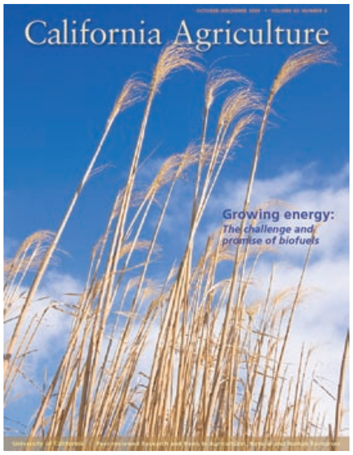
OCTOBER–DECEMBER 2009 • VOLUME 63 NUMBER 4

California Agriculture

Growing energy:

The challenge and promise of biofuels

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



COVER: Biofuels could reduce dependence on fossil fuels, but they also may affect the price and availability of food crops. Biomass crops will likely include fast-growing grasses like Miscanthus, which can be used dry (shown) or green. *Photo by Don Hamerman, University of Illinois, Urbana-Champaign*

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BIOfuels: Growing toward sustainability

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Biofuels — fuels derived from plant materials and other kinds of biomass — have ridden a rollercoaster of public debate. When Hurricane Katrina wreaked havoc on U.S. energy supplies in 2005, biofuels came into prominence as a homegrown alternative to petroleum. As world oil prices continued to rise, former President Bush heralded biofuels as one cure for the U.S. addiction to oil.

In 2006, however, scientific debate erupted over unfavorable energy balances for ethanol made from corn. These concerns receded by 2007 after more thorough and systematic review suggested modest energy gains — as well as possible reductions in climate-altering greenhouse gases. But public favor was again short-lived. Increasing food prices during 2008, perceived to be partly the result of competition between grain and fuel markets, coupled with the suggestion that intensive production and indirect land-use changes negated greenhouse-gas benefits, reignited the debate and led some to declare biofuels “a crime against humanity.” Again, thorough and systematic analysis quieted the debate, but left large uncertainties regarding the future of biofuels. Meanwhile, investment dollars dried up as the world’s economy contracted.

The complexity of issues surrounding biofuels and other types of bioenergy mirrors the structural complexity of the biomass resource that makes it valuable in myriad ways. Biomass serves multiple purposes — social, environmental, ecological, economic. Use of the resource to satisfy any significant fraction of our now vast and increasing appetite for energy will bring far-ranging consequences, and we have only recently begun to characterize standards and procedures that give us confidence to predict how such use can be sustainable. Many efforts are now under way to model global responses to different bioenergy policies and to optimize resource utilization. One of the primary, unknown quantities in global energy balance calculations is the burgeoning human population and concomitant increases in demand for energy, especially for transportation fuel. As we approach the potential carrying capacity of humans on the planet (*California Agriculture*, July-September 2006, page 106), with projected growth from almost 7 billion humans in 2008 to more than 9 billion by 2050, it remains to be seen how our energy system can be made sustainable.

The increased energy demand is exemplified by the development and production of inexpensive private autos (about $2,500) targeting consumers in developing nations, and the associated rise in numbers of vehicles on the road. Depending on economic conditions, several billion people who formerly depended on public or nonmotorized transportation will soon be able to purchase private vehicles. In India, prior to the present economic downturn, domestic car purchases nearly doubled from 2001 to 2006; while in China, private vehicle ownership has gone from 1 million to more than 40 million units in the past 17 years. The global demand for energy could soon reach staggering proportions.

Both the public and private sectors have recently made significant investments in research to make biomass conversion more economical and environmentally sustainable (see page 162). The U.S. Department of Energy, British Petroleum,

▼ The complete poplar genome has been sequenced, allowing researchers to move forward in domesticating the tree for more efficient biomass production.

Roy Kaltschmidt/Lawrence Berkeley Nat’l Laboratory

Thanks: *California Agriculture* gratefully acknowledges the faculty co-chairs for this special collection on biofuels: UC Davis Energy Institute Director Bryan Jenkins and UC Integrated Pest Management Plant Pathologist James J. Stapleton.

Chevron and others have made major grants to university and national laboratory consortia and institutes, such as the Bay Area-based Joint BioEnergy Institute (JBEI), the Energy Biosciences Institute (EBI) at UC Berkeley and the UC Davis Energy Institute, in an effort to advance bioenergy research and shorten the time to commercial deployment. Major expansion in national biofuel production is mandated by the federal Energy Independence and Security Act of 2007, under a Renewable Fuel Standard (RFS) enforcing reductions in greenhouse-gas emissions.

California seeks to reduce the greenhouse-gas intensity of transportation fuels by implementing the Low Carbon Fuel Standard (LCFS), which may also encourage greater biofuel production. Yet there is little consensus regarding pathways forward to sustainably meet this demand. For example, inclusion of the indirect effects of land-use change continues to be a central component of the debates surrounding these policies (see page 158).

Biomass applications. It is important to remember that the production of liquid transportation biofuels is only one of the applications for biomass. Other uses such as electricity, heat, hydrogen and biobased chemicals and products also offer substantial promise and possible resource competition. Given these considerations, some investigators have recently argued that electricity, rather than liquid fuel, is more efficient and environmentally preferable for the future transportation market.

Biomass has been a major source of renewable electricity for California for the past three decades. However, for economic reasons, the resource has not competed effectively against wind and geothermal power in bidding into the state's resource-neutral Renewable Portfolio Standard (RPS). Increasing use of electricity for plug-in hybrid and battery-electric vehicles, and other electric transport options, will greatly expand the market for electricity from renewable resources, including biomass. A number of developing approaches for both large-scale fuel and electricity production are likely to prove commercially successful within the coming decade. Ensuring that these and other components of our energy system are sustainable will require careful design, implementation and enforcement. Scientists, industrialists and politicians must pay attention to regional and global impacts and interactions.

Environmental concerns. Biofuel production, like any other industrial enterprise, has the potential to damage the environment, divert scarce water supplies, and lead to a number of other undesirable consequences. Indirect land-use change, which has been associated with some types of biofuel alternatives, may negatively influence atmospheric carbon balances. The use of food crops for some types of biofuels has also triggered concern about negative effects on food security for the world's urban poor. However, there is no scientific consensus on what constitutes sustainable bioenergy production practice, and not all feedstocks are equal in impact (see *Science*, July 17, 2009, Vol. 325, pages 270–1).

Public policy. Changing public policies also introduce uncertainties. We need effective mechanisms to evaluate and act upon tradeoffs among competing social and environmental objectives. California's Bioenergy Action Plan is a case in point. Established to increase jobs and wealth within the state, the plan incorporated no specific measures of sustainability to guide industry develop-

Photos: Roy Kaltschmidt/Lawrence Berkeley Nat'l Laboratory

Left, **the Joint BioEnergy Institute in the San Francisco Bay Area is focusing on developing the next generation of biofuels.**
Right, **lab technician Parul Ranar Tomar injects agrobacterium into tobacco leaves.**

ment or regulation, and our ability to model global market responses to expanding use of land, water and other bioenergy resources remains limited at best. Adaptation of the plan to address sustainability issues should be considered. Life-cycle assessment should be a factor in determining policy support and welfare analysis may provide a more comprehensive methodology to gauge impacts (see pages 191 and 199), but attention should also be given to what other fuel alternatives may emerge in the absence of substantial biofuel development. Sustainability applies to more than just biofuels and should be a guiding principle for all energy sectors.

Biofuels in California. This issue of *California Agriculture* focuses on the prospects for bioenergy, particularly the potentials and challenges for biofuels development. Californians could utilize abundant and diverse feedstocks that pose minimal competition with food production. The state currently produces a large amount of biomass as residues of agriculture and forestry, including forest management practices to reduce the threat and intensity of wildfire. Also, the urban sector produces increasing amounts of biogenic wastes, now deposited in landfills, which can serve as feedstocks for industrial energy recovery and biobased products manufacturing.

