (Bloom et al. 2002), tomato (Searles and Bloom 2003), Arabidopsis (Rachmilevitch et al. 2004) and *Flaveria pringlei* and giant redwood (Bloom, unpublished data). The C_4 species included maize (Cousins and Bloom 2003, 2004) and *Flaveria bidentis* and *Amaranthus retroflexus* (Bloom, unpublished data).

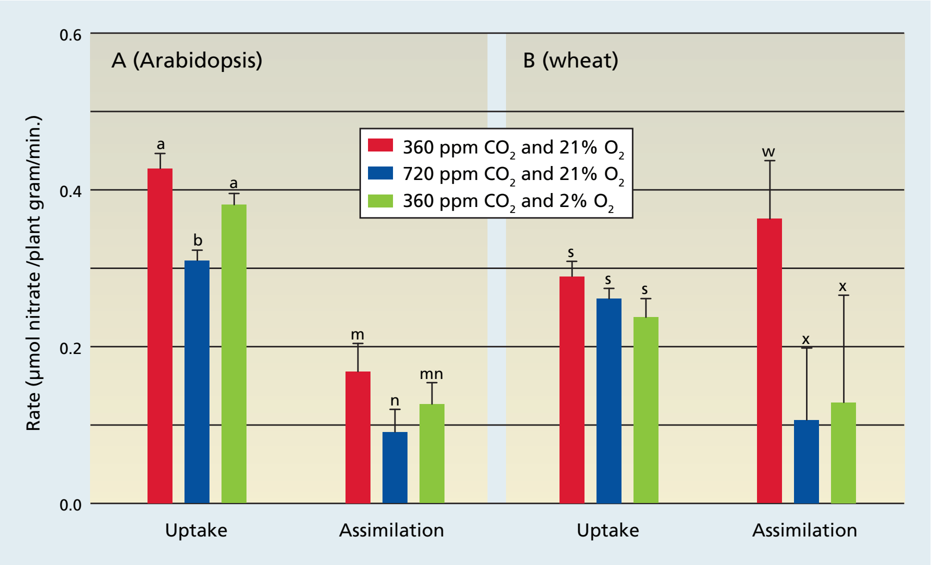
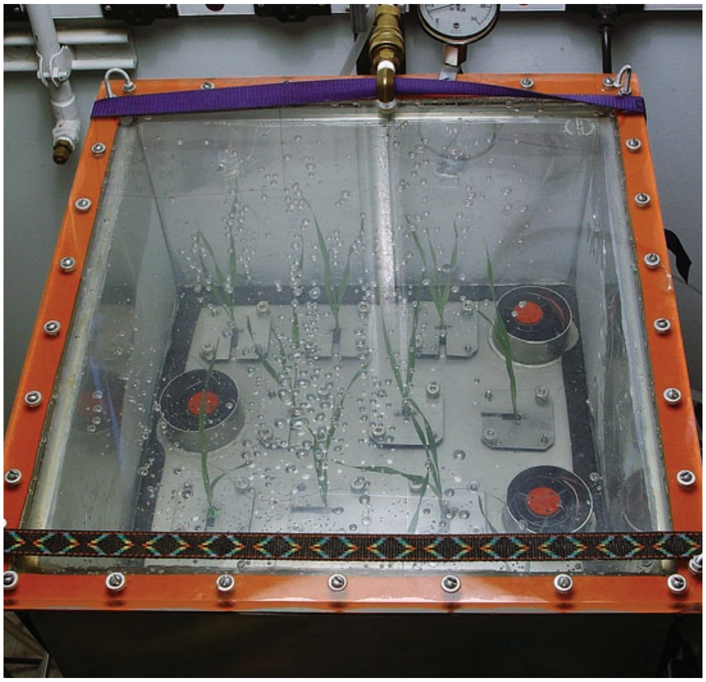


Fig. 8. Nitrate (NO_3^-) uptake as the amount of NO_3^- depleted from a medium, and nitrate assimilation as the difference between the rates of net NO_3^- uptake and net accumulation of free NO_3^- in plant tissues: (A) 36-day-old Arabidopsis or (B) 10-day-old wheat were exposed to 360 ppm carbon dioxide (CO_2) and 21% O_2, 720 ppm carbon dioxide and 21% O_2, or 360 ppm CO_2 and 2% O_2. Shown are the mean ± SE (n = 13–16). Treatments labeled with different letters differ significantly ($P \leq 0.05$). Light levels were 500 and 1,000 micromoles of quanta per meter squared per second for Arabidopsis and wheat, respectively (Rachmilevitch et al. 2004).

Environmental chambers in the UC Davis Controlled Environment Facility are helping scientists to understand how plants react to changes in atmospheric carbon, oxygen and other greenhouse gases.



Twelve wheat seedlings were subject to atmospheres containing various concentrations of carbon dioxide and oxygen. The bubbles are a thin water layer that lines the top of the chamber to control its temperature.

ration increases the availability of this compound (Backhausen et al. 1998; Igamberdiev et al. 2001). In contrast, C_4 plants generate ample amounts of NADH in leaves via a different biochemical pathway. This explains why shoot nitrate assimilation is relatively independent of carbon dioxide concentrations in C_4 plants (fig. 7).

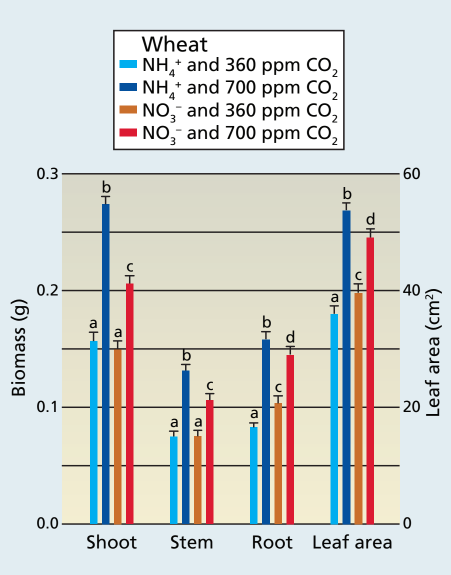


Fig. 9. Biomass (grams dry mass) and leaf area (cm^2) per plant of wheat seedlings grown for 14 days in controlled environment chambers at 360 or 700 ppm carbon dioxide and under NH_4+ or NO_3^- nutrition. Shown are mean ± SE for four replicate experiments, each with 8 to 10 plants per treatment. Treatments labeled with different letters differ significantly ($P < 0.05$) (Bloom et al. 2002).

Second, the subsequent biochemical step of nitrate assimilation is the conversion of nitrite to ammonium in the chloroplasts of leaf cells, which requires the transport of nitrite into the chloroplast. Elevated carbon dioxide inhibits this transport (Bloom et al. 2002).

Third, this subsequent step also requires chemical energy from the oxidation of a different high-energy compound called ferredoxin. Several other processes — in particular, carbon dioxide assimilation — depend on the same energy source and seem to have priority in using it. Ferredoxin becomes involved in nitrate assimilation only when carbon dioxide availability limits C_3 photosynthesis (Backhausen et al. 2000; Peirson and Elliott 1988).

Carbon dioxide and food quality

Many crops in California depend on nitrate as their primary nitrogen source. As atmospheric carbon dioxide concentrations rise and nitrate assimilation diminishes, these crops will be depleted of organic nitrogen, including protein, and food quality will suffer (Taub et al. 2008). Wheat, rice and potato provide 21%, 14% and 2%, respectively, of protein in the human diet (FAOSTAT 2007). At elevated carbon dioxide and standard fertilizer levels, wheat had 10% less grain protein (Fangmeier et al. 1999; Kimball et al. 2001). Similarly, grain protein in rice (Terao et al. 2005) and tuber nitrogen in potato (Fangmeier et al. 2002) declined by about 10% at elevated carbon dioxide concentrations.

Several approaches could mitigate these declines in food quality under carbon dioxide enrichment. Increased yields may compensate to some degree for total protein harvested (fig. 5). Several-fold increases in nitrogen fertilization could eliminate declines in food quality (Kimball et al. 2001), but such fertilization rates would not be economically or environmentally feasible given the anticipated higher fertilizer prices and stricter regulations on nitrate leaching and nitrous oxide emissions. Greater reliance on ammonium fertilizers and inhibitors of nitrification (microbial conversion of ammonium to nitrate) might counteract food quality decreases. Nevertheless, the widespread adoption of such practices would require sophisticated management to avoid ammonium toxicity, which occurs when plants absorb more of this compound than they can assimilate into amino acids and free ammonium then accumulates in their tissues (Epstein and Bloom 2005).

Several of these issues might be simultaneously addressed by fertigation, or frequent additions of small amounts of ammonium-based fertilizers in water delivered through microirrigation.

These findings have broad implications for the future of plant distributions and food production. Enriched carbon dioxide atmospheres will not enhance the performance of C_3 plants to the extent originally envisioned. A 10% decline in food protein content will further burden regions of the world already affected by hunger. With a better understanding of ammonium and nitrate use by crops and careful nitrogen management, we can turn these phenomena to our advantage.

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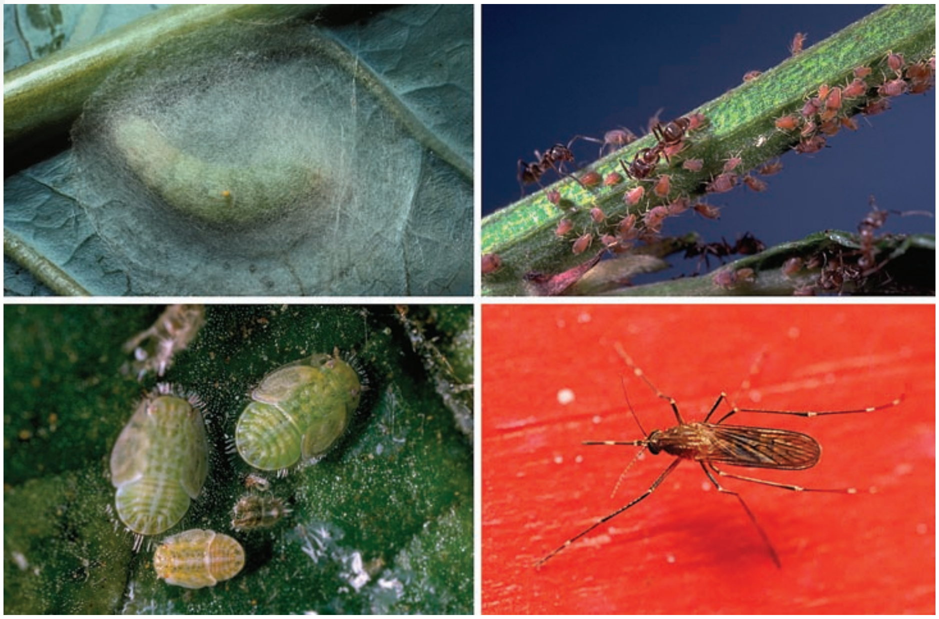
REVIEW ARTICLE

Climate change will exacerbate California's insect pest problems

by John T. Trumble *and* Casey D. Butler

The elevated carbon dioxide concentrations and increasing temperatures associated with climate change will have substantial impacts on plant-insect interactions, integrated pest management programs and the movement of nonnative insect species into California. Natural ecosystems will also be affected by the expected changes in insect diversity. Many insects will alter how much they eat in response to changing plant nutrition. Also, we can expect increased problems with many pest insects as they develop more rapidly in response to rising temperatures. If we hope to maintain sustainable agro-ecosystems and preserve native species in our natural ecosystems, we need to begin preparing now for the challenges of our changing environment.



Franklin F. Laemmlen

Jack Kelly Clark

Jack Kelly Clark

Kathy Keatley Garvey

Climate change will fundamentally alter our relationship with pest insects. *Top left*, the cabbage looper ate 20% more leaf area when lima beans were grown at high carbon-dioxide concentrations. *Top right*, Argentine ants (shown tending aphids) out-compete native ants at higher temperatures. *Bottom left*, the potato psyllid did not establish itself on earlier attempts, but its 1999–2000 migration into California was successful. *Bottom right*, mosquitoes, which carry dengue fever and malaria, emerge smaller when they breed in warmer water and must blood-feed more frequently.

Climate change is occurring. While some people may find controversy regarding the cause, there is no doubt that carbon dioxide levels, temperatures and ultraviolet levels are increasing (IPCC 2007). Most global climate models predict that rainfall patterns will change and that storms will increase in severity (Hadley Centre 2007). The cumulative effects of these changes on plants and insects in California's agricultural and natural ecosystems are likely to be substantial.

Rising carbon dioxide will increase the carbon-to-nitrogen balance in plants, which in turn will affect insect feeding, concentrations of defensive chemicals in plants, compensation responses by plants to insect herbivory, and competition between pest species (Coviella and Trumble 1999). Temperature increases already have caused changes in species diversity and distribution. For example, the mountain pine beetle, a major forest pest in the United States and Canada, has extended its range northward by approximately 186 miles (300 kilometers) with the temperature increase of approximately 3.5°F (1.9°C) (Logan and Powell 2001). Additional changes in climatic boundaries and agro-ecosystem borders will have significant implications not only for the population dynamics of native pests, but also for the occurrence and severity of invasive species (Bale et al. 2002). Even patterns of outbreaks for arthropod pathogens such as fungi are expected to vary (Stacey and Fellowes 2002). Arthropod-borne human diseases such as dengue and malaria will likely increase (Juliano and Lounibos 2005).

By some estimates, agricultural productivity in Africa, Asia and Latin America is expected to decrease by as much as 20%, with less developed countries suffering the greatest negative effects (IPCC 2007). In California, we can expect that current insect pests will extend their ranges into new areas, and that a variety of new insect pests will appear. All of these climate-driven changes present challenges and opportunities for sustainable agricultural programs based on integrated pest management (IPM). If California's food production is to keep pace with growing demand, we will need new cultivars, major changes in IPM programs, increased funding and improved response times to new pest outbreaks.

In this brief review we cannot cover all of the potential impacts of climate change. We will not discuss the predicted changes in rainfall, which are rather variable and entail an increase for Northern California and a decrease for Southern California (Hadley Centre 2007). Also, while the interactions of droughts, increasing temperatures, storms and other possible factors are likely to be important, space limitations preclude a detailed analysis. We focus instead on the two major climate-change variables that have the strongest documentation: increasing levels of atmospheric carbon dioxide and increasing temperatures.

Elevated carbon dioxide

One of the most studied aspects of climate change is the effect of increasing concentrations of carbon dioxide

TABLE 1. Examples of how increasing atmospheric carbon dioxide affects plant-insect interactions

Increasing atmospheric carbon dioxide leads to:	Reference
Increasing . . .	
Food consumption by caterpillars	Osbrink et al. 1987
Reproduction of aphids	Bezemer et al. 1999
Predation by lady beetle	Chen et al. 2005
Carbon-based plant defenses	Coviella and Trumble 1999
Effects of foliar applications of *B. thuringiensis*	Coviella and Trumble 2000
Decreasing . . .	
Insect developmental rates	Osbrink et al. 1987
Response to alarm pheromones by aphids	Awmack et al. 1997
Parasitism	Roth and Lindroth 1995
Effects of transgenic *B. thuringiensis*	Coviella et al. 2000
Nitrogen-based plant defenses	Coviella and Trumble 1999

on plants (table 1). Plants consist primarily of carbon, and elevated carbon dioxide levels allow them to grow more rapidly because they can assimilate carbon more quickly. Greenhouse growers have known this for decades, and many add carbon dioxide to encourage plant growth.

Similarly, because carbon dioxide increases the photosynthetic rates of most crop plants, scientists initially thought that increasing carbon dioxide would be a panacea for the world's food supply (LaMarche et al. 1984). In addition to growing more quickly, many crop plants would become more drought-tolerant. This is because the openings in the leaves (stomata) that let carbon dioxide in also let water vapor out, and if there is more carbon dioxide, then the stomata do not need to be open as much.

Crop yields. Under conditions of elevated carbon dioxide, LaMarche et al. (1984) suggested that the bigger, more drought-tolerant plants which developed would be expected to produce better yields even when conditions are harsh. Unfortunately, this optimistic prediction has not proven accurate. One reason that yields have not increased is that insects also eat more when plants are grown in elevated levels of carbon dioxide. Early research in California demonstrated that while lima beans (*Phaseolus lunatus*) did photosynthesize better and grow more rapidly in higher concentrations of carbon dioxide, their primary pest, the cabbage looper (*Trichoplusia ni*), also ate about 20% more leaf area (fig. 1).

This occurred because the leaves contained about 28% less nitrogen in comparison to plants grown in ambient levels of carbon dioxide. Insects are animals that must have nitrogen to develop. Because there was less nitrogen in the leaves grown in elevated levels of carbon dioxide, the cabbage loopers' response was to eat more leaf area in order to get the same amount of this critical nutrient. This effect of increased feeding has now been shown for many insect groups such as butterflies, beetles, moths and grasshoppers (Coviella and Trumble 1999). Other possible reasons for a lack of accelerated crop growth include an adaptation to elevated carbon dioxide that slows photosynthesis (Hollinger 1987) and evidence that increased temperatures will reduce the productivity of plants in tropical and subtropical climates (IPCC 2007).

Plant defenses. This abundance of carbon and shortage of nitrogen leads to other major changes in the plant that can further affect insects. Many plants have two types of chemical defenses that reduce or stop insect feeding. One group is carbon-based compounds (such as phenolics and tannins) that tend to slow insect growth, often by binding with proteins to reduce the insect's ability to digest the food. Cotton is a good example of a plant with phenolics that can reduce insect feeding. Elevated carbon dioxide levels allow many plant species to greatly increase their carbon-based defenses.