Moreover, dedicated energy-crop production could be expanded on marginal and degraded lands in the state, such as those on the west side of the San Joaquin Valley, where biomass production might help remediate salt-affected soils and drainage-impaired lands; or as a component of multicropping systems to aid in biological pest management (see *California Agriculture*, January-March 2009, page 41). Scientists have also advanced the conversion of biomass by biochemical and thermochemical means, and integrated heat, power and fuel production to optimize efficiency across a range of feedstocks and products (see page 168).

Other investigators (see page 185) have pursued plant and microbial research to improve the conversion of biomass to useful fuels and chemicals. Large energy and environmental benefits associated with the conversion of lignocellulosic materials, such as grass and wood, are limited by the inefficiency of current technology to convert complex polysaccharides into simple sugars for fermentation to ethanol and other products. Scientists are actively investigating how to better utilize other nonsugar components of cell walls. Research at JBEI and other labs seeks to develop improved enzymes for the more effective breakdown of lignocellulose and move them into yeasts and other organisms for industrial-scale processing (see pages 178).

Cost concerns. Biomass may be the only sustainable, large-scale resource for the production of compatible liquid fuels that can be readily integrated into our existing fuel infrastructure (see page 185). On a pure heating value basis, biomass feedstocks could be worth about three times their current value in comparison to crude oil at a price of $65 per barrel. However, the cost of producing ethanol from lignocellulosic feedstocks needs to be reduced in competition with current starch-based ethanol production from corn. Consolidated processes that combine biomass deconstruction and fermentation steps offer increasing fuel yields and potential cost reductions. Large-scale demonstration projects now being funded by DOE and industry should offer insights into costs of full-scale deployment.


Roy Kaltschmidt/Lawrence Berkeley Nat'l Laboratory

Sorghum is fast-growing, highly energy efficient and drought tolerant, requires minimal inputs and can grow on marginal lands. The complete genome of sorghum was published in January 2009 by the U.S. Department of Energy, Joint Genome Institute and other partners, aiding scientists in the optimization of sorghum and other crops for use as food, fodder and biofuels.

Sustainability. Sustainability must be addressed at both regional and international levels for any large-scale bioenergy development (see page 202). Governments have promoted the production of biofuels to address climate change, increase rural development and improve energy security, but are now questioning the wisdom of such policies with respect to the possible ramifications on food production and environmental quality. However, a framework that emphasizes resource-use efficiency can help identify sustainable approaches. Systems creating greater outputs for declining inputs generally constitute a move toward sustainability. In addition, public policy should distinguish among biofuels in terms of their impacts on carbon emissions, biodiversity, water and air pollution, and food availability.

The international Roundtable on Sustainable Biofuels and a number of other groups are currently in the process of defining international standards for sustainable production. The California Biomass Collaborative, a consortium of industry, government, academic, environmental and nongovernmental organizations, has recommended that performance-based sustainability standards guide future biomass development in the state. For the near-term, progress in larger scale development will require flexible, adaptive policies that also offer security for financial investment. The articles that follow assess the challenges and opportunities at hand, and offer recommendations for future policy, regulation, development and research.

Biofuel terms defined

Bioenergy is energy derived from **biomass** (living and recently living organisms). It is renewable energy if the biomass used is replenished by new growth.

Bioethanol or ethanol (C_2H_5OH) is an alcohol made by fermenting the component sugars in biomass. It can be used as a fuel for cars either in pure form, or blended with another fuel such as gasoline.

Biofuels are produced from biomass, including sugar- and starch-rich crops; oilseeds and other lipid sources such as certain types of algae; and lignocellulosic crops and residues such as grasses, woody plants, and plant or animal wastes. Biofuels can be liquids, gases or solids — alcohols or biodiesel, biogas, charcoal, and more.

Carbon intensity, as used in California's LCFS, is total direct and indirect greenhouse-gas (GHG) emissions per unit of energy produced in the full cycle of a transportation fuel. It is expressed in grams CO_2-equivalent per Megajoule (g CO_2e/MJ).

Energy balance is the total amount of energy used in a production process compared, on an equivalent basis, to the energy yielded in the resulting fuel.

Energy Independence and Security Act (EISA) of 2007 requires, among other things, that the annual total amount of biofuels in the United States increases to 36 billion gallons by 2022, from 4.7 billion gallons in 2007.

Indirect land-use change (iLUC), although part of California's LCFS regulation, is subject to debate. "Land-use change" by itself can be more or less beneficial, but may also result in release of carbon originally stored in the soil or as standing biomass, increasing GHG in the atmosphere, and reducing the overall GHG savings over a biofuel's life cycle. An iLUC occurs when a change in one location also induces a change in land use elsewhere, such as an increase in U.S. corn production for ethanol inducing rainforest conversion to agriculture elsewhere in the world.

Life-cycle analysis (LCA) is the assessment of environmental impacts of a given product or service over its full lifetime. This includes impacts of raw material production, manufacture, distribution, use and disposal. The extent to which an LCA includes iLUC and other effects depends on where the system boundary is drawn.

Lignocellulose is the structural component of biomass that makes up much of the tough, "recalcitrant" cell walls of plants, and poses technical hurdles for some second-generation, or cellulosic biofuels. It is composed of variable amounts of complex sugars (cellulose and hemicellulose) tightly bound to lignin.

Low Carbon Fuel Standard (LCFS), ordered by Governor Schwarzenegger in January 2007, calls for at least a 10% reduction in the carbon intensity of California's transportation fuels by 2020, relative to a 2010 baseline. The California Air Resources Board (CARB) approved adoption of LCFS regulations in April, including use of iLUC effects in computing carbon intensity for certain types of biofuels.

Pyrolysis is decomposition by heat to produce gases, liquids and char (solid residue); all can be used as fuels, or utilized as feedstocks for chemical or material industries.

Renewable energy is generated from natural resources (sunlight, wind, tides, biomass and others) and replenished in a sustainable cycle of use and replacement.

Renewable Fuel Standard (RFS), under the EISA, mandates renewable fuel production volumes over time in the United States for various classes of biofuels and enforces reductions in GHG emissions by fuel type.

Renewable Portfolio Standard (RPS), enacted in California in 2002 and accelerated in 2006, requires electricity corporations to expand their renewable energy portfolios by 1% each year until reaching 20% in 2010. Governor Schwarzenegger also ordered the state's electricity providers to supply 33% of their electricity from renewable sources by 2020, and recently charged the CARB with adopting a regulation by July 31, 2010, to achieve that goal.

Thermochemical processing is the conversion of biomass by the action of both heat and chemical reaction, and includes pyrolysis, gasification and combustion.

About California Agriculture

California Agriculture is a quarterly, peer-reviewed journal reporting research, reviews and news. It is published by the Division of Agriculture and Natural Resources (ANR) of the University of California. The first issue appeared in December 1946, making it one of the oldest, continuously published, land-grant university research journals in the country. The circulation is currently about 15,000 domestic and 1,800 international.

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.

Indexing. The journal is indexed by AGRICOLA; Current Contents (Thomson ISI's Agriculture, Biology and Environmental Sciences, and the SCIE databases); the Commonwealth Agricultural Bureau (CAB) databases; EBSCO (Academic Search Complete); Gale, including Lexis-Nexis; Google Scholar; Proquest; and others including open-access journal databases. It has high visibility in Google searches. Peer-reviewed articles are posted at the California Digital Library's eScholarship Repository.

Authors. Authors are primarily but not exclusively from UC ANR; in 2007 and 2008, 22% and 15% (respectively) were based at other UC campuses, or other universities and research institutions.

Reviewers. In 2007 and 2008, 19% and 14% (respectively) of reviewers came from universities and research institutions or agencies outside ANR.

Rejection rate. Our rejection rate ranged between 20% and 25% in the last two years, and in the year ending May 31, 2008, associate editors sent back 24% of manuscripts for major revision prior to peer review.