A second group of common plant defenses is nitrogen-based compounds (such as alkaloids and cyanogenic glycosides) that either act as toxins and kill the insects or act as repellents and make the plants unpalatable. For example, potatoes and plums are plants containing defensive compounds based on nitrogen. Elevated carbon dioxide levels often reduce concentrations of these nitrogen-based defenses.

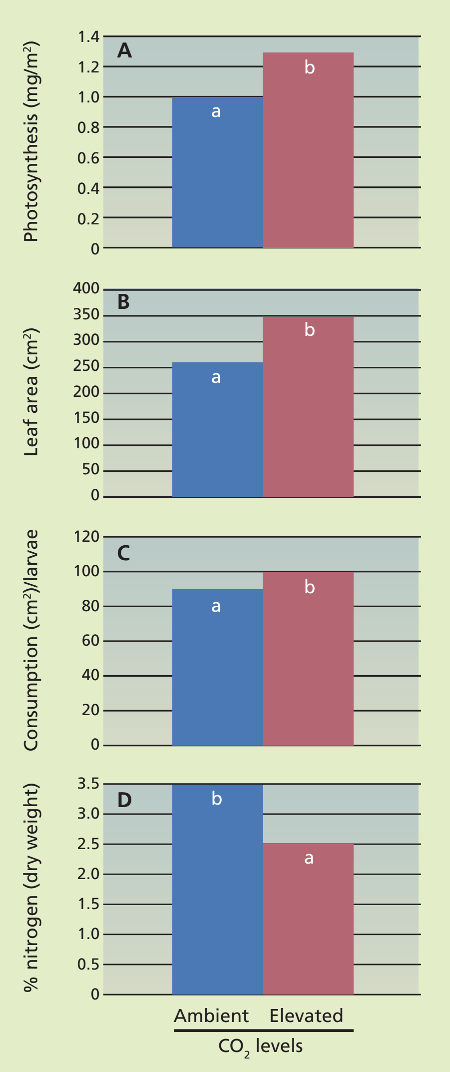


Fig. 1. (A) Photosynthetic activity, (B) leaf area, (C) leaf area consumption by cabbage looper larvae and (D) nitrogen content of lima bean plants grown in elevated (900 ppm) and ambient (385 ppm) carbon dioxide (Osbrink et al. 1987). Different letters above bars indicate significantly different values ($P < 0.05$).

The trade-off between carbon- and nitrogen-based plant defenses will have many potentially far-reaching effects on insect feeding. In natural ecosystems that have limited nitrogen availability, plants may have lower levels of nitrogen-based toxins and so be subject to greater insect damage. In agricultural systems, however, growers typically manipulate the availability of nitrogen, which can affect the concentrations of these defensive compounds. For example, when cotton plants were grown with 2.5 times the normal amount of nitrogen fertilizer, the concentrations of carbon-based defenses dropped dramatically (fig. 2).

Transgenic plants and insecticides. Interestingly, such changes have important implications for the use of certain transgenic plants that are resistant to insects. Currently, the most commonly used genetic modification in corn and cotton is the addition of proteins from the bacterium *Bacillus thuringiensis* (Bt). These proteins are nitrogen-based defenses that have a major impact on several common insect pests, greatly reducing yield losses. In our studies, growing these transgenic plants in elevated carbon dioxide resulted in a nearly 25% reduction of the expression of these proteins (fig. 3). This reduction allowed some beet armyworms (*Spodoptera exigua*) to survive on these plants, which would likely lead to the rapid selection of pest populations resistant to these proteins.

Again, growers can overcome this effect by adding additional nitrogen. However, this is an expensive proposition and may also increase the nitrogen runoff from fields, causing problems for adjacent aquatic systems. Because most commercial fertilizers are manufactured from petroleum, an increase in nitrogen use would also cause an undesirable increase in carbon dioxide released into the atmosphere. We suspect that new methods of making transgenic plants, such as linking expression to mitochondria, ultimately will be employed to overcome this problem.

In contrast to insect-resistant transgenic plants, some insecticides that are applied to plant foliage will likely work better in elevated carbon dioxide. As noted earlier, insects eat more leaf area when plants are grown in elevated carbon dioxide. This means that chewing insects that eat more would get a larger dose of any toxin on the plant. We tested this hypothesis with spray applications of an organically acceptable *B. thuringiensis* preparation, many of which are widely available. Not surprisingly, the insects that ate more leaf area received a greater dose of the toxin and died significantly faster and in higher numbers (Coviella and Trumble 2000). Thus, the selection of pesticides that act as stomach poisons may become an increasingly important strategy for insect control as carbon dioxide levels rise.

Increased temperatures

Temperatures in most regions of the world are increasing, and there are already indications that insects and plants are responding (table 2, page 76). These temperatures are not just the result of warmer summer days but also of fewer cold days, cold nights and frosts (IPCC 2007). In coastal California, average temperatures are predicted to increase by up to 10°F (5°C) inland and 5°F (2.5°C) along the coast in this century (Hadley Centre 2007). In California, we should plan on: (1) the range expansions of insects that are already here, (2) the arrival of more

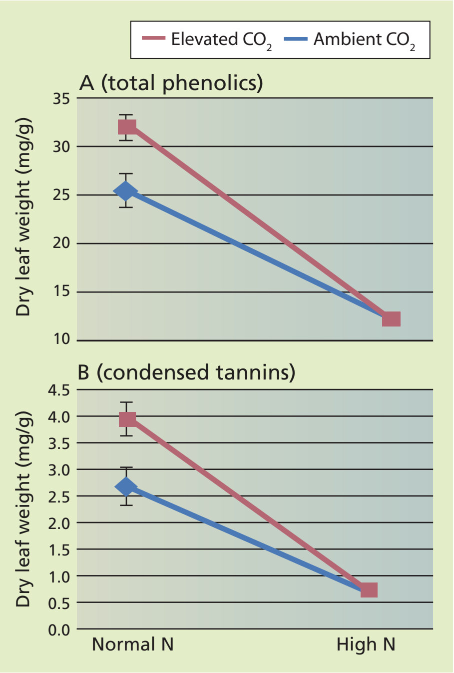


Fig. 2. Increased nitrogen (N) fertilization led to reduced production of carbon-based defensive compounds in cotton grown in elevated (900 ppm) versus ambient (385 ppm) carbon dioxide for (A) total phenolics and (B) condensed tannins (Coviella et al. 2002). Values are significantly different at normal nitrogen fertilization levels. Data are presented as interaction plots following a 2x2 factorial ANOVA with least square means tables calculated for all significant interactions.

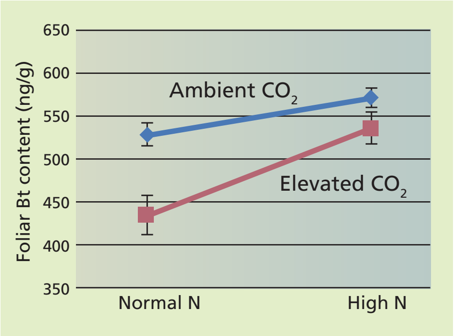


Fig. 3. Interactions of ambient (385 ppm) and elevated (900 ppm) carbon dioxide and nitrogen fertilization on expression of *Bacillus thuringiensis* (Bt) proteins in cotton (ng/g = nanograms/gram) (Coviella et al. 2000). Values for foliar Bt content are significantly different for normal (1×) and high (2×) nitrogen fertilization levels. Data are presented as an interaction plot following a 2×2 factorial ANOVA with contrast analyses calculated for all significant interactions.

Carlos Coviella

Plants grown at elevated carbon dioxide have lower nitrogen levels in the leaves, so insects must eat more to get the same amount of nutrient. In this chamber study, insects eating plants treated with *Bacillus thuringiensis* received a higher dose of the toxin as well, and died at significantly higher rates.

new insect pests and (3) changes in ecosystems that will allow some insect species to reach dramatic new population levels while forcing other species into extinction.

Range expansion. In the Northern Hemisphere, insect populations are already migrating northward. Even though regional temperatures have increased by only 3°F to 4°F (2°C) in the past 25 years, rather dramatic shifts of 185 miles in range have been reported for the green stinkbug (*Acrosternum hilare*) in England and Japan. Likewise, the Edith's checkerspot butterfly (*Euphydryas editha*) is expanding its population northward in the United States while declining at the southern end of its range in Mexico (Parmesan 2006). In the past 15 years, the mountain pine beetle (*Dendroctonus ponderosae*), a destructive pest of pine trees, has extended its range more than 180 miles northward (Logan and Powell 2001). This movement has allowed adults at the northern extent of the beetles' range to cross through Pine Pass to reach the east side of the Rocky Mountains. These migrations are not unexpected, as similar range shifts have been observed in the fossil insect record when climatic conditions changed (Elias 1994).

One reason for such range expansions is a change in frost patterns (Fleming and Volney 1995; IPCC 2007). As temperatures increase, the frequency of spring frosts declines and the resulting extended frost-free periods increase the duration and intensity of insect outbreaks. Growers can also be expected to take advantage of the changing climate by planting earlier. These plants will then be available for crop-infesting insects, allowing insect populations to get an even quicker start and potentially add additional generations during a typical growing season. For many crop pests, this means much bigger populations by the end of the season. For these reasons, the Intergovernmental Panel on Climate Change (a scientific body set up by the World Meteorological Organization and the United Nations Environment Program) lists increasing insect outbreaks as "virtually certain" (IPCC 2007).

New pests. New insect species arrive frequently in California, primarily due to the rapid movement of people and goods. However, increasingly warmer temperatures mean that insects that previously could not survive here can now thrive. For example, while a destructive pest known as the potato psyllid migrated into California on several occasions in the 20th century, those populations usually lasted only for a year. Cool temperatures during the winter forced this insect to retreat to Mexico and the southernmost tip of Texas. However, the potato psyllid migrated into California again in 1999 or 2000, and has since established large, year-round populations as far north as Ventura County that have persisted for the last 7 years. The tomato, potato and pepper industries have suffered substantial losses as a result (Liu and Trumble 2007).

Ecosystem changes. Warmer temperatures will benefit some insect species over others. In our studies, even a 5°F to 6°F (3°C) increase in average summer temperatures in Southern California would reduce offspring production by about 90% for an important beneficial wasp, the common parasite *Cotesia marginiventris* (C.D. Butler and J.T. Trumble, unpublished data). This seemingly minor temperature increase is therefore likely to eliminate populations of this parasite in many interior valleys. The loss of this insect could lead to increased damage from some caterpillar species, and would likely result in increased pesticide applications.

Because insect development is more rapid at higher temperatures, populations will develop faster and crop damage will occur more rapidly than currently expected.

On the other hand, higher temperatures will favor some agricultural and urban pests. Argentine ants (*Linepithema humile*), which have already expanded throughout Southern and Central California, are better competitors against native ant species at higher temperatures (Dukes and Mooney 1999). As temperatures rise, this pest will likely spread farther north, displacing more native ant species. The spruce budworm (*Choristoneura fumiferana*) will also benefit from warmer temperatures. The number of eggs laid by this pest of conifers is 50% greater at 77°F (25°C) than at 59°F (15°C) (Regniere 1983). In addition, higher temperatures can shift the timing of reproduction in spruce

TABLE 2. Examples of how increasing temperatures affect arthropod species and arthropod-related systems

Increasing atmospheric carbon dioxide leads to:	Reference
Increasing . . .	
Northward migration	Parmesan 2006
Migration up elevation gradients	Epstein et al. 1998
Insect developmental rates and oviposition	Regniere 1983
Potential for insect outbreaks	Bale et al. 2002
Invasive species introductions	Dukes and Mooney 1999
Insect extinctions	Thomas et al. 2004
Occurrence of human and animal diseases	Juliano and Lounibos 2005; Patz et al. 2003
Decreasing . . .	
Effectiveness of insect biocontrol by fungi	Stacy and Fellowes 2002
Reliability of economic threshold levels	Predicted in this paper
Insect diversity in ecosystems	Erasmus et al. 2002
Parasitism	Hance et al. 2007; Fleming and Volney 1995


Jack Kelly Clark

In a warmer environment, frost may be eliminated entirely in some regions, allowing certain insect pests to breed year-round. *Above*, frost damage to pear.

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The mountain pine beetle (inset) has dramatically increased its range over the past 15 years, causing extensive damage to British Columbian pine forests (shown); in recent years, it has spread east across the Rocky Mountains.

budworms so that they may no longer be affected by the parasitoids that usually keep populations down (Fleming and Volney 1995).

Thus, the potential for damaging insect pest outbreaks can be expected to increase as temperatures climb. These outbreaks can lead to substantial ecosystemwide changes in carbon and nitrogen cycling, biomass decomposition and energy flows (Haack and Byler 1993). For example, outbreaks that lead to defoliation or premature leaf drop by plants would change the typical nutritional composition of leaf litter, thereby affecting the success of organisms that decompose decaying biomass. The long-term effects of changes at such fundamental levels are difficult to predict with the available research knowledge.

Another logical outcome of increasing temperatures is an increase in the occurrence and intensity of forest fires. In some cases, particularly when higher temperatures occur along with droughts, trees become more susceptible to insect attack. This effect was seen early in this century in Southern California, with the thousands of acres of trees dead from bark beetle attacks fueling huge forest fires. Some species are attracted to fire-damaged trees, and these insects can be expected to reach exceptional populations if their food resources continue to increase.

Preparing for climate change

Modifying IPM practices. IPM is the most widely used strategy for insect control in California. This approach generally integrates biological controls (predators, parasites and pathogens), chemical controls (pesticides) and cultural controls (such as resistant crop varieties and planting times) to reduce insects below the population threshold that will cause economic losses. Most researchers and growers try to design IPM programs that maximize economic returns and sustainability while minimizing potential environmental impacts (Trumble 1998). This strategy is based on extensive knowledge of just how many insects can be tolerated before yield losses occur. Researchers and growers have designed and field-tested these programs over many years.

Unfortunately, we predict that scientists and growers will need to modify many of these carefully constructed IPM programs to address several important effects of increasing temperature. Because insect development is more rapid at higher temperatures, populations will develop faster and crop damage will occur more rapidly than currently expected. For example, treatment thresholds based on insects per plant will need to be reduced to prevent unacceptable losses. Those IPM programs that rely on degree-day models may need only minimal modification, unless the control strategies include biological control agents. Reports are already available that even the relatively modest increases in temperature that have occurred to date can reduce the effectiveness of insect pathogens (Stacy and Fellowes 2002). In some cases, increasing temperatures can greatly reduce the pest suppression provided by parasites (Hance et al. 2007). These differences between the thermal tolerances of the host and parasitoid can lead to temporal or geographical separation, resulting in pest outbreaks. For example, the fly *Drosophila simulans* is a suitable host for the wasp *Leptopilina heterotoma* at temperatures between 64°F and 72°F (18°C and 22°C), but becomes a poor host at 79°F (26°C) (Ris et al. 2004).

In addition, increasing temperatures will likely favor insects with multiple generations each year over those with only a single generation (Bale et al. 2002). Due to the increased developmental rate at higher temperatures, such species could add even more generations and so could potentially achieve much higher numbers by the end of the season. A maximum effect can be expected in those regions where increasing temperatures will entirely eliminate frosts, allowing such insects to breed throughout the year. This will permit a variety of new tropical and subtropical insects to expand into these areas. The effects of such diversity changes on our natural, agricultural and urban ecosystems will probably be profound.

Vectors of human pathogens. In particular, most scientists expect that the recent and predicted increases in temperature will have a major impact on medically important insects such as mosquitoes (Juliano and Lounibos 2005). According to the World Health Organization, the expected climate changes will affect insect-borne diseases such as dengue fever and malaria by increasing insect ranges, reproductive rates and biting rates (Patz et al. 2003). In the case of dengue fever, warmer water temperatures at breeding sites reduce the size of emerging adult mosquitoes that subsequently must blood-feed more frequently to develop their eggs.

Also, the infectious agents that cycle through insects are quite susceptible to even subtle temperature variations. The development of the dengue virus inside the mosquito also shortens with higher temperatures, increasing the proportion of mosquitoes that become infectious at a given time. Higher temperatures have also increased the geographic range of the malarial parasite *Plasmodium falciparum*. This parasite is generally limited to the tropics and subtropics because it requires an average temperature above 64°F (16°C) to develop. In the past 5 years, temperature increases have extended the range of malaria to elevated urban areas in Africa that had been free of the disease through recorded history (Epstein et al.

1998). Similarly, much larger portions of the United States now exceed the 64°F (16°C) development threshold, making the important work of mosquito control districts even more critical.

Increased research needs

Researchers will be hard-pressed to deal with the combined effects of climate change. The capabilities of California's agricultural research community will be stretched by changes in pest species composition and developmental rates, the need to modify IPM strategies, the desirability of introducing new biocontrol agents against invasive species, changes in plant resistance and nitrogen use, and the need for new drought-resistant crop cultivars as well as new cropping systems. In addition, substantial research will be needed to guide management efforts to maintain the functionality of natural systems, given the expected northward movement of plant and animal species, the appearance of new invasive and nonnative species, and the likely ecosystem-wide changes in carbon and nitrogen cycling, biomass decomposition and energy flow.

At the same time, human populations in California and the rest of the world are rapidly increasing. Most people live in urban settings and, not surprisingly, do not always have an appreciation for the needs of natural and agricultural ecosystems. In addition, population growth has created exceptional demands for energy, land and water in California, in turn causing conflicts with growers and those who manage protected lands. Unfortunately, this is occurring at a time when we are discovering that reducing costs by outsourcing our food production to other countries does not always produce a safe and nutritious product (Martin and Palmer 2007). The recent discovery that imported eggs, fish and many other food products can contain dangerous levels of melanine serves as an excellent example. The need for additional research to help predict the long-term effects of climate change on agricultural systems is of vital importance to California and the world.