Peer-review policies. All manuscripts submitted for publication in *California Agriculture* undergo double-blind, anonymous peer review. Each submission is forwarded to the appropriate associate editor for evaluation, who then nominates three qualified reviewers. If the first two reviews are affirmative, the article is accepted. If one is negative, the manuscript is sent to a third reviewer. The associate editor makes the final decision, in consultation with the managing and executive editors.

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The 50th anniversary of a great idea

Landmark *Hilgardia* article on "integrated control" considered "most important" pest control paper of 20th century

Fifty years ago in October, four pioneering University of California scientists outlined a new way of thinking about pest control, establishing a pest management framework that changed the way the world farms.

The scientists recognized — way ahead of their time — that imposing a harsh chemical on a natural system threw it off kilter, causing many more problems in the long run. They believed that combining an array of pest control methods would be more effective, safer for farmworkers and kinder to the environment. The scientists proposed:

- Recognition that agriculture is part of the larger ecosystem, comprised of all the living organisms of an area and their environment.
- Supervision of insect levels so that chemical applications take place only when and where they are absolutely necessary.
- Promotion of beneficial insects through conservation and augmentation.
- Use of products and application timing to target specific pests, minimizing the effect of treatment on pests' natural enemies.

Vernon M. Stern, Ray F. Smith, Robert van den Bosch and Kenneth S. Hagen presented their ideas in a landmark and often-cited article published in the October 1959 agricultural science journal *Hilgardia*, published by the UC Division of Agriculture and Natural Resources. The 20-page paper clearly and concisely described the consequences of pesticide overuse and detailed their vision of a sustainable pest control system.

None of the paper's four authors is alive today. All of them are probably best remembered for their role in inventing integrated pest management (IPM).

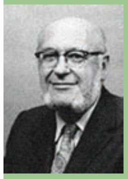
"In essence, they laid the foundation of all IPM methods that we use today," says Peter B. Goodell, UC IPM advisor with the UC Kearney Agricultural Center near Parlier. "The concept is so fundamental, we haven't added much to it. We've just nibbled around the edges and refined it for individual crops and pests."

At the time the article was published, Stern, Smith, van den Bosch and Hagen could only have dreamed that their ideas would spread across the globe, prompt the development of a new scientific discipline, and be credited with substantially reducing the use of pesticides while making farming more efficient and sustainable.

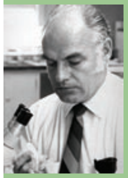
They wrote their seminal treatise about agriculture's unhealthy dependence on pesticides several years before Rachel Carson published *Silent Spring*.

Founders of IPM

Vernon M. Stern (1923–2006) served on the entomology faculty at UC Riverside for 35 years, until his retirement in 1991. Throughout his career, he worked on developing the integrated control concept to improve management of lygus bugs in cotton. For example, he led work that showed strip cutting of alfalfa could dramatically reduce lygus migration into cotton and subsequent damage.



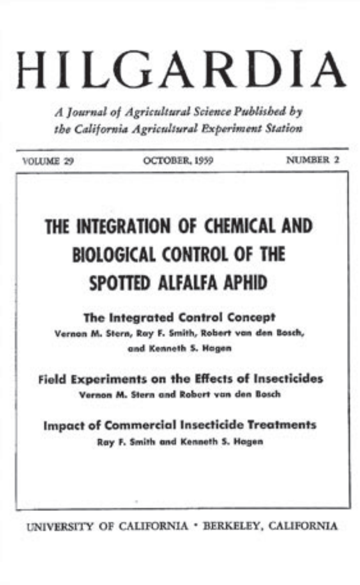
Ray F. Smith (1919–1999) was an entomology professor at UC Berkeley. He worked with key international agencies to carry the new pest strategy around the world. In 1974, he organized the United Nations Food and Agriculture Organization's Global Project for Integrated Pest Management for Major Crops, and soon thereafter initiated projects on cotton, rice and food crops in Africa, the Near East and Asia. The *Hilgardia* paper was hailed by the National Academy of Sciences as "the single most important paper published on crop protection in this century" when Smith was elected to the academy in 1981.



Robert van den Bosch (1922–1978) began his career as an entomology professor in biological control at UC Riverside and transferred to UC Berkeley in 1963. His concern for the environment and other broad concerns of society were expressed in talks and writings to his colleagues and students, and to farmers, politicians, farmworkers, environmentalists, agribusiness employees and lay people all over the world. His strongly held convictions were brought together in his last book, *The Pesticide Conspiracy*, published in 1978 and still in print today. In his book, he calls integrated pest management a "technology." "It is scientific pest control and, as such, the only way we can hope to gain the upper hand in our battle with insects." The Robert van den Bosch Scholarship in Biological Control is awarded to doctoral students at UC Berkeley each year.

Kenneth S. Hagen's (1919–1997) research career covered some 50 years of service at UC Berkeley. Although he retired in 1990, he continued full-time research and teaching until the day of his death. Hagen's accomplishments in research were widely recognized and respected internationally. He was a world authority in several areas of entomology and biological control. Perhaps his favorite research topic was the behavior and biology of ladybird beetles.

Jack Kelly Clark



HILGARDIA

A Journal of Agricultural Science Published by the California Agricultural Experiment Station

VOLUME 29 OCTOBER, 1959 NUMBER 2

THE INTEGRATION OF CHEMICAL AND BIOLOGICAL CONTROL OF THE SPOTTED ALFALFA APHID

The Integrated Control Concept
Vernon M. Stern, Ray F. Smith, Robert van den Bosch, and Kenneth S. Hagen

Field Experiments on the Effects of Insecticides
Vernon M. Stern and Robert van den Bosch

Impact of Commercial Insecticide Treatments
Ray F. Smith and Kenneth S. Hagen

UNIVERSITY OF CALIFORNIA • BERKELEY, CALIFORNIA

Effective integrated pest management (IPM) is based on regular monitoring and good record keeping. *Above*, an IPM scout inspects plants for disease. *Right*, "The Integrated Control Concept," a seminal article published in the October 1959 *Hilgardia*, provided the foundation for modern IPM.

In fact the four men are considered the fathers of IPM. They wrote their seminal treatise about agriculture's unhealthy dependence on pesticides several years before Rachel Carson published *Silent Spring*, the 1962 classic that some believe kick-started the environmental movement.

Both stories begin with the sudden availability of DDT after World War II. DDT's effectiveness at killing pests on contact lifted the heavy burden of pest management from the shoulders of farmers laboring to feed the nation. At first, the chemical seemed almost magical. But it didn't take long before farmers and scientists realized that it put U.S. agriculture on a fast-moving pesticide treadmill.

An example cited in the *Hilgardi*a article is the 1947 explosion of cottony cushion scale in citrus. Widespread use of DDT to control other citrus pests in the San Joaquin Valley virtually eliminated the scale's natural enemy, the vedalia beetle. Another unintended consequence of DDT use was eggshell thinning in birds of prey, waterfowl and song birds, which put the populations of bald eagle, brown pelican, peregrine falcon and osprey into severe decline.

DDT was banned for all agricultural uses in 1972, but its initial success had spurred research in the chlorinated hydrocarbon chemistry and stimulated the development of other organic pesticides, the 1959 *Hilgardia* article said. The authors did not oppose chemical pest control in agriculture. "Without question, the rapid and widespread adoption of organic insecticides brought incalculable benefits to mankind, but it has now become apparent that this was not an unmixed blessing," they wrote.

They advocated the for judicious use of chemical control measures in an integrated systems approach. "Integrated control," they wrote, "is most successful when sound economic thresholds have been established, rapid sampling methods have been devised and selective insecticides are available."

UC IPM entomologist Walt Bentley, who worked with Stern early in his career, says the four men's foresight was inspiring.

"I am just amazed that work done in the mid-1950s, and published in 1959, listed worker safety and the almost unheard-of potential for litigation," Bentley says. "I don't think at the time they knew DDT was causing the thinning of raptor egg shells, but they understood that you could overuse a product with broad toxicity and end up with no pest control at all over time."