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RESEARCH ARTICLE

Direct measurements improve estimates of dairy greenhouse-gas emissions

by Frank M. Mitloehner, Huawei Sun *and* John F. Karlik

California is the leading dairy state in the United States, producing 21% of the nation's milk supply. The state's highest concentration of dairies is in the San Joaquin Valley, a region that violates federal limits for ozone and particulate matter in the air. Volatile organic compounds and greenhouse-gas emissions from dairies contribute to regional air-quality challenges and also play a role in climate change. We used an environmentally controlled chamber to monitor greenhouse-gas emissions from dairy cattle over a 24-hour period, and we measured the emissions from waste slurry using a simulated dairy waste lagoon. This research helps to quantify emissions from dairies in California and suggests possible approaches for their mitigation.

Holstein dairy cows were housed in an environmental chamber for 24 hours to accurately measure all their emissions of greenhouse gases, including methane and nitrous oxide; the cows were fed a total mixed-ration diet.

Warming of the climate system is unequivocal, according to the Intergovernmental Panel on Climate Change (IPCC 2007). Further, it is more than 95% likely that the observed increase in globally averaged temperatures since the mid-20th century is due to human activity, principally through the observed increases in concentrations of greenhouse gases. In other words, there is less than a 5% probability that this temperature increase is caused by natural climatic processes alone (IPCC 2007). Climate change will affect California in a number of ways, if it has not already.

The three major anthropogenic greenhouse gases are carbon dioxide, methane and nitrous oxide, and agriculture contributes significant amounts of each. The IPCC estimated that globally, agriculture contributed 10% to 12% of anthropogenic carbon dioxide (CO_2), 40% of methane (CH_4) and 60% of nitrous oxide (N_2O) emissions in 2005. Agricultural processes and sources generating greenhouse gases include the burning of fossil fuels, deforestation, rice cultivation, biomass burning, enteric fermentation by ruminants (gas belched from the stomachs of cattle, goats and sheep), the fermentation of animal manure and the application of nitrogenous fertilizers. The livestock industry is estimated to contribute half of total U.S. agricultural greenhouse-gas emissions, with a quarter each coming from ruminant enteric fermentation and animal waste (USDA 2004).

Livestock emissions

Ruminants' enteric fermentation and manure produce both methane and nitrous oxide emissions (Kaspar and Tiedje 1981; IPCC 2007; Jarvis and Pain 1994; Jungbluth et al. 2001; Phetteplace et al. 2001). Considering the global warming potentials of these two greenhouse gases (see box, page 80), methane contributes an estimated three-quarters and nitrous oxide an estimated one-quarter of the total greenhouse-gas emissions in carbon dioxide equivalents from the U.S. livestock industry.

Methane. Dairy cow methane emissions can be affected by factors such as animal feed intake, size and growth rate, milk production and particularly energy (carbohydrate and fat) consumption (Jungbluth et al. 2001). Most California dairies manage animal waste in corrals and flush liquid manure slurry with water into uncovered, anaerobic (oxygen depleted) storage lagoons. Each of these manure methods has different biochemical pathways that result in varied greenhouse-gas emissions rates. For example, corrals (or drylot systems) usually have relatively high nitrous oxide and low

Global warming potential of gases

Greenhouse gases absorb energy (heat) in specific wavelength bands in the infrared, also called thermal infrared or long-wave radiation. These gases include water vapor, ozone, carbon dioxide, methane (natural gas) and nitrous oxide. Water vapor is the most important because of its concentration in the atmosphere, but changes in water vapor concentrations are not responsible for observed climate warming (IPCC 2007). Other greenhouse gases also absorb outgoing long-wave radiation emitted by Earth's surface (blackbody radiation), and play important roles in absorption across certain atmospheric wavebands where water vapor is relatively transparent. Global warming potential (GWP) is an index for comparing the outgoing thermal infrared radiation trapped by a specific gas to that trapped by a reference gas, which is usually carbon dioxide. The atmospheric lifetime of both gases is also taken into account in the global warming potential calculation.

Both high thermal infrared absorbance and long atmospheric lifetime can elevate global warming potential. In greenhouse-gas inventories, the global warming potential of a gas or gas mixture is often expressed as carbon dioxide equivalents (CO_2e). Methane and nitrous oxide have global warming potentials of 21 and 310 carbon dioxide equivalents, respectively, and are therefore important in discussions of climate change, even though their atmospheric concentrations are less than one-hundredth that of carbon dioxide.

Ozone in the lower atmosphere is also a greenhouse gas, although its effects on climate are complex and sensitive for its vertical distribution profile (Finlayson-Pitts and Pitts 2000). Ozone is the principal air pollutant in California air basins with regard to regional air quality. Ozone in the lower atmosphere is produced via reactions of volatile organic compounds and nitrogen oxides, in the presence of sunlight. Volatile organic compounds contain carbon and are found in the gas phase at typical ambient temperatures; they include compounds emitted from both anthropogenic sources (such as motor fuels) and biogenic sources (including green plants and animal agriculture). Nitrogen oxides are a byproduct of high-temperature combustion. Elevated levels of ozone are found where both volatile organic compounds and nitrogen oxide emissions are high, solar intensity is high, an air mass is trapped, and air temperature is high enough to allow rapid chemical reactions. Higher ambient temperatures during the summer, brought about by climate change, will tend to enhance ozone production in the lower atmosphere and provide positive reinforcement for additional temperature increases.

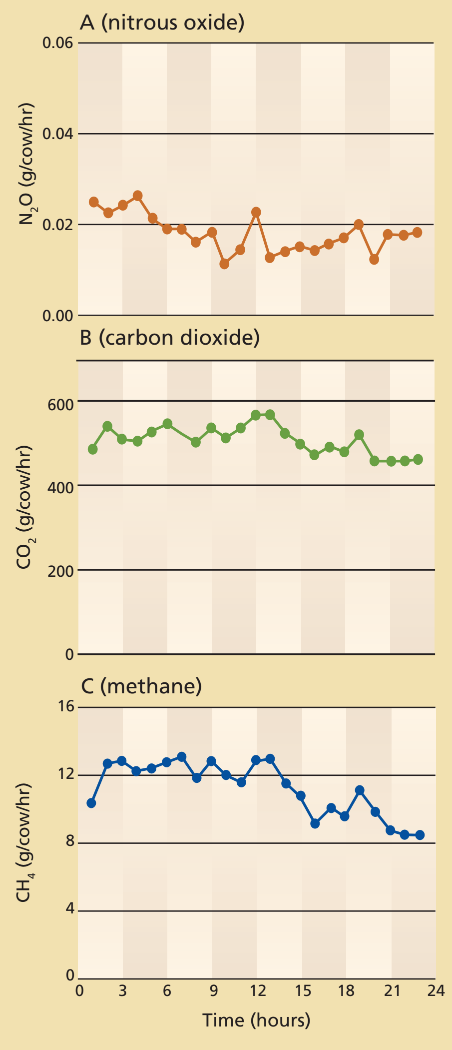

Fig. 1. Greenhouse-gas emissions from Holstein cows (three groups of three cows each; n = 3) housed in an environmental chamber, tested for (A) nitrous oxide (N_2O), (B) carbon dioxide (CO_2) and (C) methane (CH_4) from cows and their fresh waste over 24 hours.

methane emissions, while anaerobic lagoons have low nitrous oxide and variable methane emissions (USDA 2004). Previous studies predicted methane emissions from dairy cows based on their physiology and the animal's feed energy consumption (Holter and Young 1992). Direct measurements of methane emissions from cows and dairy facilities have been made, but rarely under controlled conditions (Kinsman et al. 1995; Jungbluth et al. 2001; Sneath et al. 1997).

Nitrous oxide. The manure of ruminant animals can be a considerable source of nitrous oxide. The production of this gas from dairy waste depends on the waste composition, bacteria involved and conditions following excretion. Mostly, nitrous oxide can be emitted as an intermediate product during nitrification (the aerobic process that forms nitrate from ammonium nitrogen) and denitrification (the anaerobic process that forms nitrogen gas from nitrate). These reactions generally occur in the soil when chemical fertilizers or animal manure nutrients are applied to crops (Groffman et al. 2000). Nitrate reduction (forming nitrogen gas) can occur in the rumen of the cow and then escape during eructation (belching of gas from the first stomach), resulting in the emission of methane and some other gases, including nitrous oxide. However, ruminant animals are considered a small source of nitrous oxide emissions (USDA 2004).

Compared to methane emissions, literature on nitrous oxide emissions from dairy cows is scarce (Jungbluth et al. 2001). Direct measurements of nitrous oxide emissions from dairy facilities range between 0.01 and 0.08 gram of nitrous oxide per livestock unit (1,102 pounds of animal) per hour (Amon et al. 2001; Jungbluth et al. 2001; Sneath et al. 1997).

Anaerobic digestion systems could be one of the best available technologies to reduce greenhouse gas from dairies.

Volatile organic compounds. Livestock also emit volatile organic compounds, such as alcohols, ketones, aldehydes and volatile fatty acids. Volatile organic compounds contribute to ozone formation, which acts as a greenhouse gas in the lower parts of the atmosphere (see box). However, there have been few reports on the emissions rates of volatile organic compounds from dairy cows and waste (Filipy et al. 2006; Rabaud et al. 2003). Miller and Varel (2001) measured alcohol concentrations in both fresh and aged cattle manure slurries under laboratory conditions. Martensson et al. (1999) monitored volatile fatty acids in dairy barns and detected acetic, butyric, lactic and formic acid in the air. With respect to ozone-forming volatile organic compounds, no comprehensive research had been conducted until a recent UC study (Shaw et al. 2007).

Dairy cow emissions

Controlled chamber. In 2008, we used an environmentally controlled chamber at the UC Davis Department of Animal Science to measure greenhouse-gas emissions from lactating dairy cows and their fresh waste (fig. 1). The 185-cubic-yard chamber had one air inlet and one air outlet, and a continuous ventilation rate of 2,930 cubic yards per hour, or a 6-minute air turnover rate at 70°F and 1 atmosphere. We assembled three free-stall beds (rubber-floored individual resting places) so that the cows could rest, to simulate typical dairy free-stall housing conditions. Cows had free access to feed and water. Cow excreta (urine and feces) accumulated on the concrete floor until the chamber was cleaned. The Association for Assessment and Accreditation of Laboratory Animal Care International certified the environmental chamber facility, and the UC Davis Institutional Animal Care and Use Committee approved the project to certify the health and welfare of the animals.

Nine lactating Holstein dairy cows from the UC Davis dairy herd were used for the experiments, in groups of three. The average cow's weight in the study was 1,446 pounds, its dry matter feed intake was 25 pounds per cow per day, and its milk yield was 62 pounds per cow per day. Cows were fed a total mixed-ration diet (table 1).

Background air samples were collected in the empty chamber before the first hour of each 24-hour experimental period to assess baseline greenhouse-gas concentrations in the incoming and outgoing air. After 1 hour of empty chamber measurements, three cows were placed inside. The animals were kept in the chamber for 24 hours, and manure accumulated. The cows were milked with a mobile milking unit both before placement in the chamber and after 10 hours inside the chamber. After 24 hours, the cows were taken out of the chamber.

Emissions fluxes. Nitrous oxide, carbon dioxide and methane emitted from the dairy cows and their fresh excreta were continuously measured using an INNOVA model 1412 Field Gas Monitor (INNOVA AirTech Instrument, Ballerup, Denmark). This gas analyzer can selectively measure up to five component gases and water vapor simultaneously through the use of optical filters. The detection limits of this analyzer were 210 micrograms per cubic meter (µg/m^3) for methane and 39.9 µg/m^3 for nitrous oxide. The greenhouse-gas emissions fluxes were calculated as the concentration difference between the chamber outlet and inlet air streams, multiplied by the constant air flow, as seen in the following equation:

$$E = \frac{\sum_{n} Q \times (C_{out} - C_{in})}{n \times N}$$

where E = gas emission rate from chamber (grams/hour); C_{out} = mass concentration in exhaust air (grams per cubic meter [grams/m^3]); C_{in} = mass concentration in incoming air (grams/m^3); Q = air flow at 68°F (20°C) and 1 atmosphere (m^3/hr); n = total effective measurement numbers; and N = cow numbers.

Greenhouse gases measured

Methane. When cows entered the chamber, methane fluxes immediately increased (fig. 1), indicating that enteric fermentation rather than fresh waste is the main process responsible for production of this gas from cows. After the cows were removed from the chamber, methane fluxes returned to background levels. The mean emissions rate of methane from lactating cows and manure was 11.36 grams per cow per hour. Fresh manure produces negligible methane fluxes, and under commercial conditions it is usually flushed out of the animal housing area into the waste lagoon three times per day on average. As a result, methane emissions from the animal housing components of a dairy can be estimated largely on the basis of animal (enteric) emissions. Several recent reports showed similar flux rates from lactating cow facilities (Kinsman et al. 1995; Sneath et al. 1997).

TABLE 1. Ingredient and chemical composition of cattle diets in controlled chamber study

Item	Diet
	%
Ingredient, as-fed basis	
Grain mix*	37.51
Alfalfa	36.15
Almond hulls	11.97
Whole cottonseed	9.58
Soybean meal	2.08
Minerals	1.6
EnerG II	0.8
Salt	0.32
Component, dry matter (DM) basis	
Acid detergent fiber†	21.6
Neutral detergent fiber	29
Ash	8.4
Nonfiber carbohydrate	41.6
Crude protein	17.2
Calcium	0.9
Phosphorus	0.39
Magnesium	0.33
Potassium	2.06
Sodium	0.43
	ppm
Iron	274
Manganese	63
Zinc	97
Copper	19

* Barley (41.5% DM), corn (41.5% DM), beet pulp (13.8% DM) and tallow (3.2% DM).

† The fraction of indigestible plant material in forage, usually cellulose fiber coated with lignin.

Nitrous oxide. Kaspar and Tiedje (1981) reported that a small quantity of enteric nitrous oxide was emitted from cows. Similarly, we found nitrous oxide emissions of 0.02 gram per cow per hour (fig. 1).

Laboratory-scale reactors were used to test the effectiveness of various manure treatments.

Strategies to reduce methane emissions from dairies include modifying cattle diets to enhance digestibility and improving milk production so that fewer cows are needed.

Volatile organic compounds. In a UC study, Shaw et al. (2007) showed that major volatile organic compounds from cows include methanol. This study also showed that of the volatile organic compounds from cows, the reactive (ozone forming) fraction was 6 to 10 times lower than the value for cows and fresh waste that California regulatory agencies have historically used to develop volatile organic compound inventories for ozone attainment in the San Joaquin Valley. Ozone contributes to global warming and thus all such ozone precursors should be considered in climate-change discussions.

Dairy waste lagoon emissions

To study greenhouse-gas emissions from liquid dairy waste storage, we simulated a column of dairy wastewater in a lagoon with laboratory-scale reactors — devices that support a biologically active environment. These reactors had a cylinder column made of polyvinyl chloride pipe that was 2.7 yards deep and 6 inches in diameter. The total liquid volume in each reactor was 1.3 cubic feet, and the total liquid depth was maintained at 2.33 yards. The reactors were initially seeded with liquid pumped from a commercial dairy wastewater lagoon. The liquid contained 0.41 pound per cubic foot (lb/ft^3) total solids and 0.24 lb/ft^3 volatile solids (organic compounds), and had a pH of 7.4. The reactors were operated according to the design guidelines of anaerobic lagoons for the San Joaquin Valley, with a loading rate of 0.32 pound volatile solids per cubic yard per day and a hydraulic retention time of 70 days.

A mixture of fresh dairy feces and urine was collected directly from lactating cows, and then diluted with fresh water and passed through a screen with 2-millimeter openings to make a manure liquid of 1.0 pound per cubic foot total solids and 0.75 pound per foot volatile solids. The reactors were fed with the manure liquid once a day. The average storage temperature of about 61.7°F (16.5°C) was close to the annual average temperature in the San Joaquin Valley. The headspaces of the reactors were provided with a fresh air-flow at a constant rate of 0.035 cubic foot per minute using compressed air, which was controlled with a mass-flow controller. Concentrations of greenhouse gases at the air inlets and outlets of the reactors were measured using the same INNOVA multigas photoacoustic monitor for 2 days every week. The entire experiment lasted 6 months.

The lagoon-water methane and nitrous oxide emissions were 0.46 ± 0.20 and 0.00095 ± 0.00015 gram per cubic meter per day, respectively. Assuming that a lactating cow produces 150 pounds of manure per day with 17.6 pounds of volatile solids, an average 65.4-cubic-yard lagoon volume is required for storage, based on standards from the American Society of Agricultural and Biological Engineers (ASABE 2005) and USDA (2004). In the present study, approximately 1.22 pounds of methane and 0.002 pound of nitrous oxide were produced from dairy-waste lagoon water per lactating cow per day.

Methane and nitrous oxide emissions from animal waste can also be calculated as described by USDA (2004). However, our study found a slightly lower methane and a higher nitrous oxide emissions rate than those predicted in the USDA study (2004). Their calculation showed that approximately 1.49 pounds of methane and 0.000926 pound of nitrous oxide per cow per day were emitted from the dairy wastewater lagoons, which are commonly used for manure storage at medium (200 to 700 head) and large (more than 700 head) operations in the United States, according to the EPA definition (US EPA 2007; USDA 2004).

Reducing livestock emissions

Enteric fermentation and wastewater lagoons are two distinct sources of greenhouse gases from livestock, especially methane emissions from dairies.

There are a number of potential strategies to effectively control methane emissions from enteric fermentation (Mosier et al. 1998; USDA 2004). USDA (2004) suggested that these strategies may include: (1) increasing the digestibility of forages and feeds by making feed digestion more efficient; (2) using feed additives to tie up hydrogen in the rumen, because hydrogen is an important intermediate product to produce methane; (3) inhibiting rumen bacteria (methanogens) that produce methane; (4) enhancing rumen microbes to produce usable product rather than methane; and (5) improving milk production efficiency to reduce animal numbers.