The IPM techniques outlined in the *Hilgardia* paper are also applicable in home gardens and landscapes. Cheryl Wilen, UC IPM horticulturist based in San Diego County, advocates the use of the same concepts in landscapes and gardens that have proven so successful in agriculture.

"People will see an insect or weed problem and ask, 'What is it and what can I do to control it now?'" Wilen says. "IPM is really a long-term sustainable program. I tell them, 'This is what you have, this is what you can do, and this is what you can do prevent the problem from recurring.'"

— Jeannette Warnert

Biofuels caught in changing regulations

The role of land-use changes and carbon emissions is being debated by scientists and policymakers

California's new regulations for transportation-fuel carbon emissions are shaking up the biofuels industry. When biofuels first took off, corn ethanol was touted as having the potential to cut carbon emissions by nearly 20%. But now the carbon intensity of corn ethanol can exceed that of gasoline under the state's Low Carbon Fuel Standard (LCFS), which was adopted in April 2009 and requires a 10% cut in greenhouse-gas emissions by 2020. Moreover, the impact of the new regulations could be widespread because they are set to be the basis of fuel standards elsewhere in the country and world.

"Two years ago crop biofuels were elevated as saviors, now they're seen as a negative force," says Pamela Ronald, a UC Davis plant pathologist and vice president of feedstocks at the Emeryville-based Joint BioEnergy Institute. "But the science hasn't changed at all."


UC San Diego

Jim Demattia

The San Diego Center for Algae Biotechnology (SD-CAB), a partnership led by UC San Diego, is developing innovative methods for converting algae into biofuels. *Top*, postdoctoral associate Dawn Adin examines streaks of algae in the lab of Susan Golden, UC San Diego professor of biological sciences. *Above*, "raceway" ponds at a 40-acre algae farm located east of the Salton Sea in the Imperial Valley circulate 20,000 to 37,000 gallons of growing algae to test the feasibility of large-scale commercial production.

What has changed is the way California estimates carbon emissions from transportation fuels. Under the LCFS, the carbon intensity of a fuel accounts for all emissions, from production to use. In addition, crop-based biofuels are accountable for emissions from converting wildlands to agriculture because this releases plant and soil carbon dioxide into the atmosphere.

Called land-use changes, these conversions can be direct or indirect. The former include conversions of nonagricultural land to cornfield, while the latter include conversions of soybean to corn field that in turn result in nonagricultural land–to-soybean conversions elsewhere, to satisfy global demand. Including indirect land-use change is what bumped up corn ethanol's average carbon intensity in the new regulations.

Controversy over indirect land-use change

Scientists are mixed on holding biofuels accountable for indirect land-use changes. Opponents include David Zilberman, a UC Berkeley agricultural and resource economist. "It's arbitrary, difficult to calculate and damaging in the long run," he says. "It will impede the industry. People will think twice about investing in advanced, second-generation biofuels."

On top of that, Zilberman does not think the new regulations will work. "It's like a band-aid. The state is trying to solve a global problem with a local solution," he says. Instead, Zilberman advocates accounting for just direct carbon emissions combined with land protections such as ecological service–based fees or bans on biofuels produced from converted wildlands.

Similarly, Ronald and more than 100 other California scientists signed a letter in March 2009 asking the state not to penalize biofuels for indirect land-use changes. "It doesn't make sense to burn down tropical forests or use really fertile agricultural land for crop biofuels, because there are other ways to produce biofuels," Ronald says. "The biofuel industry can plant perennial grasses rather than corn on marginal or abandoned agricultural lands."

The biofuel industry also has options even under the new LCFS. For example, corn ethanol's carbon intensity varies with the production method, ranging from 10% more than gasoline for biorefin-

UC biofuel research centers

Bioenergy Research Group (BERG): Established in 2005, BERG is part of the UC Davis Energy Institute and includes more than 100 campus researchers from across the sciences and economics. BERG focuses on bioenergy development and policy, and includes work funded by a 5-year, $25 million grant from Chevron for developing affordable, renewable transportation fuels from farm and forest residues, urban wastes and crops grown specifically for energy (bioenergy.ucdavis.edu).

California Biomass Collaborative (CBC): CBC is part of the statewide California Renewable Energy Collaborative, which is managed by the UC Davis Energy Institute, and includes more than 500 members from government, industry, academia and environmental organizations. Established 2003, CBC has a 2-year, $800,000 grant from the California Energy Commission to coordinate the development of sustainable bioenergy, focusing on feedstock supply, energy conversion and environmental impacts (biomass.ucdavis.edu).

Energy Biosciences Institute (EBI): Established in 2007, EBI is a partnership of UC Berkeley, the Lawrence Berkeley National Laboratory and the University of Illinois. With a 10-year, $500 million commitment from BP, more than 300 researchers will initially focus on developing clean next-generation biofuel from sustainable sources such as nonfood crops. EBI provides data to help policymakers minimize the environmental impacts of biofuels. (see page 165) (www.energybioscienceinstitute.org).

Joint BioEnergy Institute (JBEI): Led by Lawrence Berkeley National Laboratory, JBEI includes Sandia National Laboratories, Lawrence Livermore National Laboratory, UC Berkeley and UC Davis, and the Carnegie Institution for Science. One of three such centers nationwide funded by the U.S. Department of Energy (DOE), JBEI was established in 2008 with a 5-year, $135 million DOE grant, and focuses on developing the next generation of biofuels from plant biomass. (www.jbei.org).

San Diego Center for Algae Biotechnology (SD-CAB): Established in 2008, SD-CAB is a partnership of UC San Diego, Scripps Institution of Oceanography, The Scripps Research Institute and private industry. SD-CAB's goal is developing biofuels from algae, fast-growing plants that thrive in salt water and wastewater, and can yield up to 50 times more oil per acre than food crops (algae.ucsd.edu).


Roy Kaltschmidt/Lawrence Berkeley Nat'l Laboratory

U.S. Department of Energy undersecretary Kristina Johnson (left) discusses Arabidopsis plants with Josh Heazlewood, the Joint BioEnergy Institute's director of systems biology.

eries fired by coal to nearly 20% less than gasoline for those fired by natural gas, and lower still for those fired by biomass. "The LCFS is a performance standard, so the industry can make changes to meet the requirements," says Bryan Jenkins, a UC Davis biological and agricultural engineer who directs both the UC Davis Energy Institute and the California Renewable Energy Collaborative.

Supporters of California's approach to biofuel standards include Chris Somerville, a UC Berkeley plant biologist who directs the UC Berkeley–based Energy Biosciences Institute (EBI). "In my opinion, the sole purpose of biofuels is to do something that's environmentally positive, and the argument for including indirect land-use change is good," he says. However, Somerville cautions that further evaluation is needed before calculating carbon emissions from indirect land-use changes.

"The big question is how to calculate it — the data are not good," Somerville says, adding that so far the state has set standards for only corn and sugar cane ethanol, and that EBI economics research will help the state set standards for additional biofuels. About 90% of conventional biofuels are bioethanols from a variety of starch- or sugar-rich crops, and the rest are biodiesels from vegetable oil, used cooking oil and animal fat.

Beyond California

The controversy over California's LCFS notwithstanding, more states may be poised to adopt similar regulations. Eleven Northeastern and Mid-Atlantic states have committed to developing a regional LCFS based on California's, and they expect to draft a memorandum of understanding (MOU) by the end of 2009. Likewise, British Columbia and Ontario signed a 2007 MOU to match California's LCFS.