Likewise, multiple options are available for reducing greenhouse-gas emissions from dairy waste. In general, oxygen inhibits the methanogens in cow waste, which then produce less methane. Our recent study showed that the partial deep aeration of lagoon water can reduce methane emissions significantly (data not shown). However, these systems produce higher nitrous oxide emissions, which could offset the methane reduction likely due to increased nitrification rates (USDA 2004).

Anaerobic digestion systems (covered lagoons or methane digesters) are another option for reducing greenhouse-gas emissions from dairy waste. Unlike conventional uncovered lagoons, digestion technologies provide actual treatment through increased microbial processes. From a waste treatment standpoint, anaerobic digestion systems could be one of the best available technologies to reduce greenhouse gases from dairies (USDA 2004).

However, future research is needed to address the mitigation of methane and nitrous oxide from cow enteric fermentation, which we have shown to be the chief of all dairy contributors to climate change.

Covered lagoons and methane digesters are an option for reducing greenhouse-gas emissions from dairy waste. In Germany, the village of Juehnde built a digester for livestock waste and other biomass. The methane is combusted to produce electric power and heat for homes in the village, which is the first in the world to go "off the grid" through the use of its own waste.

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RESEARCH ARTICLE

Modeling shows that alternative soil management can decrease greenhouse gases

by Steven De Gryze, Maria V. Albarracin, Rosa Català-Luque, Richard E. Howitt *and* Johan Six

Agricultural management has a significant impact on the amount of greenhouse gases emitted by cropped fields. Alternative practices such as winter cover cropping and avoiding overfertilization can decrease the total amount of greenhouse gases that are produced. Policymakers are considering a structure in which parties (such as factories) who exceed their greenhouse-gas emissions cap can pay incentives to encourage farmers to adopt practices that curb greenhouse gases. Based on data from field studies and an ecosystem computer model, we assessed impacts on yields and the total potential for reducing greenhouse-gas emissions of certain alternative practices in California.

ltras.ucdavis.edu

To develop computer models to estimate the contribution of alternative agricultural practices to carbon sequestration, researchers utilized data from a variety of California field studies. *Top*, the Long-Term Research on Agricultural Systems (LTRAS) project at UC Davis was initiated in 1993 as a 100-year experiment (shown in 2003). *Above*, Jeff Mitchell of UC Cooperative Extension and colleagues have been studying conservation tillage and cover cropping at the UC West Side Research and Extension Center.

Within the California Global Warming Solutions Act of 2006 (AB32), a legally binding cap-and-trade approach for limiting greenhouse-gas emissions is being developed. Parties who exceed their greenhouse-gas emissions allowance would be able to meet their cap either by buying excess allowance from other parties or by financing activities that decrease the amount of greenhouse gases emitted to the atmosphere.

It has been suggested that agriculture could take part in California's carbon market; alternative agricultural practices such as reduced tillage, cover cropping and organic farming can cut greenhouse-gas emissions. An evaluation of the potential for this market participation requires answers to three questions. First, are yields affected by these alternative practices? Second, how much can these practices reduce greenhouse-gas emissions? Third, given the costs of these practices and potential decreases in yield, how much should farmers be paid to change their management? We focus on the first two questions; for approaches to the third, see Howitt et al. (2009) (page 91).

California has a diverse range of microclimates, soil types and crops; and crops are grown in complex rotation schedules. As a consequence, detailed analysis is needed to model this diversity and complexity. It is impractical to continuously monitor and measure greenhouse-gas fluxes across and among all combinations of crop rotations, soil types and microclimates, as well as their interactions. Rather than field measurements, this study uses an ecosystem computer model, which is the preeminent tool to simulate greenhouse-gas exchanges between land and atmospheric fluxes (Smith et al. 1997). This model study focuses only on the most important annual crops and does not include orchards or vineyards.

Agricultural greenhouse gases

Although carbon dioxide (CO_2) is the best-known greenhouse gas, there are two other greenhouse gases produced or consumed by soil microorganisms: methane (CH_4) and nitrous oxide (N_2O) (Conrad 1996). The yearly total of carbon dioxide exchanges between the land and atmosphere is usually quantified by changes in organic carbon levels in the soil. Alternative practices, such as conservation tillage or those that increase plant production, can capture more atmospheric carbon in the soil because the soil is less disturbed and/or more crop residues are produced, promoting the conversion of crop residues into soil organic carbon. In other words, atmospheric carbon dioxide can be sequestered in soil organic carbon through decreased soil disturbance and/or increased crop production.

Methane is produced primarily in rice systems by so-called methanogenic bacteria that live in close proximity to the fine roots of the rice plant. In addition, other bacteria, called methanotrophic bacteria, can transform methane into carbon dioxide in well-aerated soils, which includes most of those not cropped with rice in California; this process is called methane oxidation.

Microorganisms in the soil produce nitrous oxide if excess mineral nitrogen, readily decomposable carbon and moisture are simultaneously present; the processes involved are called nitrification and denitrification.

The three greenhouse gases produced and/or consumed by soils and crops differ in their "forcing" of global warming. More specifically, one molecule of nitrous oxide gas has the same global-warming effect as 289 molecules of carbon dioxide, while one molecule of methane has the same global-warming effect as 25 molecules of carbon dioxide. When taking into account these variable impacts, the total combined potential of a mixture of the three greenhouse gases is called global warming potential (GWP) and is expressed in carbon dioxide equivalents (CO_2e). This concept makes it possible to compare and rank agricultural practices according to their potential to cause or mitigate global warming.

The aims of this study were to: (1) calibrate an ecosystem computer model for California conditions using data from several long-term field experiments, (2) use the calibrated model to evaluate changes in crop yields resulting from alternative management practices and (3) evaluate the biological potential of greenhouse-gas mitigation by these practices.

Long-term field experiments

Before an ecosystem computer model can be applied to a certain region, it must be adjusted for the specific conditions of that area, such as the typical management practices, number of tillage passes, irrigation regime, climate, and planting and harvesting periods. For this purpose, we selected four long-term agricultural research experiments in California with which to adjust and test the model.

LTRAS. The Long-term Research on Agricultural Systems (LTRAS) project (http://ltras.ucdavis.edu) was established in 1993 by researchers at UC Davis. We used data from four corn-tomato rotations that are investigated at LTRAS: (1) a conventionally managed system, (2) a legume cover crop followed first by unfertilized corn and then by conventionally fertilized tomato, (3) an organic system with poultry manure amendments and no chemical fertilizer and (4) a winter legume cover crop. In addition, each of the three replicate plots were split in half between standard and conservation tillage (Denison et al. 2004).

SAFS. The Sustainable Agriculture Farming Systems (SAFS) project (http://safs.ucdavis.edu) was conducted at UC Davis from 1989 through 2000. Data from the following three SAFS systems was used: (1) a conventionally managed system under a 4-year, tomato-safflower-corn-wheat-bean rotation, (2) a similar 4-year system with the addition of legume cover crops preceding each summer crop and (3) a 2-year, conventionally managed tomato-wheat rotation (Clark et al. 1999).

West Side REC. The West Side Research and Extension Center (WSREC) in Five Points has four replicated tomato-cotton rotations comparing standard and conservation-tillage practices with and without winter cover cropping. The conservation-tillage systems still included midseason cultivation within the furrows for tomato production and the undercutting of cotton after harvest (Mitchell et al. 2008).

Photos: Dennis Bryant

The Sustainable Agriculture Farming Systems (SAFS) project at UC Davis has compared conventional and alternative farming systems since 1988. In plots at the Russell Ranch Sustainable Agriculture Facility, where SAFS experiments have taken place, *left*, a winter wheat cover crop is roll-chopped and left as surface residue. *Right*, commonly practiced flail mowing shreds the cover-crop biomass into a slurry before its incorporation into the soil.

Jack Kelly Clark

The computer model incorporated crop management and environmental factors to compare a range of cultural practices, such as the addition of compost mulch (shown).

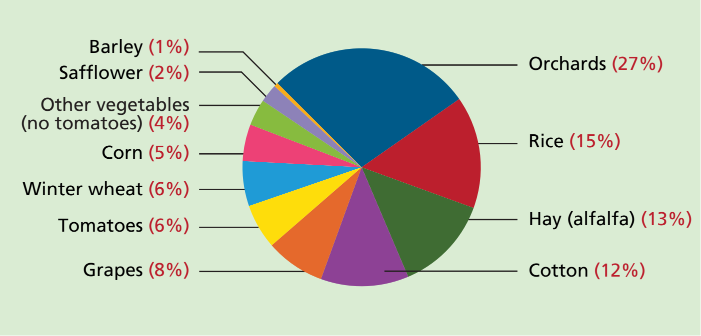

Fig. 1. Most important crops studied in 10 counties of the Sacramento and San Joaquin valleys. Source: USDA 2002.

Field 74. Field 74 was established in 2002 near Davis. The field was split into conservation- and standard-tillage halves. Sampling points were established across the field using a uniform grid with 70-yard (64-meter) spacing. Wheat was planted in fall 2002 and harvested in spring 2003. Corn was grown in 2004 and sunflower in 2005. During 2006, the last year of the experiment, chickpea was grown without fertilizer (Lee et al. 2006).

Ecosystem model

The DAYCENT computer model was used to simulate crop yields and greenhouse-gas emissions under the different alternative management practices considered (Del Grosso et al. 2000). This DAYCENT model is a daily version of the well-known CENTURY ecosystem model, which has a monthly time interval (Parton et al. 1987). The DAYCENT model simulates all major processes that affect the dynamics of soil carbon and nitrogen, including plant production, water flow, heat transport, soil organic carbon decomposition, nitrification and denitrification, and methane oxidation. Because the production of methane is not simulated, however, the predicted reductions in greenhouse-gas emissions for rice systems are provisional and should be used only as coarse indicators. The crop submodel simulates plant growth, plant tissue carbon-to-nitrogen ratios, carbon allocation between roots and shoots, and growth responses to light and temperature. A variety of management options can be specified, including crop type, tillage, fertilization, the addition of organic matter such as manure, harvest with a specified amount of residue removal, drainage, irrigation, burning and grazing intensity.

Data from the four field experiments was used to adjust the model parameters. First, simulated soil-moisture contents were checked against measured values from Field 74 and the LTRAS site. Parameters such as saturated hydraulic conductivity, or the wilting point, were fine tuned within the model. Second, predicted crop yields and dry-matter production were verified using published and measured root-to-shoot ratios, harvest indexes (ratio of harvestable part over total aboveground biomass) and carbon-to-nitrogen ratios. After this was accomplished, the amounts of standing stubble and plant residue litter were checked and compared with measured data and literature values. If necessary, parameters controlling root or shoot death were modified. Next, tillage intensity was altered until changes in soil carbon corresponded to those observed. Finally, modeled nitrous oxide fluxes were verified with data from Field 74 and compared to data from an extensive literature review (Stehfest and Bouwman 2006). Specific parameters controlling soil moisture and nitrous oxide production were further adjusted.

Simulation parameters

The Sacramento and San Joaquin valleys were considered separately in the simulations because these two regions differ substantially in climate, soil type and agricultural management. The simulations in the Sacramento Valley were carried out in eight counties — Butte, Colusa, Glenn, Sacramento, Solano, Sutter, Yolo and Yuba, totaling about 1.6 million acres (0.7 million hectares) of agricultural land. The simulations in the San Joaquin Valley were carried out in two counties — Kings and Fresno, totaling about 1.5 million acres (0.6 million hectares) of agricultural land.

Due to a lack of testing data in woody perennial systems (vineyards and orchards), only annual and nonwoody perennial cropping systems (such as alfalfa) were considered in this study. The latter systems comprise about 64% of agriculture in the 10 counties studied. The study was limited to the seven most abundant crops in both valleys: rice, alfalfa, cotton, tomatoes, winter wheat, corn (for grain in the Sacramento Valley and silage in the San Joaquin Valley) and safflower (fig. 1). The “other vegetable” category was omitted due to the large number of different vegetables produced. Harvested area for the seven crops was 76% of the total harvested area of total annual crops from 1980 to 2006; vegetables were 30% from 1980 to 2006 (of which 7% was tomato, which we included). These annual crops are always cultivated in a rotation system together with other crops. Therefore, sunflower and melons (honeydew, cantaloupe and watermelon) — the most commonly rotated crops in the systems that we considered — were also included in the simulations. Data on crop rotations was extracted from Pesticide Use Reports, agricultural commissioners and survey data. Based on this information, 10-year crop rotation schedules were generated for 1997 through 2006.

Alternative management practices considered included conservation tillage, manure application and winter cover cropping, and all possible combinations of these practices. The winter cover crop simulated was a legume/small-grain mixture with a carbon-to-nitrogen ratio of 25 at plow down. It was planted 1 month after harvest of the preceding crop, and incorporated

1 month before planting of the succeeding crop. A practice in which nitrogen fertilizer was reduced by 25% was also included. Winter cover cropping was not simulated for winter wheat. Alternative management practices were limited for alfalfa systems because they require almost no tillage or fertilization.

Data sources, model adjustments

Details on conventional management practices in the region (such as planting and harvesting dates, fertilization rates, irrigation amounts and pest management) were obtained from the four long-term field experiments described, the Agronomy Research and Information Center (http://agric.ucdavis.edu) and UC Davis cost and return studies (http://coststudies.ucdavis.edu).

The most detailed geographical input data was used (fig. 2). We extracted soil data from the geographic information systems (GIS) database in the Natural Resources Conservation Service's Soil Survey Geographic Database, and used the crop-use and field-boundary GIS layer from the California Department of Water Resources (DWR). Solano and Placer counties were surveyed in 1994; Yuba County in 1995; Yolo County in 1997; Colusa, Glenn and Sutter counties in 1998; Butte County in 1999; Fresno and Sacramento counties in 2000; and Kings County in 2003. Daily climate data for 1.86-mile-by-1.86-mile (3-kilometer-by-3-kilometer) grid cells from 1980 through 2003 was extracted from the DAYMET model (www.daymet.org) developed at the University of Montana. For 2004 until 2006, we obtained weather station data from the DWR California Irrigation Management Information System (www.cimis.water.ca.gov).

We adjusted the model for California conditions using data measured in the four long-term field experiments. Data on crop yields, dry matter production, soil organic carbon changes and nitrous oxide emissions was used to calibrate the model. Only the measured and modeled yields are presented here (fig. 3). The model was able to capture general yield trends in these experiments adequately. However, the yearly differences in yield due to climate and management within a crop were modeled less well. The model satisfactorily

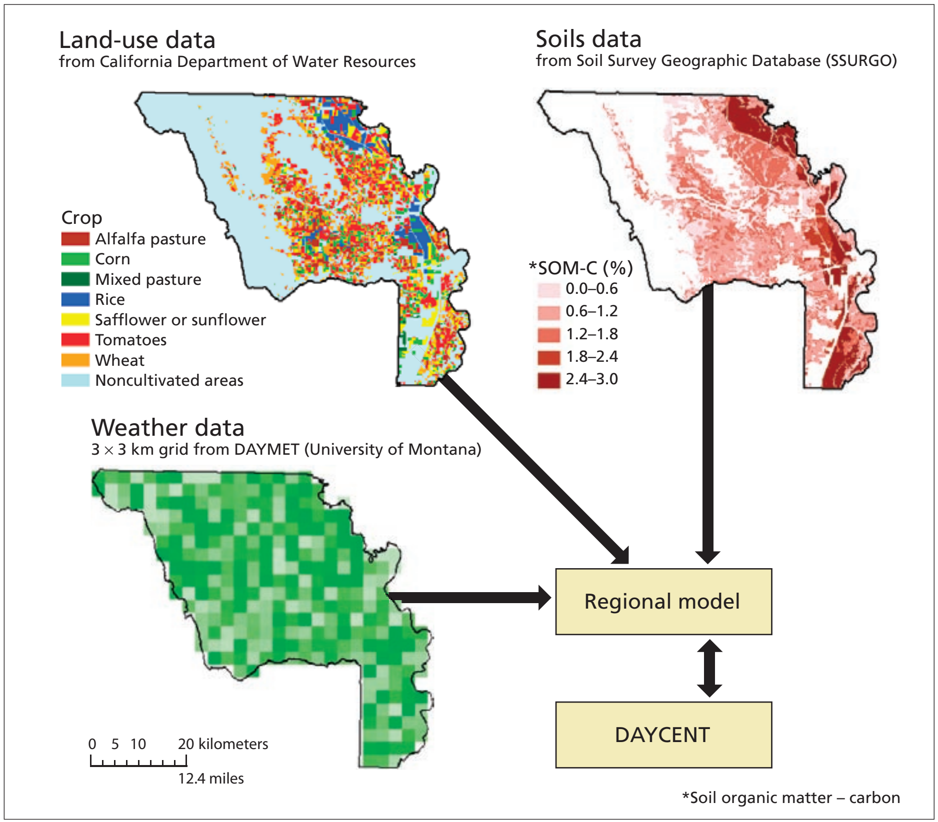

Fig. 2. Data sources for regional modeling.