The U.S. Environmental Protection Agency also included accounting for indirect land-use changes in

Photo credits, *left* to *right*: Roy Kaltschmidt/Lawrence Berkeley Nat'l Laboratory; Peggy Greb/USDA-ARS; Stephen Ausmus/USDA-ARS; Wikimedia Commons *

Potential biofuels, *left* to *right*. Biomass from eucalyptus, an oily Australian hardwood, could be heated at high temperatures to produce "bio-oil" for fuel. Native to the North American prairie, switchgrass has been used for conservation plantings and cattle feed; it produces high yields with minimal inputs, and can sequester carbon in soils for extended periods. Poplar hybrid trees are characterized by rapid growth and easy propagation. Rice hulls are currently being burned for electricity, and rice straw can be converted into low-cost ethanol.

a May 2009 proposal for new, national, renewable fuel standards. However, now the agency plans to wait 5 years for further evaluation, Somerville says. This approach is in keeping with that of the European Union, which in 2008 adopted a revised Fuel Quality Directive stipulating that biofuels must be produced sustainably but waiting until the end of 2010 to set any standards accounting for indirect land-use changes.

Other aspects of transportation-fuel standards could also use re-evaluation, Jenkins says. For example, currently indirect land-use change applies only to biofuels, which could unfairly put them at a disadvantage. "Implementing sustainability standards only on bioenergy or biofuels may lead to market distortions for these types of energy," Jenkins says. "Rather, standards should be applied across the energy sector."

Advanced biofuels

Whatever the ultimate outcome, current trends in regulating crop biofuels increase the urgency of developing advanced biofuels from noncrop plant materials such as algae and grasses. Conventional bioethanol comes from plant-derived sugars that either are naturally abundant in sweet crops or are easily made from starches abundant in crops such as corn. While advanced or cellulosic bioethanol also comes from plant-derived sugars, these are made from lignocellulose and other cell-wall compounds that are currently difficult to break down efficiently.

Once production is optimized, however, advanced biofuels have the potential to decrease carbon emissions by 70%, according to the International Energy Association. Promising feedstocks for advanced biofuels include agricultural residue, which is plentiful in California; logging and tree thinning residue, which is plentiful in California and the Pacific Northwest; switchgrass, which is native to Midwest; and municipal green waste.

Beyond carbon

The new California regulations could also favor biofuels from nonfood crops that are grown either in rotation with food crops or as cover crops. Good candidates include grasses and mustards, which could yield bioethanol and biodiesel, respectively. Nonfood crops can also offer additional environmental benefits, such as controlling soil pests and clearing soil of selenium and other toxic elements or compounds. "Right now the focus is on global climate change but there are many other important environmental issues," says James Stapleton, plant pathologist and natural resources coordinator for the UC Statewide Integrated Pest Management program. "We also have to consider soil, water and other air-quality issues" (see *California Agriculture*, Vol. 63, No. 1).

However, favoring nonfood crop biofuels could also have drawbacks. "Although this is politically expedient, it may very well limit industry innovation and farm production options," Jenkins says.

As EBI's Somerville observes, nothing is black and white when it comes to biofuels. But he remains optimistic, adding that "we're having a good debate and going in a good direction."

— Robin Meadows

*After press run, original photo of wild rice replaced with image of Japonica species, predominant in California rice production. Credit: Wiki Commons.

Dozens of UC research projects pursue fossil-fuel alternatives

Energy Biosciences Institute seeks renewable, sustainable, environmentally friendly biofuels

Now completing its second year of a 10-year funding commitment from the energy company BP, the Energy Biosciences Institute (EBI) finds itself a central player in the international network of scientists looking for sustainable, renewable, environmentally friendly alternatives to transportation fossil fuels. With headquarters in Berkeley and a satellite unit at the University of Illinois, EBI has launched 51 different research projects in an effort to develop an integrated, holistic understanding of the energy biosciences. Cellulosic biofuels, prime targets in the EBI mission, are unusually complex and involve research questions not only in the production area (see pages 178 and 185) but also concerning social and economic impacts on other regions and nations.

"No miracles are required to develop cost-effective cellulosic biofuels," says Chris Somerville, UC Berkeley plant scientist and EBI director. "A series of two-fold improvements in the efficiency of various steps could make biofuels less expensive than liquid fossil fuels."

However, implementing rational improvements in the overall process is challenging. Managing the various components will require coordinated, integrated knowledge from many scientific and engineering disciplines. This is what EBI was established to do, and scientists at UC Berkeley, Lawrence Berkeley National Laboratory (LBNL), and University of Illinois are heavily into the collaborative quest. This fall, another call for proposals was issued by EBI, and 10 to 15 additional programs or projects will be under way by 2010. BP has pledged $500 million for a decade of research.

Other major UC participants in the search for biofuels include EBI's neighbor to the north, the Joint BioEnergy Institute (JBEI) in Emeryville, as well as the California Biomass Collaborative and the Bioenergy Research Center, both based at UC Davis, and the San Diego Center for Algae Biotechnology at UC San Diego (see box, page 163).

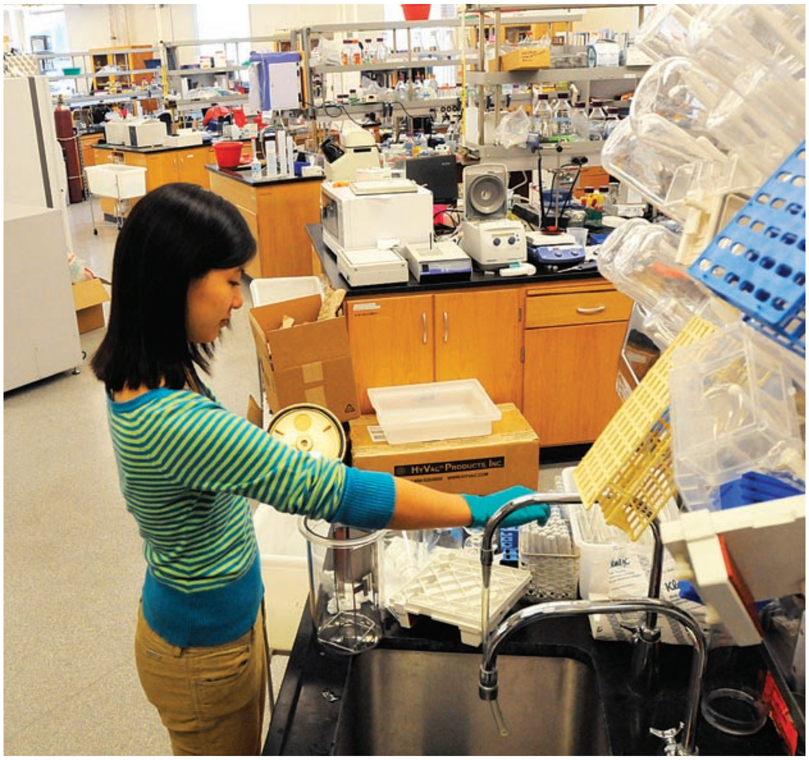
Research questions

EBI is interested in addressing three main questions. First, how much land can be used sustainably for cellulosic fuel production around the world without negatively affecting food production or the environment? Second, which types of plants can be used for energy, how can they be grown sustainably with minimal inputs, and how can they be harvested, stored and transported to the point of utilization? And third, what are the most efficient ways of converting cellulosic biomass to liquid fuels?

"This involves a broad investigation of how various types of organisms — ranging from those found in compost heaps to the complex systems in termite guts and cow rumen — degrade biomass," Somerville says. "Work is also proceeding on new chemical catalysts that can convert the components of biomass to novel fuels."

In each of five primary work areas, EBI has established interactive teams, which now total more than 130 faculty members and 160 graduate students, postdocs and undergraduates.

Feedstocks. It begins with the feedstocks, those crops that will provide the biomass from which fuels can be developed. Relying greatly upon a 320-acre "energy farm" near the Urbana-Champaign campus in Illinois, agronomists are searching for the ideal plant that will provide high productivity


Peg Skorpinski

Scientists are looking for better ways to convert plant sugars into fuel, by utilizing organisms and enzymes that can efficiently degrade cell walls. *Above*, UC Berkeley undergraduate researcher Valerie Chan works in the Calvin Laboratory, where three Energy Biosciences Institute projects are under way.

***Above*, at the Energy Biosciences Institute's Energy Farm in Illinois, researchers are comparing biofuel production methods. *Inset*, postdoctoral student Matthias Hess of the Joint Genome Institute and EBI's bovine rumen project stands with Miscanthus in an Illinois field.**

with a minimum of inputs. Further, the feedstock should involve no displacement of food crops, no major water requirements and a reduction in net greenhouse-gas emissions.

One species receiving particular attention is a perennial grass called Miscanthus, whose 70% solar conversion rate is 60% more productive than corn, from which ethanol is currently made.

"Miscanthus also possesses a root system that binds the soil and prevents erosion while providing nutrients to the plant, high productivity in temperate climates and sustainability via carbon sequestration," says EBI deputy director Steve Long, who oversees the Institute's agronomy program in Illinois. Researchers are modeling Miscanthus for solar radiation, water content and soil depth to predict yields under varying conditions.

Fuel conversion. Once the optimal feedstock has been identified for a particular region, the hard work begins — converting the cellulose-based plant material into fermentable sugars on a commercial scale. EBI is attacking the problem on several fronts: the discovery and characterization of fungi and thermophiles that produce new enzymes for lignin and cellulose deconstruction; protein engineering and kinetic modeling of improved enzymes; new organism discovery and cellular engineering for enhanced biofuel production and improved tolerance of the biofuel product; and bioprocess engineering to optimize fermentation.

In Berkeley, for example, teams are collaborating on understanding the mechanisms of *Neurospora crassa*, a model fungus that breaks down woody fiber, and the way its enzymes, transporters and regulators function. The excellent genetic resources available in *N. crassa* have allowed the researchers to undertake a systematic analysis of what each gene contributes to biomass degradation. Another set of researchers is probing the digestive properties of microbes found in the stomach of cows, in search of enzymes that might be produced or engineered for commercial application. And other groups are probing the physical, biological and chemical basis for the enzymatic activity.

Lignin, the complex binding compound in plant cells that can constitute up to 30% of the cellulosic biomass, is especially problematic for deconstruction. Through imaging and chemical analysis, EBI scientists are studying nature's unique systems in hopes that chemical reactions can be discovered to undo what the millennia have evolved.

Biofuel production. Then there is the actual biofuel production, by methods such as fermentation — the basic practices used to make beer and wine — and chemical transformations. EBI is exploring several options in parallel. One is using the techniques of systems biology to characterize new types of microbes and by testing genetic modifications of promising organisms. This involves researching chemical and fermentation routes to products more hydrophobic than ethanol and butanol. The investigation of the pathways that will lead to the large-scale production of high-density fuels involves the development of new genetic analysis tools, the study of single-cell gene expression and genome-scale modeling.

EBI is also addressing nonbiological approaches to deconstructing biomass and converting the products into biofuel alternatives. One idea is the potential use of ionic liquids — salts containing organic cations — to dissolve virtually all cellulosic components of biomass at or near room temperature. Upon hydrolysis, the glucose produced can be converted to a variety of products by combinations of acid and metal catalysts.

"Early research results indicate that the option is certainly worth pursuing, either as a stand-alone chemical process or in conjunction with biological methods," says UC Berkeley chemical engineer Alex Bell, who heads the biofuel chemistry team.

Exploring ecosystem impacts

Global impacts. Meanwhile, dozens of researchers are working to understand the potential environmental, economic and societal impacts of meeting a growing portion of the world's energy needs through cellulosic or algal biofuels. They are working to understand how land is used around the world, and to model the impacts of growing bioenergy crops on current cropland that is not used for food production, or land that provides key ecosystem services such as carbon storage or biodiversity (see pages 191 and 202).

One team is using five models to conduct geospatial analysis, bioenergy crop modeling and agroeconomic analysis around the globe. One of the first tasks is looking at marginal lands, which are prospective targets for growing Miscanthus and other feedstocks. They are exploring new and better modeling techniques by assimilating the elements of existing systems. The decision support tools that emerge will help to identify prioritized land based on crop value, pasture value and the optimization of soils.

Another team is studying the entire life cycle of a biofuel, to provide models of greenhouse-gas emissions and realistic numbers for each stage of development and use, all of which will result in human health and ecosystem impacts. "The overarching metric is money — the total cost of ecosystem services and environmental impacts," says UC Berkeley environmental engineer Arpad Horvath, whose team is analyzing the entire life cycle of a biofuel. He said metrics will be developed for human health, natural environments, natural resources, human-made environments and life-support systems.

Economics and policy. World economics is another area of intense study. The price of energy is extremely flexible, and future biofuel pricing will be dependent on imports and exports of fuel, corn and oil costs, demand for foreign oil, and government mandates and standards. With this much volatility in the market, fiscal viability for processors and growers becomes difficult.

EBI groups are closely watching two policies that will affect the future of biofuels: the federal Renewable Fuels Standard, which requires 36 billion gallons of biofuel to be blended with gasoline by 2022, and the state Low Carbon Fuel Standard, which calls for a reduction of at least 10% in the carbon intensity of California's transportation fuels by 2020. EBI researchers will evaluate the impacts of these policies on the economics of the energy sector and the environment.

Microorganism biology

One other area of interest was added to the EBI portfolio in 2009. Significant populations of microorganisms are found in both coal and petroleum reservoirs deep underground. These microbial populations can be potentially positive influences, with activities such as altering the porosity of the reservoirs, allowing the more efficient recovery of oil. Studies are under way to characterize the organisms found in various reservoirs using the tools of modern biology.

"By understanding the genomics of the reservoir microbes, it may be possible to infer how their activities can be better controlled toward useful purposes," says LBNL senior earth scientist Terry Hazen. Initial research in what is called Microbially Enhanced Hydrocarbon Recovery (MEHR) has begun in a demonstration injection well in Decatur, Ill.

— Ron Kolb

Peg Skorpinski

Chris Somerville (center), director of the Energy Biosciences Institute in Berkeley, shows Miscanthus seedlings to postdoctoral students Christian Voigt (left) and Bill Underwood.

Sustainable use of California biomass resources can help meet state and national bioenergy targets

by Bryan M. Jenkins, Robert B. Williams,
Nathan Parker, Peter Tittmann, Quinn Hart,
Martha C. Gildart, Steve Kaffka,
Bruce R. Hartsough *and* Peter Dempster

Biomass constitutes a major renewable energy resource for California, with more than 30 million tons per year of in-state production estimated to be available on a sustainable basis for electricity generation, biofuels production and other industrial processing. Annually, biofuel production from these resources could exceed 2 billion gallons of gasoline equivalent, while providing opportunities for agricultural and rural economic development. Continuing research and large-scale demonstrations now under way will test alternative technologies and provide much-needed information regarding costs and environmental performance. Biomass can help meet state goals for increasing the amounts of electricity and fuels from renewable resources under the Renewable Portfolio Standard (RPS) and the Low Carbon Fuel Standard (LCFS), and can similarly help meet national biofuel targets under the federal Renewable Fuel Standard (RFS). Internationally consistent sustainability standards and practices are needed to inform policy and provide direction and guidance to industry.

Wadham Energy power plant in Colusa County near Williams generates 26.5 megawatts of electricity from rice hulls, enough to power about 22,000 homes. The plant is one of about 30 operating in California that generate electricity from solid biomass.

From the time humans first learned to control fire a quarter of a million years ago or more, biomass has served as an important energy resource. Harnessing fire enabled greater control over natural ecosystems and the eventual development of agriculture, which supported increasing populations. As technological sophistication increased, traditional uses of biomass — mostly inefficient and polluting open fires for land clearing, cooking, heating and lighting — evolved to take greater advantage of this chemically complex resource. Although traditional uses are still widely practiced throughout the world and are often associated with undesirable consequences to health and the environment, more modern, sustainable approaches to utilizing biomass offer significant promise for environmental improvement and economic benefit.