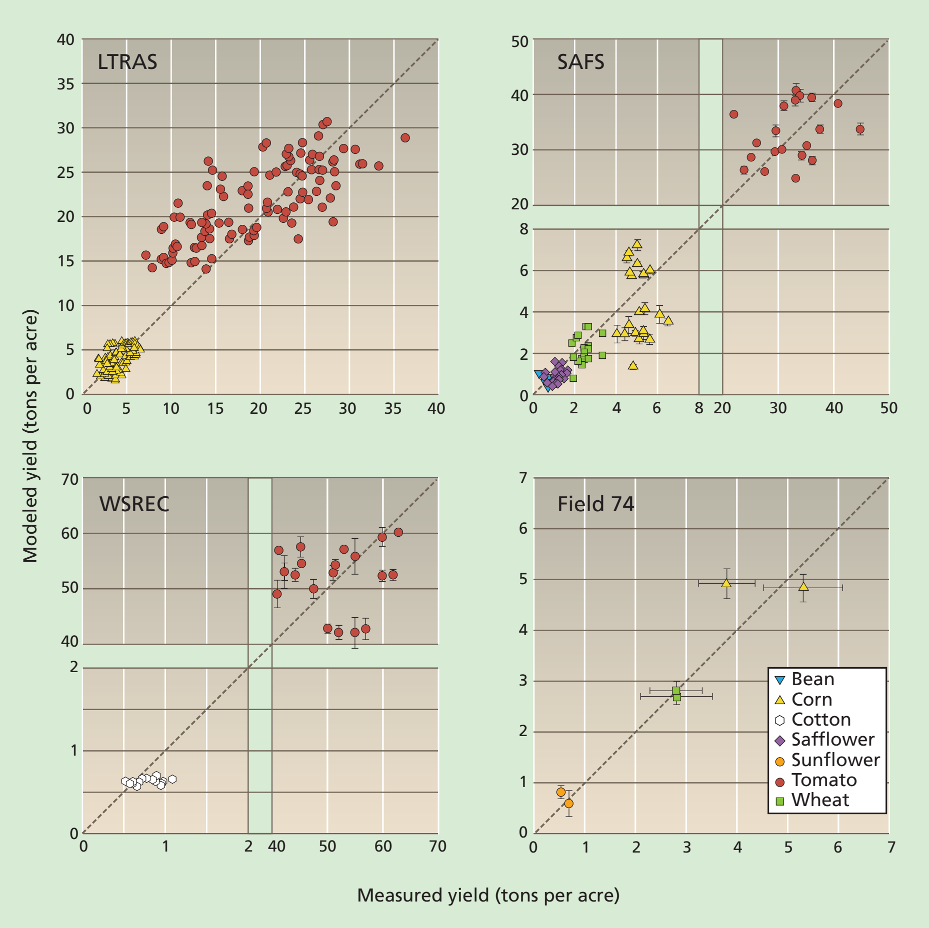

Fig. 3. Modeled versus measured yields across years, replicates, treatments and crops at four long-term field experiments in California. Error bars show ± 1 standard deviation around modeled results.

Carbon offsets generated by increases in soil organic carbon are temporary and reversible, while those generated by decreases in nitrous oxide emissions are permanent.

simulated observed changes in other measured data, such as soil organic carbon and nitrous oxide emissions (De Gryze et al., unpublished data).

Yields and alternative management

Once the computer model was calibrated for California conditions, it could be used to predict changes in yields under alternative management practices. The model predicted that most crop yields would be little affected by the alternative management practices that were considered in this study (table 1). Safflower showed the greatest predicted yield reduction, up to 13%. Predicted yield reductions in other crops were generally less than 5%.

These results are in agreement with those of the field experiments, showing that alternative practices like those studied here maintain yields when properly managed. For example, applying manure instead of mineral fertilizer did not affect corn yields (Miguez and Bollero 2005) or wheat yields in a study in a Mediterranean climate (Deria et al. 2003). The same was found for tomatoes in California (Drinkwater et al. 1995). At the LTRAS site, yield differences between conventional and manure treatments were obscured by the relatively larger yield variability caused by weather (Denison et al. 2004). At the SAFS site, there was only a yield decrease with two of the four organic treatments (Clark et al. 1999). Snapp et al. (2005) concluded that cover cropping frequently increases yields by up to 15%, while Mitchell et al. (2008) reported a small decrease of 5% to 10% in some years. Likewise, conservation tillage at the WSREC site had a minimum impact on tomato and cotton yields and in general was found to maintain yields in California (Mitchell et al. 2008).

It may seem surprising that yields decreased only minimally when nitrogen fertilizer was reduced by 25%. However, this is an indication that in many crop systems the conventional amount of fertilizer applied is above what is actually taken up by the crop. Overfertilization is a common practice in California, due to farmers' desires to minimize the risk of yield reductions due to nitrogen limitation and the low price of nitrogen fertilizer (Cassman et al. 2002). Fertilizer rates are selected so that the least productive parts of a field still receive sufficient nitrogen. Experimental evidence for the sustainability of similar low-input systems can be found in Clark et al. (1999) and Denison et al. (2004).

TABLE 1. Average relative changes in yield of alternative compared to conventional practices*

Tillage	**Conv.†**	**Conserv.**	**Conv.**	**Conserv.**	**Conv.**	**Conserv.**	**Conv.**	**Conserv.**
Fertilizer	**Mineral, 75%**	**Mineral**	**Mineral**	**Mineral**	**Manure**	**Manure**	**Manure**	**Manure**
Cover crop	**No**	**No**	**Yes**	**Yes**	**No**	**No**	**Yes**	**Yes**
				yield change (%)				
Sacramento Valley								
Alfalfa	—‡	—	—	—	—	—	—	—
Corn	—	3	—	—	—	−3	−2	−3
Rice	—	—	—	—	—	−5	−4	—
Safflower	−13	—	4	4	−4	—	—	−6
Sunflower	—	—	—	—	—	—	—	—
Tomato	−4	—	—	—	—	−4	−4	−3
Wheat	—	—	—	—	−4	−3	−2	—
San Joaquin Valley								
Alfalfa	—		—	3	3	—	—	4
Corn	—		—	—	—	—	—	—
Cotton	−2		—	−4	−4	—	—	−5
Melon	−7	—	—	—	—	—	—	−3
Rice	—	—	—	−3	−3	—	—	−4
Tomato	−5	—	—	−4	−4	—	—	−4
Wheat	—	—	—	—	—	−3	−4	−3

* Conventional practices = 100% mineral fertilizer, no cover crop and conventional tillage. Values are averages over individual fields,1997–2006. Crops are grown in their typical rotations. Values are biophysical potentials not reflecting limitations of combining practices.

† Conv. = conventional tillage; conserv. = conservation tillage.

‡ Yield changes within −2% and +2% not considered significant.

Reduction potentials evaluated

The emissions reductions due to winter cover cropping, manure application or conservation tillage alone were modest and between −0.2 and −0.6 (metric ton carbon dioxide equivalents per acre per year ($MtCO_2e$/acre/yr) or −0.5 and −1.4 metric tons carbon dioxide equivalents per hectare per year ($MtCO_2e$/ha/yr). However, by combining these individual practices, larger emissions reductions are possible. Most markedly, combining manure application with winter cover cropping seems to be an efficient option for curbing greenhouse-gas emissions. Although combining all three alternative practices has the greatest potential, this does not seem feasible from a farmer's practical standpoint. Excluding this option, potential reductions in greenhouse-gas emissions ranged from −0.28 to −1.05 $MtCO_2e$/acre/yr (−0.7 to −2.6 $MtCO_2e$/ha/yr) for the Sacramento Valley, and from −0.2 to −0.77 $MtCO_2e$/acre/yr (−0.5 to −1.9 $MtCO_2e$/ha/yr) for the San Joaquin Valley (fig. 4).

Note that these values do not include further reductions in carbon dioxide emissions due to reduced fuel use under conservation tillage, which could account for an extra 0.1 to 0.2 $MtCO_2e$/acre/yr (0.25 to 0.50 $MtCO_2e$/ha/yr) (data not shown). In addition, these values do not account for greenhouse gases produced during the production, storage and transport of manure and mineral fertilizer.

In general, cropping systems in the Sacramento Valley showed more potential to mitigate greenhouse gases than those in the San Joaquin Valley. Probably, warmer temperatures in the San Joaquin Valley increase the decomposition of soil organic carbon compared to that of the Sacramento Valley. In addition, the decreases in nitrous oxide emissions related to manure application were much less apparent at warmer temperatures.

Reducing greenhouse gases

Agricultural greenhouse-gas emissions can be curbed (and carbon credits generated) in three ways: by increasing soil organic carbon, decreasing nitrous oxide and methane emissions, and decreasing fuel use by field equipment. Whether the decrease in greenhouse-gas emissions comes from an increase in soil organic carbon, or from decreases in nitrous oxide emissions, severely affects the longevity or permanence (and hence the price) of the generated carbon offsets. This is because carbon offsets generated by increases in soil organic carbon are temporary and reversible, while those generated by decreases in nitrous oxide emissions are permanent.

Soil organic carbon. Increases in soil organic carbon accounted for 70% to 90% of the carbon offsets from alternative management practices such as winter cover cropping and conservation tillage. This creates a potential legacy for the future: if proper soil management is not maintained, all of the additional organic carbon sequestered in the soil will be released back into the atmosphere as carbon dioxide. Therefore, the carbon offsets generated by increases in soil organic carbon would be reversible and only last for the duration of the contract period. This is referred to as the "permanence issue." It is inevitable that such reversible credits will be sold at a high discount compared to carbon offsets generated by permanent reductions. Additionally, the capacity of a soil to continue storing organic carbon is limited (Six et al. 2004; VandenBygaart et al. 2002). Therefore, management options that increase soil organic carbon seem to be viable for curbing greenhouse gases only in the short term — for 10 to 20 years.

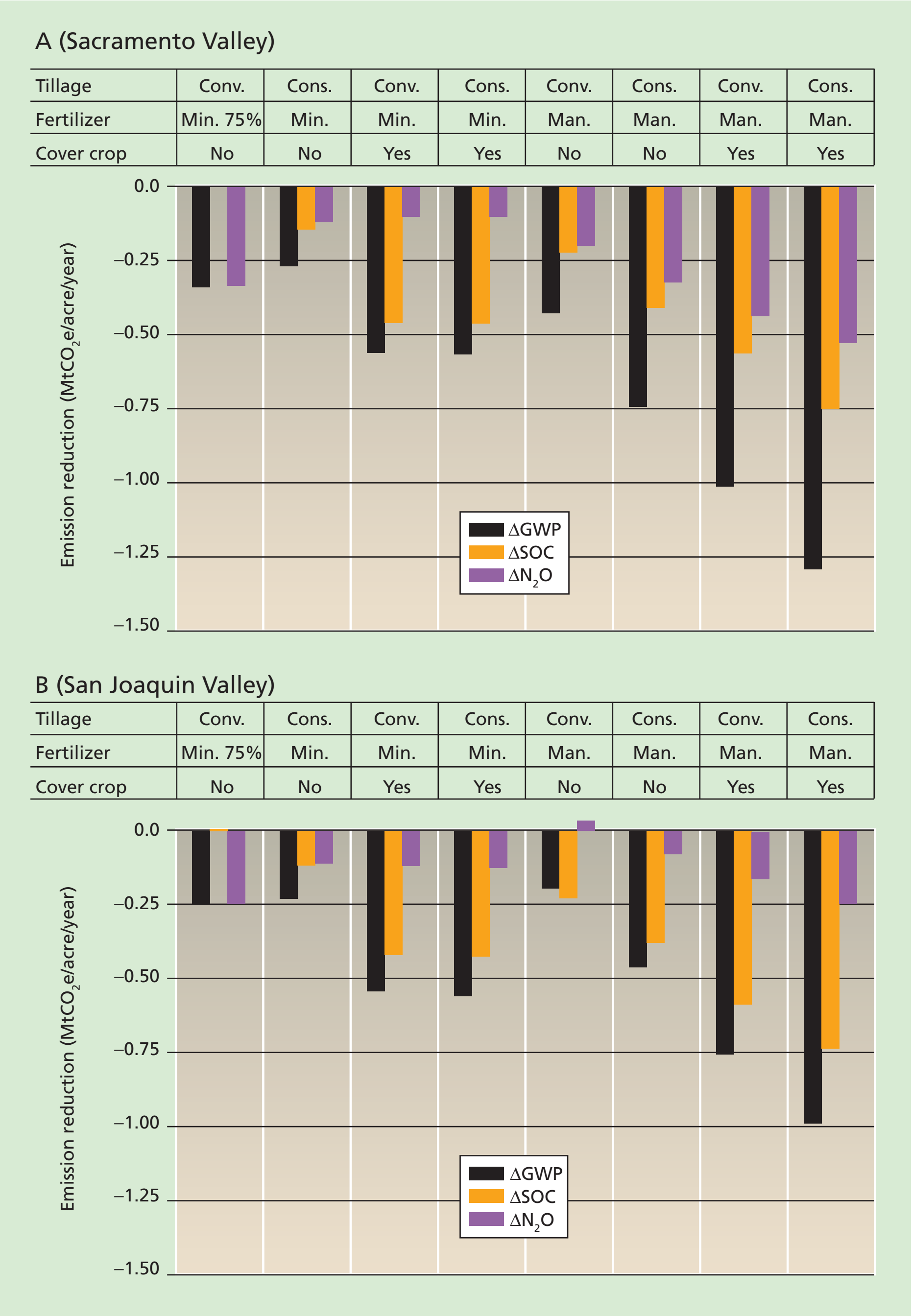

Fig. 4. Difference in global warming potential (GWP) emissions for alternative and conventional practices in Sacramento and San Joaquin valleys, and contribution of changes in soil organic carbon (SOC) content versus nitrous oxide (N_2O) emissions to overall changes in GWP. Negative values indicate reductions in total greenhouse-gas emissions, emissions of N_2O or increases in SOC. Conv. = conventional; cons. = conservation; min. = mineral; man. = manure.

Nitrous oxide and methane. In contrast to increases in soil organic carbon, reductions in nitrous oxide or methane emissions are permanent. A reduction in nitrogen application will lead to a permanent reduction in nitrous oxide emissions and so does not pose a legacy problem for the future (Smith et al. 2007). In our study, when manure was used instead of mineral fertilizer or when less mineral fertilizer was used, nitrous oxide emissions decreased from −0.2 to −0.49 $MtCO_2e$/acre/yr (−0.5 to −1.2 $MtCO_2e$/ha/yr). Because these reductions in greenhouse-gas emissions are permanent, they are better solutions in the long term. Avoiding nitrous oxide emissions is in essence about avoiding excess mineral nitrogen in the soil pore water (McSwiney and Robertson 2005). Manure releases nitrogen to the soil system slowly, resulting in better synchronization between the supply of this nutrient and the crop's demand for it. Cutting back on nitrogen fertilizer also decreases the amount of mineral nitrogen in the soil, and has the additional advantage of reducing operating costs.

Fuel use. A similar argument can be made for the fuel-use reduction in conservation-tillage systems. While this extra reduction in emissions may be modest and ranges from −0.1 to −0.2 MtCO_2e/acre/yr (–0.25 to −0.50 MtCO_2e/ha/yr), it is permanent and unlimited because the fuel that is not used in these systems will never be used. In addition, conservation tillage is simple to implement, and generally leads to a direct reduction in costs (Howitt et al. 2009; see page 91).

Making the model more accurate

There is substantial uncertainty in our model's prediction of how much an individual agricultural field can contribute to a reduction in greenhouse-gas emissions. This uncertainty can range from zero to about double the predicted value. The variability is due mainly to differences in soil characteristics, such as clay content, permeability or organic matter content. If a carbon-offsetting contract combined (or aggregated) different fields, the overall uncertainty would be substantially reduced. Such aggregated carbon-credit contracts will be necessary because the success of a carbon trading system depends on the accuracy of estimates of greenhouse-gas emissions.

Of all greenhouse gases produced in agriculture, the uncertainty in reductions of nitrous oxide emissions is largest, and often three times the average predicted value. This variability is caused by differences in moisture levels, which control nitrification and denitrification. More research is necessary to further develop the simulation models and make these predictions more accurate.

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When attempting to quantify how practices in a particular field affect greenhouse-gas emissions, factors such as soil characteristics and moisture levels must be considered. *Above*, studies at Field 74 near Davis informed the computer model.

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Realistic payments could encourage farmers to adopt practices that sequester carbon

by Richard E. Howitt, Rosa Català-Luque, Steven De Gryze, Santhi Wicks *and* Johan Six

Carbon sequestration in agricultural land has been studied over the past few years to determine its potential for ameliorating climate change. Agricultural soils can be efficiently exploited as carbon sinks with a variety of techniques, such as reduced tillage, cover cropping and organic systems with better manure management. However, to fully understand the potential of carbon sequestration in agriculture, the economic costs of switching from conventional to conservation management must be estimated. Since carbon sequestration depends heavily on management, crop and soil type, we conducted a field-level survey of its economic aspects in Yolo County for the 2005 growing season. The survey showed that organic and conservation management can be more profitable for field crops than conventional management in Yolo County. Finally, we demonstrated how to combine the survey data with an agronomic process model to predict the rate of adoption for conservation techniques in response to carbon payments.


Jack Kelly Clark

Actual management and economic information for alternative agricultural practices in Yolo County was used to develop a model for predicting grower reactions to carbon contracts. *Above*, a no-till air drill is used to plant wheat into safflower stubble.

The Conservation Security Act — title II of the 2002 Farm Bill — authorized the U.S. Department of Agriculture to make payments to farmers who adopt environmental practices such as conservation tillage, cover crops and manure application (USDA 2002). This was a significant shift from prior conservation policies, which provided incentives to retire agricultural land. The revised Conservation Security Act switched the focus to maintaining lands in agricultural production while encouraging sound environmental practices. Carbon sequestration — or storage — in agricultural soils can mitigate climate change (Paustian et al. 2006), and so could also qualify for payments under the Act. (The 2008 Farm Bill continues and builds upon these policies.) Before implementation, however, payment policies for carbon sequestration must be tested for their economic effectiveness.

California has the potential to sequester additional amounts of carbon in its forests, agricultural soils and geological formations. The agricultural sector can realize its potential for carbon sequestration by adopting new forms of management. De Gryze et al. (2009) (see page 84) addresses questions of whether changes in management affect yields, and the total biophysical potential for greenhouse-gas mitigation. We ask what financial incentives farmers would require to change their management such that carbon sequestration increases in Yolo County.

This question is particularly relevant since agricultural carbon sequestration is at the center of a debate. Skeptics argue that there are uncertainties about the amount of carbon that can be effectively sequestered due to complex interactions between agronomics and economics. Proponents argue that besides reducing greenhouse gases, carbon sequestration presents an opportunity to make more sustainable farming methods profitable to farmers, since practices that sequester carbon also reduce drain-water pollution, dust and other air pollution.

Carbon sequestration in agriculture depends on microclimates, soil types, management practices and crop choices. The fundamental result of these practices is to increase the organic matter sequestered in the soil. All of these factors vary over agricultural regions, and region-specific research is needed to make policy decisions about the effectiveness of carbon sequestration. We first present results of a survey of all farmers practicing conservation management in Yolo County in 2005, then combine our results with those from De Gryze et al. (2009) to derive a carbon-sequestration supply curve for the county.

Carbon-sequestration economics

Most studies of the economics (and agronomics) of sequestration have focused on Midwestern agriculture, with little empirical research in California. There are several reasons for this. First, the rotations in Midwestern agriculture are typically simpler to simulate and predict than those in the more complex Californian crop agriculture. Most available empirical studies (McCarl et al. 2007; Mooney et al. 2004) are based on typical Midwestern row-crop systems such as corn-soy-feed crop rotations, where the typical feed crops

Predicting farmer reactions to carbon contracts requires information on field-level costs and management practices, while controlling for soil and weather factors.

include silage corn and sorghum, and Great Plains dryland grain systems (crop-fallow rotations). In order to make the analysis feasible, empirical examples are often restricted to regions where wheat is a prominent crop and a simple wheat-fallow rotation is used. This greatly simplifies the subsequent economic analyses, since the research can focus exclusively on the farmer's management decision in response to a carbon contract without the complication of crop changes.

For California agriculture, however, the diversity of high-valued crops makes it difficult to reduce the observed field cropping patterns to stylized rotations such as those found in the Midwest or Great Plains (Metherell et al. 1995; Parton et al. 1987). California farmers face a chain of crop decisions. The agronomic and economic factors that shape future rotations depend on factors such as the farmer's beliefs about future crop and input prices, land suitability and weather conditions.

In this context, it is likely that a change in management would be accompanied by an adjustment in crop choices. Therefore, management changes induced by carbon contracts are likely to change not only how a crop is grown, but also the proportional areas of crop types on a farm. To measure the potential carbon-sequestration response, an analysis must be able to predict the effect on expected future farm profits of both the changes in management and the consequent changes in crop proportions.

Yolo County farmer survey

Predicting farmer reactions to carbon contracts requires information on field-level costs and management practice, while controlling for soil and weather factors. Current sources of information about cultivation practices are insufficient. The cost and return studies carried out by the UC Davis Department of Agricultural and Resource Economics (Klonsky 2007) are an extremely useful resource for establishing guidelines to help the farming community make management decisions. However, the studies are based on assumptions describing typical farm operations, and the level of aggregation does not allow the interaction of costs and management with the given soil characteristics of a plot.

At the other extreme, budgetary information from UC Davis experimental sites (Mitchell et al. 2005) provides an essential input to assess the effects of conventional and alternative farming systems on the environment and sustainability, but the sites are managed under experimental rather than profit-maximizing criteria. Our survey aims to fill the gap between these two sets of information by recovering actual management and economic information on alternative practices at the field level.

Farmer and crop selection. In 2005, we identified those farmers in Yolo County who were already undertaking conservation management — such as conservation tillage, cover crops and manure application — and the specific soil type on which it was applied. First, we had to narrow down the number of crops to make modeling feasible. Because of the diversity of crops a farmer can choose to plant on a given piece of land, we focused on those field crops most likely to be incorporated in a standard Yolo County rotation. After talking directly to farmers and consulting historical records, we decided to interview those farmers who grew the six most common crops suitable for alternative management: tomato, wheat, corn, rice, safflower and sunflower (CDFA 2006; CTIC 2002). We used the Pesticide Use Reports for Yolo County (CDPR 2008) to identify farmers who planted these crops under conventional or reduced (or conservation) tillage and had managed the same field for the last 4 years. We used the California Certified Organic Farmers registry (CCOF 2008) to identify organic growers of the six crops. These data sources were also used to construct a sample frame listing all relevant farmers, from which the sample selected at random. This method prevents selection bias in the sample. In 2005, 224 farmers were using conventional methods and 41 were using conservation methods to grow the six selected crops in Yolo County.

Fields and soil type. Finally, since our intention was to survey at the field level, we obtained maps from satellite images and allowed the farmers to randomly choose the field for the desig-

Based on computer modeling of Yolo County agriculture in 2005, the authors predict that growers could switch to more environmentally friendly practices if offered reasonable carbon-sequestration payments. *Above*, sunflower, one of the crops studied.

TABLE 1. Survey of conventional and conservation farmers' fields in Yolo County, 2005

	Conventional	Conservation
	fields (no.)	
Population (total)	405	198
Wheat	38	73
Tomato	53	48
Corn	28	3
Rice	133	12
Safflower	36	16
Sunflower	15	46
Sample (total)	60	54
Wheat	13	11
Tomato	6	13
Corn	6	3
Rice	21	17
Safflower	8	6
Sunflower	6	4

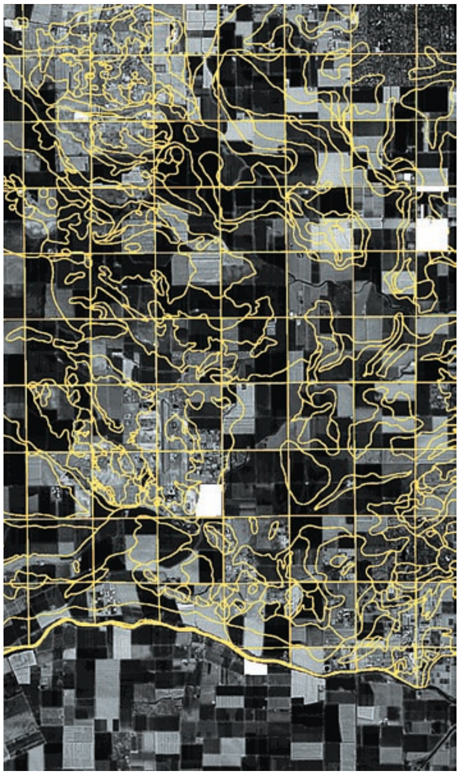

Fig. 1. Field image and soil type by town, range and section grid for Yolo County, 2005. White rectangles represent surveyed plots; irregular curves show soil-type delineations.

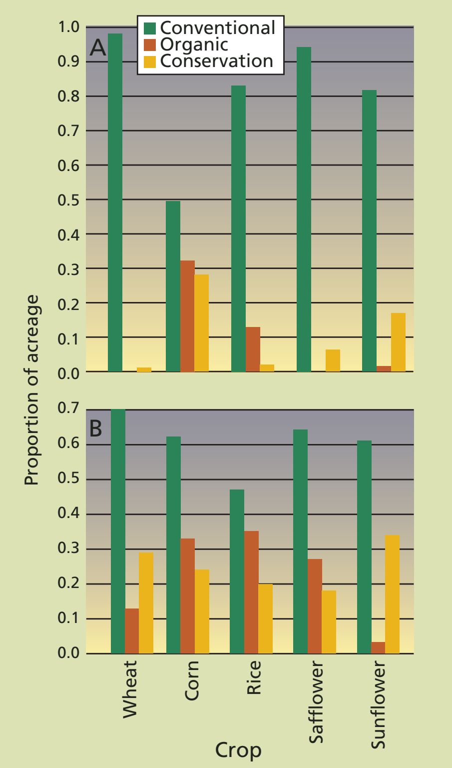

Fig. 2. Acreage proportions for (A) conventional and (B) conservation farmers in Yolo County, 2005.

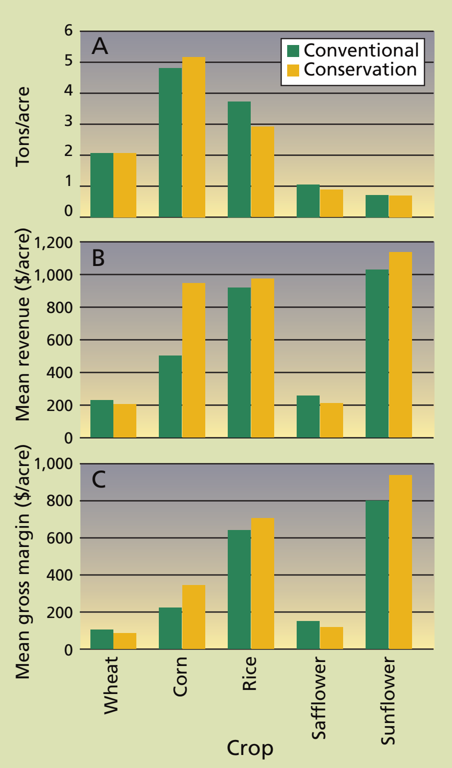

Fig. 3. Mean (A) yields, (B) revenues and (C) gross margins for crops grown under predominantly conventional or conservation management in Yolo County, 2005.

nated sample crop. In the first sampling stage, we divided the farmers by broad management choice (conservation versus conventional), and then stratified the fields by crop. Satellite images were used to precisely identify the surveyed plot boundaries (fig. 1). Field-level soil characteristics were obtained using geographic information systems (GIS) soil information to overlay the satellite image with the Soil Survey Geographic Database (NRCS 2008). The soil survey has more than 44 types, but we aggregated them into five types.

Conventional vs. conservation

Crops. A problem in obtaining a large number of observations for conventionally managed fields is that some farmers diversify by producing several of the six selected crops (table 1), but it is unreasonable to expect them to respond to more than one questionnaire. We surveyed the entire population of Yolo County growers identified as using conservation management, and obtained data on their total 2005 acreage and number of fields. Since our study is the first comprehensive survey of conservation management in California, we decided to include all the organic farmers who had grown any of the six crops during 2005. The census approach at the farmer level allowed us to identify the total number of fields under this management category.

Combined management. In Yolo County, some farmers using predominantly conventional management also grew corn and rice under organic or conservation-tillage systems (fig. 2A). Likewise, many registered organic growers and others using conservation tillage also had significant proportions of their farm under conventional crop management (fig. 2B). It appears that organic and conservation management are making inroads into conventional farm systems, while many organic growers also use conventional methods for key field crops. For example among the conservation growers, 70% of the wheat and 62% of the corn was grown with conventional methods.

Yields and returns compared. Compared to conventional management, we found that yields under conservation management were lower for rice and safflower, higher for corn, and the same for wheat and sunflower. Tomatoes were not included in the yields, due to poor wording on the survey form that did not accurately distinguish between processing and vine tomatoes (fig. 3A). On average the survey results did not show conservation managers paying a yield-loss premium. When the yields were combined with some representative organic price premiums, revenues were higher under conservation management for three of the five field crops (corn, rice and sunflower) (fig. 3B). Only wheat and safflower revenues were reported as slightly lower under conservation management.

With the exception of corn, the gross margins calculated from the survey responses had a similar pattern, showing that differences in the variable costs of production, notably in cultivation and machinery costs, were not very significant (fig. 3C). These gross margins showed that compared to conventional farming, applying conservation practices in production resulted in higher returns per acre over variable costs on average in 2005. However, this higher average value hides the fact that, from our observations, the profits among organic growers were much more volatile than those among conventional growers.

Modeling carbon sequestration

The survey was designed to be coupled with DAYCENT, an agronomic process model (Del Grosso et al. 2008; see also De Gryze et al. 2009, page 84). The DAYCENT model was tailored to encompass both county and field-level soil types and management alternatives. From this we computed the change in carbon-sequestration potential for alternative practices on each field, based on management and crop history. Combining the DAYCENT and economic models allowed us to perform a sequestration analysis that previously was possible only with experimental data. From the survey, we used farmers' actual data on management and costs to derive a county-level carbon-sequestration supply curve (function), which shows the way that a farmer's carbon sequestration responds to carbon payments.

We modeled the 405 fields from conventional farmers using land-use data provided by Pesticide Use Reports. We then used estimates for average total variable costs, and constructed estimates of profits for each field by multiplying the price per yield obtained by the DAYCENT plant-growth model for crops grown in 2005 under alternative management systems.

We modeled five alternative management practices: (1) conservation tillage, (2) conservation tillage with organic fertilizer, (3) conventional tillage with organic fertilizer, (4) conventional tillage and cover crops with organic fertilizer and (5) conventional tillage and cover crops.

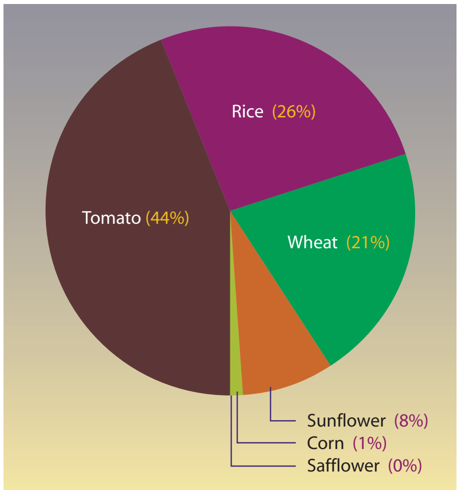

Fig. 4. Predicted allocation of total tons carbon dioxide equivalent among crops under reduced tillage in Yolo County, 2005.


Photos: Jack Kelly Clark

Of the six crops studied in Yolo County, tomatoes, wheat and rice had the greatest potential contributions to carbon sequestration. If offered payments of $3 to $8 per ton, the county's growers could sequester 33,000 to 39,000 tons of carbon annually. In Yolo County, *left*, an aerial view of rice, and, *right*, processing tomatoes next to a mature wheat field.

How farmers make decisions

Analyzing the survey data, we confirmed that a pure conservation-tillage system must be treated differently from organic systems. Organic growers reported significantly higher production costs of labor, cultivation and weed control than conventional farmers. In contrast, adopters of conservation tillage reported lower production costs due to lower fuel expenses and labor hours for ground preparation.

Modeling the simultaneous questions of how farmers choose what crop to grow and how to grow it requires a complicated statistical approach (Català-Luque 2007). Essentially, the probability that a farmer will find it attractive to make changes in both production methods and cropping pattern must be estimated jointly, but then teased apart to measure their relative contributions to farm profits.

Combining the survey information with the DAYCENT model resulted in a response curve for carbon sequestration based on the adoption of alternative practices. The response curve for Yolo County relates the increase in the total amount of carbon sequestered by conservation tillage adoption to the level of payments per ton of carbon dioxide equivalent (CO2e) per year. The model results indicated that on the whole, field productivity drives farmer decisions. Productivity is based on current and past weather and water availability, and reflects the multiple factors used by farmers to make decisions on how and what crop to grow in a particular field.

In contrast, while reported operation costs based on the survey results varied by crop and management, these seemed much less important in making the final decision of what to grow and how to grow it. This result is reasonable since it indicates that a farmer, knowing the properties of his land, is going to make use of it in the best way. Operation costs will likely have much more influence at the farm scale than at the field scale. This focus on crop productivity will help implement carbon-sequestration payments, since it makes their success dependent on well-known biophysical conditions such as soil type.

Alternative management costs

Having used the detailed field data to project our results at the county level, we summed each crop's carbon-sequestration supply for a particular alternative management. This operation calculated the amount of carbon that can be sequestered or avoided by adopting a specific management practice in Yolo County, and the associated cost of this abatement. The cost of abatement, or "price" of carbon sequestration, is the break-even cost of adopting a management practice for a given crop rotation compared with using conventional practices. Because they were statisti-

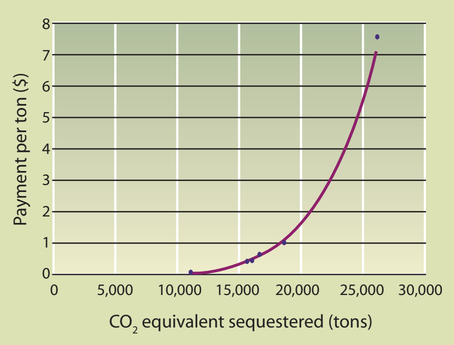

Fig. 5. Carbon supply function for tomatoes.

cally computed from the survey, these costs do not includes farmers' preferences or perceptions of risks, and thus we should interpret the results as an abatement cost curve that reflects the direct costs of management changes. If risk factors were included, we would expect a steeper abatement cost curve.

The potential for sequestration was calculated for each of the five management approaches. For reasons of space, we only present the carbon sequestration supply curve from the most promising alternative, conservation-tillage. While conservation tillage does not have the greatest physical potential for sequestration, it is probably the most promising from a joint agronomic and economic perspective. This is due to the ability to implement payments for reduced tillage in a simpler and cheaper manner.

The proportional sequestration contribution by crop showed that under conservation-tillage practices, tomatoes were the highest contributor to greenhouse-gas reduction (fig. 4). Tomatoes are the most important crop in Yolo County, and the agronomic processes involved in tomato cultivation lend themselves to conservation tillage. Wheat, rice and sunflower contributed 55% of the sequestration, and corn and safflower made small contributions to the total carbon sequestration.

Implementing carbon payments

The DAYCENT model enabled us to link a quantity of carbon sequestered to the crop and acreage, enabling the generation of a carbon-sequestration supply curve that shows the relationship between carbon payments and tons of carbon sequestered by agriculture in Yolo County (fig. 5). As a result, we can draw some conclusions about the implementation of a carbon payment system for crop agriculture.

First, the combination of economic and biophysical models enabled us to develop regional carbon-sequestration supply curves for agriculture. Second, we predict that farmers could change their crop technologies in response to reasonable carbon-sequestration payments. Third, the cost of carbon-sequestration changes with soil and crop type. We do not explore the implementation costs for carbon contracts in this paper; see Mooney et al. (2004).