The existence of fossil fuels is principally due to ancient growth and the geological conversion of algae and higher green plants to coal, petroleum and natural gas. As understanding and awareness of how current energy use affects local, regional and global environment and politics, the need for more renewable and sustainable energy supplies and greater energy-use efficiency becomes increasingly apparent, even though huge fossil resources remain — especially as coal but also as oil sands, oil shales, methane clathrates and other unconventional sources (Rogner 1997). Replacing all or any large share of the fossil fuel used globally each year — a projected 88 billion barrels of oil equivalent in 2010 (EIA 2009) — will not be easy, but the gains to environmental, economic and social health should be enormous. Solar energy is the primary energy resource of the Earth, and exclusive of breakthroughs in controlled thermonuclear fusion, the quest for more sustainable energy supplies must lead to a highly efficient solar economy including direct solar power conversion as well as indirect methods of wind, hydroelectric power plants, the ocean and biomass.

Biomass is living material. As a feedstock for energy and industrial products, biomass refers to biologically derived renewable materials (but not fossil fuels or materials derived from fossil fuels) (Jenkins 2005). Conventional food, feed and fiber products from agriculture and forestry can also serve as bioenergy feedstocks. Corn, for example, is a staple cereal grain, but is also the primary feedstock for U.S. ethanol production; and cane sugar is the principal source of ethanol in Brazil. The definition of biomass properly excludes plastics, rubber and tires found in municipal wastes. As renewable feedstocks replace petrochemicals in the manufacturing of synthetic polymers, these materials will add to the biomass resource.

Coupled with carbon capture and storage (carbon sequestration), biomass production is one of the few methods of removing surplus carbon from the atmosphere while adding to the energy supply. The sustainable use of biomass can reduce reliance on imported forms of energy, particularly petroleum, and provide other ecological and economic benefits. However, in the large-scale production of biofuels envisioned for the United States, Europe and elsewhere, importing biomass feedstock and manufactured biofuels may also become commonplace.

Large questions must be addressed concerning the potential magnitude of the bioenergy supply, renewability of this resource, sustainability of production and utilization practices, feasibility of advanced technologies for converting biomass to fuels and other products, and costs and benefits of a growing industry and commerce built around biomass. Concerns over indirect land-use changes arising from national biofuel policies have recently intensified the debate over the sustainability of biofuel production and raised questions regarding reductions in global greenhouse-gas emissions (Searchinger et al. 2008) (see page 191).

These concerns have created regulatory uncertainty in formulating California's Low Carbon Fuel Standard (LCFS), although indirect effects are incorporated into recent California Air Resources Board resolution 09-31 relating to LCFS implementation (CARB 2009). As Europe found with bioenergy targets, lack of appropriate sustainability standards can trigger concerns over the longer range impacts of what are intended as environmentally and socially beneficial policies.

Government policies aimed at stimulating biomass markets are often developed with inadequate information to properly assess full life-cycle impacts or evaluate issues of environmental justice and human rights, especially for imported fuels and materials. Formulating comprehensive, internationally consistent, performance-based sustainability standards is central to the larger development of biofuels (Jenkins et al. 2006). Further, the implementation and enforcement of sustainability standards without requiring similar standards for all fuels and energy sources are also likely to create market disparities with unforeseen and potentially undesirable consequences for bioenergy.

Resources and bioenergy potential

In California, the three primary biomass resources are agricultural residues, forest residues and urban wastes. The state produces an estimated 80 million gross tons of biomass each year,

TABLE 1. Estimated annual residue biomass potential in California (2005 biomass resource base)*

Resource	Gross production	Feedstock potential
	. . . million dry tons/year . . .	
Agricultural	20.9	8.8
All animal manures	10.3	3.5
Cattle manure	8.4	3.1
Milk cow manure	3.9	1.9
Orchard and vine	2.5	1.8
Field and seed	5.0	2.2
Vegetable	1.6	0.1
Food processing	1.5	1.2
Forestry	26.8	14.3
Mill residue	6.2	3.3
Forest thinnings	7.7	4.1
Logging slash	8.0	4.3
Shrub	4.9	2.6
Municipal solid waste	35.2	9.1
Biosolids	0.8	0.5
Biomass	34.4	8.6
Total biomass	82.8	32.2

Source: Gildart et al. 2006.

* Does not include landfill gas from municipal waste in landfills, or biogas from municipal wastewater treatment facilities.

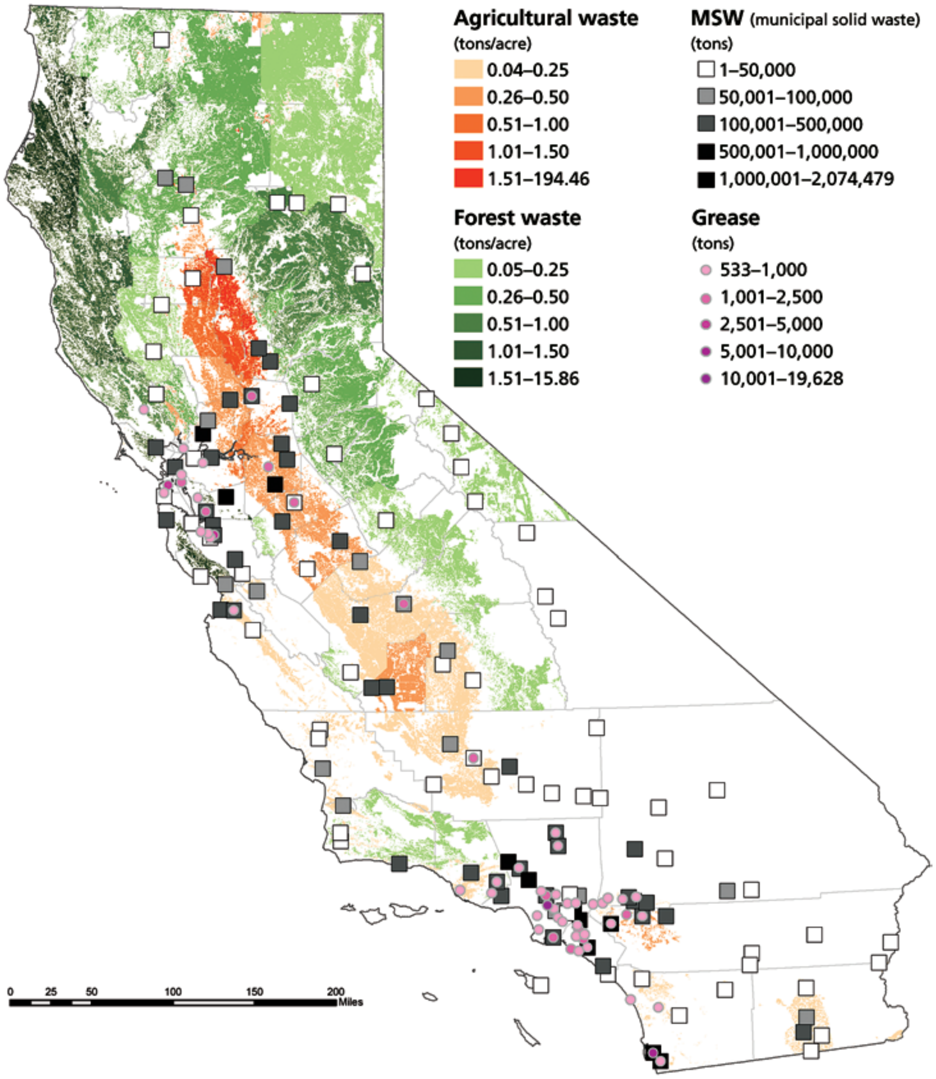


Fig. 1. Distribution of annual biomass resources in California. Source: Tittmann et al. 2008.

with sustainable feedstock potential of 32 million tons (Gildart et al. 2006) (table 1). Resources are geographically distributed according to the producing regions and urban centers (fig. 1).