The carbon-sequestration supply curve shows that by adopting conservation-tillage practices in response to carbon payments of $3 to $8 per ton per year, Yolo County could sequester as much as 33,000 to 39,000 tons of carbon, approximately 3% of the county's total carbon release. Given that current carbon payments on the Chicago Climate Exchange vary around $7 per ton, this is a realistic policy. If U.S. carbon emissions were capped in the future, carbon prices would increase and additional alternative-management practices and greater sequestration would occur.

It should be noted that the shape of the carbon-sequestration supply curve indicates that relatively low carbon payments can induce the adoption of sequestering technologies by farmers. While the carbon reduction from this single sequestration policy is small, many other beneficial ecosystem services are associated with alternative management methods. For example, conservation tillage reduces water runoff, the generation of dust particles and associated pollution. Plans are under way to extend the Yolo County model to other counties. Since the adoption model is largely driven by biophysical factors, a carbon-sequestration supply curve can be developed for different areas using the existing regional field data on cropping patterns, microclimates and soil types.

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From kiosks to megastores: The evolving carbon market

by Deb Niemeier *and* Dana Rowan

Markets can play a key role in mitigating the effects of climate change by providing added flexibility, allowing emissions reductions to occur at a lower cost while maintaining a set level of emissions reductions. With careful regulatory design, both industry and consumers can benefit from low costs. We review the state of carbon trading globally and in the United States, the West and California. New policies and regulations related to AB32, which mandates reductions in California's greenhouse-gas emissions to 1990 levels by 2020, are beginning to take shape. California has a unique opportunity to establish a new ethos for carbon trading by acknowledging unavoidable mitigation costs, and by designing a market-based solution that is fair, equitable and transparent, and protects the most vulnerable members of society.

UN Photo/Mark Garten

Globally, carbon trading is expanding rapidly as a means for using markets to reduce greenhouse-gas emissions. In December 2008, Secretary-General Ban Ki-moon opened the United Nations Climate Change Conference in Poznan, Poland.

The carbon market is growing exponentially; at $30 billion, worldwide trading in 2006 was nearly triple that observed in 2005. A carbon market is created when an emissions cap is set — either through a political or regulatory process — and an emissions allowance is then passed down to regulated entities. If the total carbon emissions produced by a company exceeds its cap (or allowance), then the company must purchase credits (or allowances) from those polluting less than their allowance; this transfer is known as a carbon trade. In theory, carbon markets allow companies to choose least-cost methods of compliance, which results in a net societal financial gain when overall emissions are reduced to the desired level. Today's carbon market can be loosely organized into the regulated (or compliance) market and the voluntary (or noncompliance) market; the volume and value of trading is substantially greater in the former than in the latter (fig. 1). Both types of markets trade in greenhouse-gas emissions, which include carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, hydrofluorocarbons and perfluorocarbons, and are measured in carbon dioxide equivalents (CO_2e).

When regulated entities are subject to greenhouse-gas limits, those emitting less than the cap can theoretically trade with those emitting above the cap. Carbon trades can also occur with offset projects that reduce emissions from unregulated greenhouse-gas-producing activities (such as capturing methane from cows in California and using it to produce electricity), or via unregulated carbon-sequestration activities (such as planting trees in Brazil).

The regulated carbon market transacts about a million metric tons of carbon dioxide equivalents ($MMtCO_2e$, the standard measurement for amounts of greenhouse gases emitted into the environment) annually, and includes the European Union Emissions Trading Scheme, the United Kingdom Emissions Trading Scheme, the New South Wales Greenhouse Gas Abatement Scheme, and offset projects certified under the Kyoto Protocol, a 1997 international treaty to reduce greenhouse gases.

The voluntary carbon market includes the Chicago Climate Exchange, which allows businesses to voluntarily set a reduction target and trade emissions or buy offsets. Individuals and businesses can also purchase retail "over-the counter" greenhouse-gas-emissions offsets, such as TerraPass. The voluntary market, which has been referred to as "the Wild West" of offset trading (Fahrenthold and Mufson 2007), currently transacts about 24 $MMtCO_2e$, and this amount is projected to roughly double by 2011.

Carbon market history

Voluntary emissions reductions and offsets can be traced back at least 20 years, driven by the desire to reduce greenhouse-gas emissions in the absence of formal regulations. Nonetheless, the decision to allow offsets is separate from the decision to impose a regulatory cap. In addition, the types of projects allowed as offsets and the criteria by which they are evaluated are also policy decisions. When credits are generated through offset investments, the transaction costs — the costs of providing the services, information and enforcement required to support a trade — may be much higher than anticipated and are directly related to policy decisions about how to evaluate and monitor projects over time (Michaelowa and Jotzo 2005). With the right price signals, both industry and consumers generally benefit from more cost-effective emissions reductions, which might include purchasing or financing offsets (Wara 2007).

The Kyoto Protocol was instrumental in establishing the necessary foundation for carbon markets to develop. Adopted in 1997 at the Third Conference of the Parties of the United Nations Framework Convention on Climate Change, the Kyoto Protocol requires that Annex I nations reduce their greenhouse-gas emissions to 5% below their total 1990 levels over the 2008-to-2012 commitment period. Annex I nations include industrialized countries that were in the Organization for Economic Co-operation and Development (OECD) in 1992, such as the United States, the United Kingdom and countries in the European Community. They also include countries with economies in transition (EIT parties) such as the Russian Federation, the Baltic States, and several Central and Eastern European states. Certain developed nations (OECD members but not EIT parties) contribute to an adaptation fund to be used in non–Annex I (developing) nations such as China, India and Mexico. The purpose of the adaptation fund is to provide financial assistance to developing countries that are particularly susceptible to the effects of climate change, helping them to address adverse impacts.

The protocol includes provisions for trading emissions credits as a mechanism to reduce greenhouse-gas abatement costs, though member states can meet their targets with any combination of direct regulation, incentives, taxes or cap-and-trade. By Oct. 23, 2007, 175 countries had ratified the Kyoto Protocol (UNFCCC 2007), providing much of the world with a formal mechanism to regulate and trade emissions.

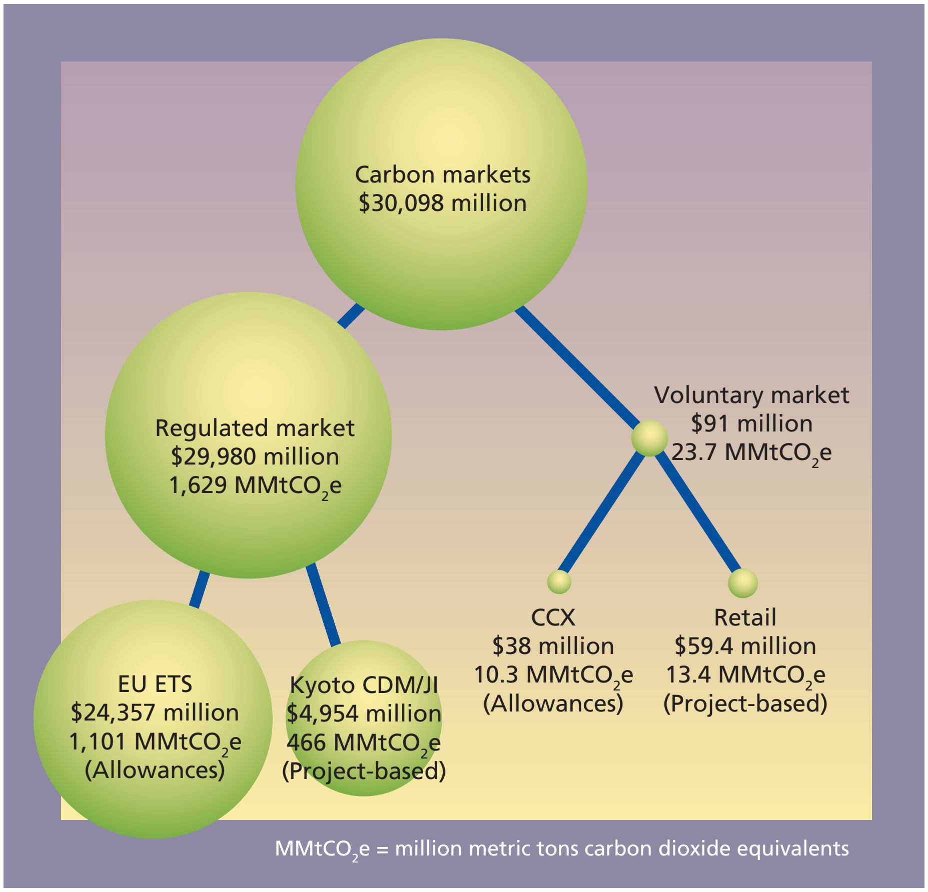


Fig. 1. Market trading, 2006. Total carbon market includes smaller market trades not shown; regulated market includes New South Wales and the U.K. Emissions Trading Schemes (ETS). Kyoto CDM/JI = clean development mechanism/joint implementation; CCX = Chicago Climate Exchange. Adapted from Capoor and Ambrosi 2007; Hamilton 2007.

In nations such as the United States that have not yet ratified the Kyoto Protocol, and so are not bound by it, greenhouse-gas emissions regulations and trading mechanisms are also being established at subnational scales. These include upcoming limits in California and the Northeastern states. In the meantime, unregulated parties, from industries in nonratifying nations and non–Annex I nations to individual consumers worldwide, still look to a growing voluntary trading market to mitigate climate change.

Regulated carbon markets

Under the Kyoto Protocol, Annex I member states can meet their assigned targets in three ways:

Emissions trading. First, when greenhouse-gas allowances are exchanged by emissions trading, an Annex I party that is under its assigned target may transfer those excess credits (or assigned amount units) to another Annex I party that does not expect to meet its assigned target.

Joint implementation. Second, the Kyoto Protocol also allows carbon credits from project-based offsets. Article 33 (UNFCCC 1998) allows project-based credits for avoided deforestation, reforestation and afforestation, which entails planting forests in places that have not been forested for at least 50 years, to increase carbon stored in or decrease carbon released by soils and trees. Under Article 3.4, forest, crop and grazing land management can be used to generate carbon offsets (UNFCCC 2002). Joint implementation allows an Annex I party to develop and implement an emissions reduction (or sink) project in another Annex I party's territory and receive credit (emission reduction units [ERUs]) toward its own target. Most joint implementations to date have targeted economies in transition, but recently a New Zealand wind farm was implemented jointly.

TABLE 1. Early greenhouse-gas offset projects

Start date	Sponsors	Location	Type	Original mitigation estimate
				$MMtCO_2e$
1989	Applied Energy Services, CARE	Guatemala	Forestry, agroforestry	60
1990	U.S. Forest Service	United States	Tree planting (private land)	59–238
1991	World Bank, Global Environmental Facility (GEF)	Philippines	Geothermal energy	—*
1991	UN Development Program, GEF	Zimbabwe	Photovoltaic energy	—
1992	Face Foundation, Innoprise Corp.	Malaysia	Enrichment planting, forest rehabilitation, sustainable timber	15.6

* Data unavailable.

Clean development mechanism. Third, under the clean development mechanism, Annex I parties can implement emissions reductions or sequestration projects in non–Annex I territories and receive certified emissions reductions that count toward their assigned target. These projects include hydropower, biomass generation, and methane and waste-heat recovery projects.

EU Emissions Trading Scheme. The largest carbon-trading volume to date has occurred under the EU Emissions Trading Scheme, a regulated, Kyoto-based market mechanism. Each member state sets the maximum allowances (or greenhouse-gas caps) for five primary industrial sectors: power and heat, metals, cement, oil and gas, and pulp and paper. Regulated emitters (or installations) can buy and sell EU emissions allowances in order to meet targets set by their member state's plan (Europa 2007). Evolving since 2005, trades of emissions reduction units (offsets from joint implementation projects) and certified emissions reductions (offsets from clean development mechanism projects) are permitted under the scheme (European Parliament 2008), except for projects involving land use, land change and forestry. In principle, entities that purchase or invest in projects resulting in certified emissions reductions and emission reduction units convert the credits into allowances that satisfy the caps. The European Union limits the proportion of allowances that can be exchanged for project-based emissions reductions.

The voluntary carbon market

The voluntary market is fueled in part by the growing willingness of individuals and companies to make a commitment to offset their greenhouse-gas emissions.

Chicago Climate Exchange. In the United States, the voluntary market has grown beyond just offsets to include voluntary allowance trading. For example, the Chicago Climate Exchange is a cap-and-trade system with more than 300 members who have agreed to reduce their emissions 6% below their own individual baselines by 2010. Members must either directly reduce emissions or purchase offsets or credits to meet their targets. This exchange trades greenhouse gases in carbon financial instruments (CFI), each of which is equal to 0.0001 $MMtCO_2e$. Although project-based offsets are traded on the Chicago Climate Exchange, the majority of trading is allowance based.

In 2006, approximately 23.7 $MMtCO_2e$ were transacted in the voluntary market (fig. 1), of which 43% was traded through the Chicago Climate Exchange (Hamilton et al. 2007). The remaining offset volume was traded through retail transactions such as TerraPass and similar companies. While the voluntary market still remains a relatively small proportion of overall trading, its volume grew considerably between 2005 and 2006; the Chicago Climate Exchange was up by more than 900% and retail transactions doubled (Capoor and Ambrosi 2007).

Forestry projects. Several voluntary greenhouse-gas offset projects were initiated in the early 1990s by public, private and nonprofit entities. These were mostly forestry-based projects in developing nations to support conservation programs (table 1). One of the first was initiated in 1989 by Applied Energy Services and the humanitarian organization CARE International, in conjunction with the World Resources Institute (Trexler et al. 1989). At the time, CARE was seeking funds to extend and expand its work in Guatemala. The project involved offsetting emissions from a new Applied Energy Services coal-fired power plant in Connecticut with a range of activities in Guatemala, including agroforestry and multiuse plantings for community woodlots, fuel wood, soil conservation, fruit and nut production, alley cropping and live fencing. The World Resources Institute estimated that approximately 60 $MMtCO_2$ would be sequestered over 40 years (Trexler et al. 1989), though that estimate has since been revised to 37 $MMtCO_2e$ (WRI 2007).

In 1990, the Dutch Electricity Generating Board set up the Face Foundation to mitigate greenhouse-gas emissions through forestry (www.stichtingface.nl). In 1992, the Face Foundation and the Innoprise Corporation jointly initiated the first Face project in Sabeh, Malaysia (Stuart and Moura 1998), which included enrichment planting and restoration for managed timber harvesting. The expectation was that the offset project would sequester 15.6 $MMtCO_2e$ over its 99-year lifetime.

One of the first U.S. government programs that publicized the benefits of climate-change mitigation was also a forestry project. In 1990, the U.S. Forest Service's America the Beautiful Program planted trees on private land, with predicted offsets of 59 to 238 $MMtCO_2e$ per year after 10 years of planting (Kinsman and Trexler 1993).

Renewable energy projects. Around the same time, several energy-based projects were surfacing. In 1991, the U.N. Development Program, U.N. Environment Program and World Bank helped to establish the now-independent Global Environment Facility (http://gefonline.org) to provide funding for developing countries to protect global environmental resources (Kinsman and Trexler

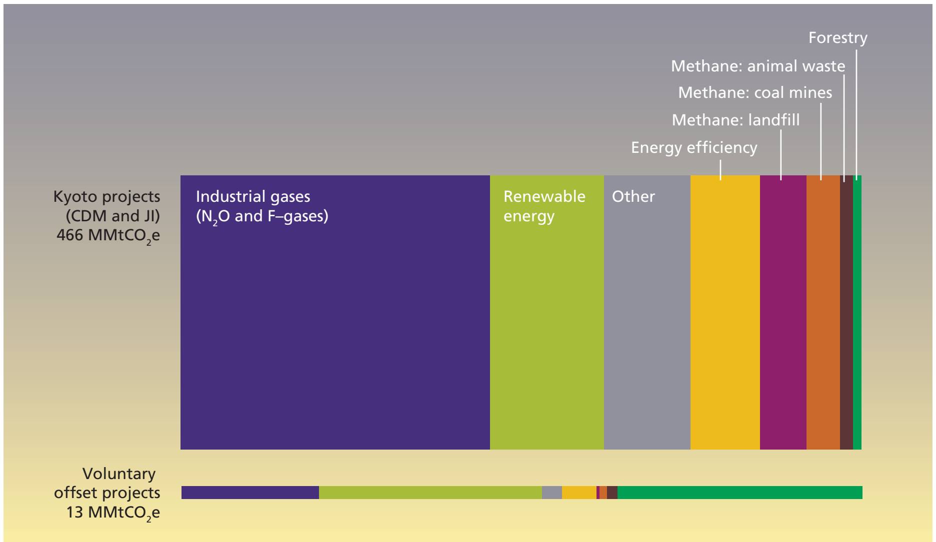


Fig. 2. Project type and proportional volume, 2006. Adapted from Bellassen and Leguet 2007.

1993). In its first year, the Global Environment Facility approved six projects aimed at climate-change research and mitigation. Two focused on implementing energy-saving technologies, including a geothermal electric power generation project in the Philippines and a photovoltaic project in Zimbabwe.

These early prototypes served as a proving ground, testing the feasibility of offset projects and helping to refine methodologies. Since the early 1990s, both the number and range of offset projects have grown. Although the voluntary and regulated offset markets cover a more or less similar range of sectors, forestry and renewable energy projects currently dominate the voluntary market. This is in contrast to Kyoto's clean development mechanism and joint implementation projects, where the majority of offset projects are aimed at decreasing emissions of industrial gases (fig. 2).

Offset supply pathways

A number of offset supply pathways have developed, due to the rapidity with which carbon demand has increased as well as the lack of formal government oversight or regulatory policy structure for managing supply in the voluntary offset market (fig. 3). Credits can pass directly from developer to buyer, or indirectly through a verifier, which may or may not be certified by a regulatory agency, an aggregator/wholesaler and/or a retailer. Project developers tend to organize a range of different-sized offset projects (Hamilton et al. 2007). They sell offsets to aggregators or wholesalers, retailers and even directly to consumers. The aggregators bundle smaller offsets for bulk sales, while retailers pass along smaller numbers of credits to individuals and organizations. Both retailers and wholesalers own portfolios of credits.

The voluntary supply chains are becoming increasingly diversified, with fewer big players and greater product specialization. This contrasts with the pathways for allowances, which are tradable within the EU Emissions Trading Scheme and on the Chicago Climate Exchange. Allowances pass through EU member states (and regulated sectors) to the market, while carbon financial instruments pass through the Chicago Climate Exchange.

In 2006, about half to three-quarters of the demand for carbon credits was estimated to come from businesses offsetting emissions (Hamilton et al. 2007). Individuals who either purchase offsets through retailers or buy products from companies that offset their emissions drive about a third of market demand; the latter can be thought of as carbon "rebates." Finally, while still a small proportion of the total demand, an increasing number of event organizers and nonprofit and governmental organizations are offsetting their carbon emissions.

While still fairly small, the retail offsets market could play an important role

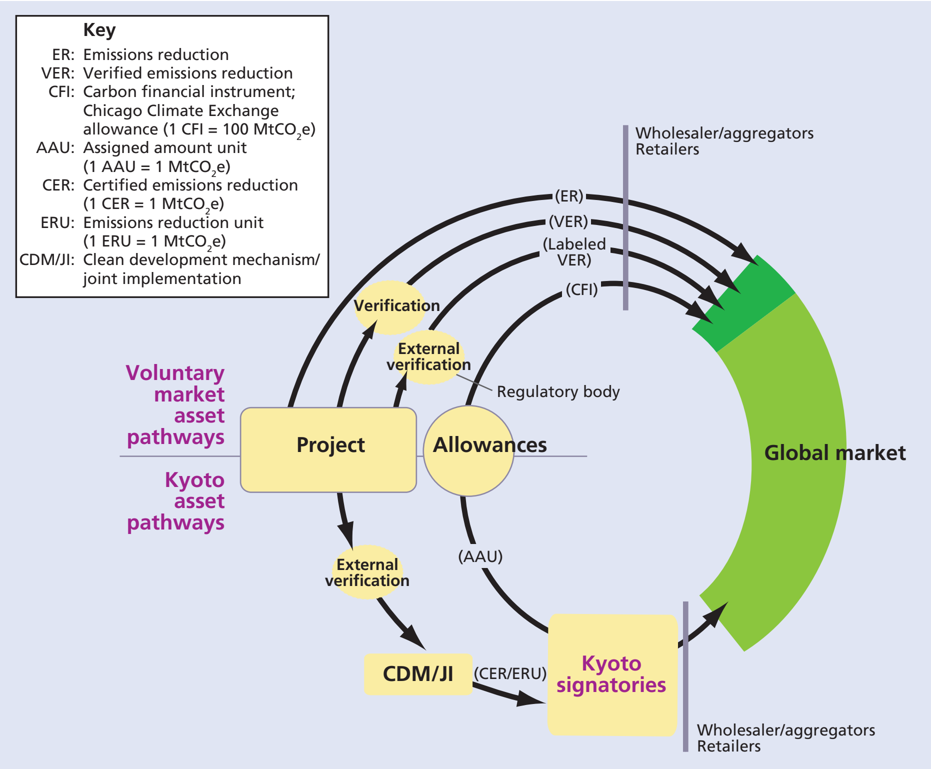


Fig. 3. Conceptual pathways to the carbon market.

Geoffrey Hammond

Carbon markets, both regulated and voluntary, set caps for greenhouse-gas emissions. When polluters exceed these targets, they can pay to mitigate or offset the environmental damage. For example, investments in cleaner wind power can offset more heavily polluting sources. *Above*, a Palm Springs wind farm.

in consumer perceptions of carbon trading (Capoor and Ambrosi 2007). Retail offset credits are referred to as carbon offsets or "verified" when they have been verified by an independent third party, or as verified emissions reductions (VER) when the verifier has been certified by a regulatory body.

Rather than being driven by a cap, the voluntary market is driven by individual and corporate buyers, who are motivated by philanthropy, internal goals and sustainability reporting, corporate responsibility, public relations and branding, reduced liability, cost avoidance, regulation preemption, and appeal to consumers and investors (Hamilton et al. 2007; Arora and Cason 1996; Hoffman 2005; Videras and Alberini 2000; Vidovic and Khanna 2007; Welch et al 2000).

Quality of voluntary offsets

Concerns. Although the voluntary market is believed to promote more innovative offset projects, the quality of its offsets has come under increasing public scrutiny. In contrast to the certification processes for joint implementation and clean development mechanism, the voluntary market does not have a commonly-agreed-upon standard for what constitutes a quality offset. In recent years, a number of news articles have been highly critical of the quality of some offsets (e.g., BusinessWeek, March 26, 2007).

The quality of a carbon offset, whether traded on the voluntary or regulated markets, is usually defined relative to criteria outlined in the Kyoto Protocol. In general, offset projects must have clearly defined boundaries and a well-demonstrated baseline level of emissions, with monitoring methodologies to measure real emissions reductions. Reductions must be verifiable and "additional"; emissions reductions are counted as additional if they would not have occurred in the absence of the project. So-called additionality is often the most difficult requirement, especially for land-use change and forestry projects (Chomitz 2000). Offset projects must also account for "leakage," or changes in emissions outside of the project boundaries that may occur as a result of the project. Other criteria may include whether an emissions reduction is reversible, and if so, on what time scale, and whether project-related social and environmental effects on a community can be appropriately mitigated (Capoor and Ambrosi 2007; Chomitz 2000). There is also some concern that over time, a continued lack of confidence in voluntary offset quality could extend to other projects in the categories of clean development mechanism and joint implementation.

Standards. Partially as a result of this concern, new protocols are proposed almost monthly for offset standards or certification programs. Among the better known standards are ISO 14064 (a voluntary carbon standard), the Gold Standard (endorsed by a large number of nonprofit organizations), the Voluntary Carbon Offset Standard and the Voluntary Carbon Standard. In addition, the U.K. Department of Environment and Rural Affairs has prepared a Code of Best Practices to assist consumers in identifying quality offsets.

Registries. Greenhouse-gas registries are also a critical component for improving the quality of voluntary market transactions. Registries provide accounting and tracking systems for offsets, which can help to reduce the double-counting of carbon credits. For example, the Canadian Greenhouse Gas Challenge and the World Economic Forum serve as tracking systems, and the Environmental Resources Trust GHG Registry and the Bank of New York Global Registry provide carbon accounting systems. The California Climate Action Registry provides both a tracking system and some sector-specific protocols (accounting mechanisms), and is currently serving as the model for a national registry.

Voluntary agricultural offsets

In most countries, agriculture is one of the few industries that currently has the opportunity to benefit from the voluntary carbon market without the burden of direct costs due to regulation, although farms may suffer from the indirect costs of greenhouse-gas regulation (such as higher fuel or supply prices) and adaptation costs if regulation is unable to prevent climate-change impacts. So far, agriculture has not been subject to carbon caps in the EU Emissions Trading Scheme or in proposed U.S. cap-and-trade programs, largely because it is difficult to measure greenhouse-gas emissions from agricultural activities such as soil tillage, animal waste, land conversion and fuel use (European Commission 2008). However, the New Zealand government (2007) currently has plans to cap agricultural emissions.

Agricultural production entities that are not regulated may be able to sell carbon reductions as offsets, if an emitting farm is willing to assume the costs of monitoring and self-enforcement to reduce its emissions. As of May 2008, the Chicago Climate Exchange had approved 10 agricultural soil offset projects and 14 agricultural methane-reduction projects (four of which are in California), and had approved the methodology for rangeland soil carbon management (CCX 2007a, 2007b). Retail offsets have also included projects to capture methane and build wind energy infrastructure on farms (NativeEnergy 2007).

Emerging U.S. markets

The regulation of greenhouse gases will undoubtedly affect many existing industries, from energy and transportation to agriculture and forestry. The effect on each market is a function of the structure and rules of regulatory mechanisms. Within the United States, climate change is being addressed through a number of different state, local and voluntary carbon-emissions reduction initiatives.

Regional agreements. At present, three regional agreements provide a framework for cap-and-trade schemes between states: the Regional Greenhouse Gas Initiative, the Western Climate Initiative and the Midwest Greenhouse Gas Reduction Accord. The Regional Greenhouse Gas Initiative encompasses emissions from power plants in 10 Northeast states, and began trading 2009 emissions credits in 2008. The Western Climate Initiative (2008) began in February 2007 and released a cap-and-trade program proposal in September 2008. This program would encompass seven Western states including California and four Canadian provinces beginning in 2012, and is designed to reduce emissions to 15% below 2005 levels by 2020. The Midwest Accord includes six states and one Canadian province, which agreed in November 2007 to establish a cap-and-trade program within 30 months.

With 23 U.S. states involved in regional agreements as of July 2008, and 10 states and the District of Columbia as official observers (www.rggi.org, www.midwesternaccord.org, www.westernclimateinitiative.org) the lack of federal guidance does not seem to have hampered mobilization to reduce greenhouse gases in the United States.

California mandate. The California Global Warming Solutions Act of 2006 (AB32) mandates reductions in the state's greenhouse-gas emissions to 1990 levels by 2020. This sets the stage for yet another entry into the regulated carbon-trading market. The Act authorizes — but does not require — the California Air Resources Board to employ market-based regulatory mechanisms to achieve greenhouse-gas emissions reductions (CARB 2008a).

The board's scoping plan, adopted in December 2008, includes regulations, fees and voluntary measures, some of which would be partially nested within a cap-and-trade program that could potentially cover up to 85% of the state's emissions by 2020 (CARB 2008a). The specific measures are expected to achieve 140 MMtCO_2e in reductions by 2020, 112 MMtCO_2e of which would be in capped sectors. An additional 34 MMtCO_2e would also be reduced under the cap-and-trade program, such that the total emissions of capped sectors would be fixed at 365 MMtCO_2e in 2020.

The plan also calls for linkages with Western Climate Initiative partner programs, although it stipulates that no more than 49% of required reductions can come from the combination of al-

3 Phases Renewables

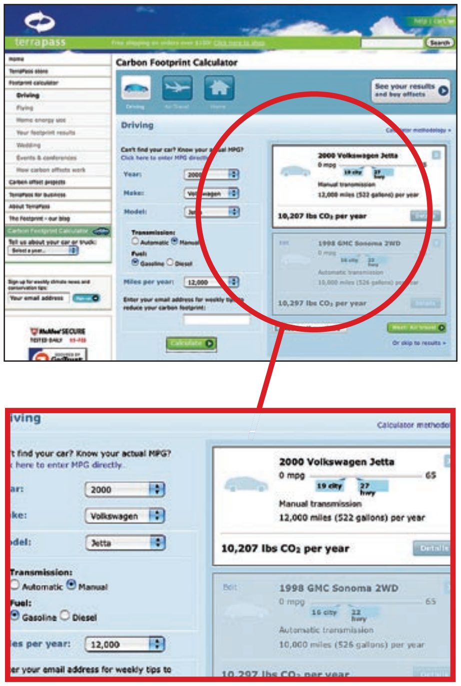
Hilarides Dairy in Lindsay, Calif., has installed covers on its manure lagoons to capture methane for electricity generation and vehicle fuel. The dairy hopes to capture the economic value of destroying methane by selling carbon offsets once the market is established.

Face Foundation 2007

The Dutch Electricity Generating Board set up the Face Foundation in 1990 to mitigate energy-related emissions via forestry. Its first project, with Innoprise Corporation, was to restore a degraded forest in Sabeh, Malaysia.


John Decker/Office of Governor Schwarzenegger

On Sept. 27, 2006, on Treasure Island in San Francisco, Gov. Arnold Schwarzenegger signed AB32, landmark legislation to address climate change by reducing California's greenhouse-gas emissions to 1990 levels by 2020. Among its provisions, AB32 authorizes the California Air Resources Board to institute market-based emissions trading.



Carbon Footprint Calculator

Driving

Can't find your car? Know your actual MPG?
Click here to enter MPG directly.

Year: 2000
Make: Volkswagen
Model: Jetta
Transmission: ○ Automatic ● Manual
Fuel: ● Gasoline ○ Diesel
Miles per year: 12,000

Enter your email address for weekly tips to reduce your carbon footprint:

2000 Volkswagen Jetta
0 mpg 65
19 city 27 hwy
Manual transmission
12,000 miles (522 gallons) per year
10,207 lbs CO_2 per year

1998 GMC Sonoma 2WD
0 mpg 65
16 city 22 hwy
Automatic transmission
10,000 miles (526 gallons) per year
10,297 lbs CO_2 per year

TerraPass is one of several organizations that allows consumers to calculate specific dollar amounts to offset their energy usage when at home, driving or flying, or for events such as weddings or conferences.

lowances outside California and of the total offsets. Verification and offset approval are emphasized.

Western Climate Initiative. The Western Climate Initiative (2008) plans to integrate its cap-and-trade program with California's trading program. The first compliance period begins in 2012 and will include emissions from electricity generation, industrial processes, and combustion at industrial and commercial facilities. The second compliance period begins in 2015, when the program will expand to include fuel combustion at smaller sources and the combustion of transportation fuels.

California's ag carbon market

Although agricultural emissions are not included in California's proposed cap-and-trade program or mandatory measures, they are under consideration for voluntary reductions and potential future measures (CARB 2008b). California agriculture will also be indirectly affected by several greenhouse-gas-reduction policies.

California Air Resources Board. In September 2008, the California Air Resources Board adopted a methodology to calculate emissions from manure digesters (CARB 2008b). Voluntary investments in manure digesters will be encouraged with, for example, marketable offset credits, renewable energy incentives and/or utility contract incentives. The possibility of making manure digesters mandatory for large dairies will be evaluated in the plan's 5-year update. The plan also indicates that the state will consider developing protocols to quantify greenhouse-gas reductions from carbon sequestration in rangelands and woodlands, although it does not yet indicate whether those protocols would be used for voluntary or tradable offsets.

Western Climate Initiative. Under the Western Climate Initiative, the development of protocols to approve offsets from agricultural soil sequestration and manure management is a priority. Approving these offsets would likely increase and eventually stabilize the agricultural offset market. Given proposed linkages between the Western Climate Initiative and the California Air Resources Board, the former's offset rules may apply in the latter's cap-and-trade program. Although the Western Climate Initiative allows states some flexibility, California would likely follow suit with tradable agriculture offsets, given its development of methods for calculating emissions reductions from manure digesters and its investigation of carbon-sequestration protocols.

Fertilizer, energy use and biomass. Emissions from fertilizer are not included in California's proposed program, but the California Air Resources Board is conducting research into nitrogen fertilizer emissions to improve baseline calculations and management practices. Additionally, the board is currently working to enforce regulations that apply to the sale of used diesel agricultural engines and to increase fleet turnover of off-road agricultural equipment. The board's scoping plan also indicates that it will consider increasing the fuel efficiency of farm equipment, using water more efficiently (which reduces greenhouse-gas emissions by reducing the energy needed to convey water) and using biomass to produce energy. The Western Climate Initiative plan explicitly considers the combustion of approved biomass and biofuels to be carbon neutral. These policies will put biofuels and energy produced from biomass — and the crops used to make them — at an advantage in the regulated markets of the future.

California's influence

Although California will learn from other trading schemes, carbon markets are still in relative infancy and their designs are being refined. While federal rules may eventually preempt regional and state efforts, California's early market designs may "serve as a model for the federal program" (CARB 2008a).

California's environmental justice community has expressed concerns about the distribution of the economic and public health effects of climate policy, and AB32 requires that reduction measures avoid disproportionate impacts on vulnerable communities. Given the California Air Resources Board's emphasis on linkages with other trading systems and the legislative requirement to develop equitable market mechanisms, if the board succeeds in reconciling the concerns of low-income and minority communities with a stable and efficient cap-and-trade system, the rules designed in California may have an important influence on the design of larger national and global cap-and-trade schemes.

Capoor and Ambrosi (2007) note that a market-based approach is only as good as the target set by policymakers and the integrity with which the market is viewed. The current carbon market is still evolving. In November 2007, the long-awaited International Transaction Log opened, and Japan became the first nation with a transparent registry system. Likewise, the Kyoto Protocol entered its commitment period in 2008, and the strengths and limitations of market-based approaches will be tested. Where markets fail, mitigation may be needed to address any unintentional inequity and environmental impacts that result from greenhouse-gas market pressures and from climate change itself.

As the California carbon marketplace begins to form and take hold, the extent to which each sector participates and the impacts on various communities will be a function of the structure and rules associated with final regulatory mechanisms. However, public confidence will depend mostly on perceptions of offset quality, the transparency of accounting, and the distribution of costs and benefits of climate policy.

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Male *Agapostemon texanus* on cosmos flower.

The buzz on urban bees

Of about 4,000 bee species known in the United States, more than 1,600 have been recorded in California. Yet as human populations and urban areas continue to expand, global evidence is mounting that pollinators, especially bees, are declining. University of California researchers at Berkeley and Davis are investigating the diversity, range and ecological roles of native bee pollinators. In the next issue of *California Agriculture* journal, they report on urban bee surveys conducted across California from 2005 to 2007. The study indicates that many types of urban residential gardens provide suitable and abundant floral and nesting resources for native bee species. Furthermore, habitat gardening for bees can increase bee diversity and abundance — providing clear pollination benefits.

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