Forestry could provide large amounts of biomass if in-forest thinning is increased under more active management to reduce fuel loads and wildfire risks, a subject of public controversy. The amount of biomass available for annual harvesting is uncertain, and other estimates (Strittholt and Tutak 2009) incorporating greater constraints on accessible lands place the resource potential from forest lands at about a third to half of that estimated by the California Department of Forestry and Fire Protection (CDFFP 2005).

The urban sector contributes an estimated 35 million tons of biomass, mostly from municipal solid waste but also smaller amounts of biosolids from wastewater treatment. At present, about equal amounts of municipal solid waste are sent for disposal or diverted to other uses such as composting, recycling and biomass conversion. More than a million tons of urban wood fuel — mostly construction waste — are already used in biomass power plants around the state.

Nationwide, more than a billion tons of biomass could be sustainably produced from agriculture and forestry yearly (Perlack et al. 2005), sufficient to supply roughly a third of transportation fuel demand, and possibly more with future improvements in transportation efficiency. Worldwide, estimates suggest a sustainable production about five times that of the United States from current sources (Parikka 2004).

Additional biomass could come from purpose-grown crops such as switchgrass, Miscanthus, oilseeds, algae and many others, but the extent to which these can contribute to overall supply is still speculative. Water is a critical issue for energy-crop production, and California's high-value agricultural commodities may be less prone to crop shifting for bioenergy than other areas of the United States, such as the Midwest Corn Belt. Energy crops may aid in remediating salt-affected and drainage-impaired soils in the San Joaquin Valley and elsewhere (Jenkins 2005; Stapleton and Banuelos 2009). Intensively studied since at least the 1950s, industrial algae production could also significantly expand biomass resources due to high growth rates and yields (estimated maximum yields of 5,000 to 15,000 gallons of biofuel per acre per year) and potentially use drainage water, brackish water, wastewater and seawater, but future production levels and costs also remain highly speculative (Sheehan et al. 1998).

Modeling biomass quantities

The quantity of biomass that can be harvested and used economically is of critical importance. This was recently estimated using an economic optimization model coupled with a spatially explicit geographic information system (GIS) of the distribution of biomass resources, roads and other transportation infrastructure, and regional energy demand throughout California (fig. 2) (Tittmann et al. 2008). The modeling framework was initially developed as part of a study of biofuel production in the western United States (Parker et al. 2008), and has now been applied with greater resolution in California and expanded to include the entire United States. Depending on the market scenario and the extent that forest resources contribute, the estimated biomass resource that can be economically recovered in California varies between about 18 and 25 million dry tons per year at biofuel prices from $2.20 to $4.00

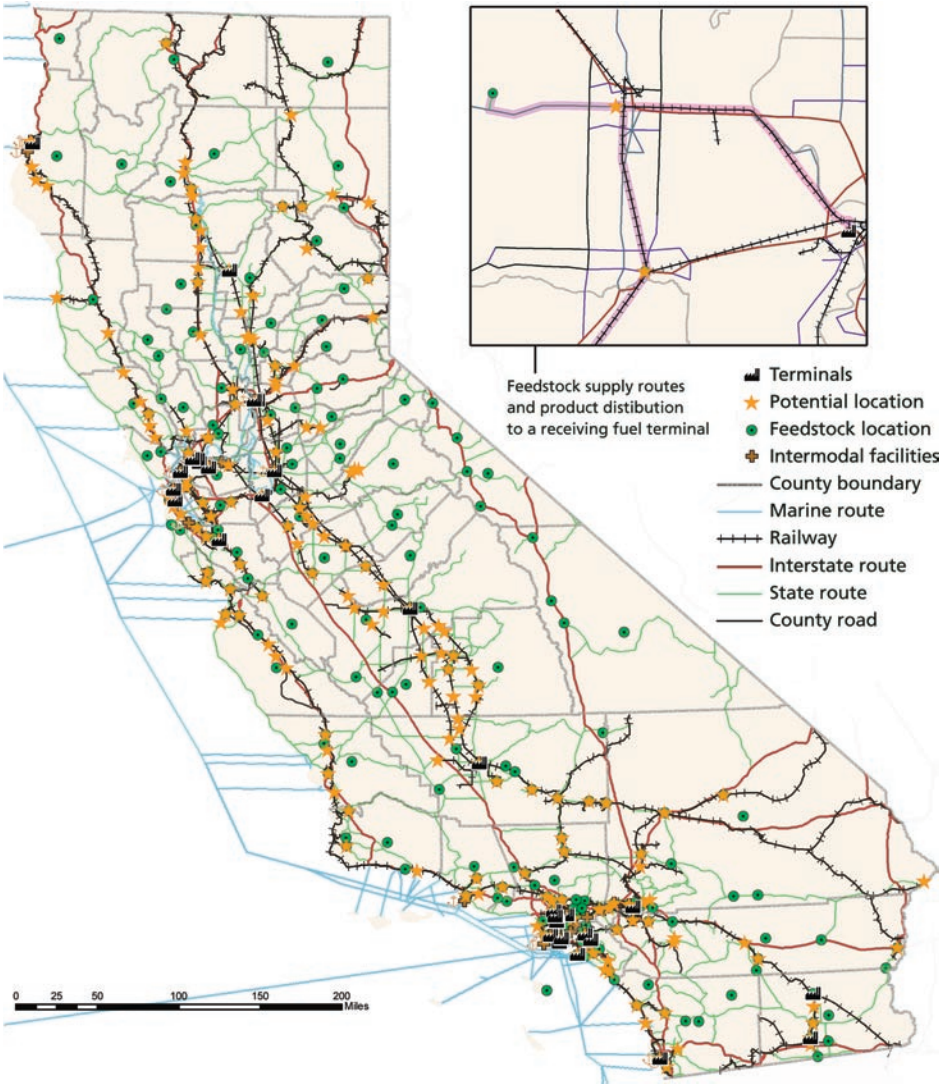


Fig. 2. Potential biorefinery locations in California from a spatially resolved economic optimization model of feedstocks, energy markets, and supply and distribution infrastructure. Source: Tittmann et al. 2008.

per gallon of gasoline equivalent (gge), excluding corn imports but including in-state waste oils and fats.

The results are sensitive to the value of heat in combined heat and power (CHP) operations, such as the use of power-plant waste heat for industrial uses. Biogas potential from landfills, animal manures and wastewater treatment is not included, but constitutes a resource equivalent to another 5 or 6 million tons of biomass beyond the 32 million of table 1. The model shows that at prices below $1.50 per gge, electricity markets provide demand for the lowest-cost biomass resources — about 5 million tons and roughly equivalent to current demand by the California biomass power sector. Above this price, the model predicts demand increasing rapidly for transportation biofuels until nearly full resource utilization at $2.50 per gge. The recent economic downturn has essentially collapsed the corn-ethanol industry in California due to high corn-feedstock prices and low ethanol market prices. Stabilizing energy prices to reduce fuel-price volatility will be an important near-term consideration for state and national policy.

Other energy sources

Projected biomass resources in California can support increasing electricity generation and the production of renewable natural gas (biomethane), liquid biofuels and eventually, hydrogen. Total production in these categories from in-state biomass resources might exceed the energy equivalent of 3 billion gallons of gasoline each year (fig. 3) (Jenkins et al. 2006), or about 6% of total statewide energy demand. Energy potentials are quite large within any one category of energy demand (table 2), but multiple uses are likely to compete for resources in the future. California's current annual harvest of starch and sugar crops alone would be sufficient to produce more than 300 million gallons of ethanol (230 million gge) (Williams 2007). For economic reasons, a complete shift of grain and sugar supplies to energy markets is not likely to occur. Statewide lignocellulosic ethanol potential from agricultural, forestry and urban residues is about 1.2 billion gge per year, and with additions of bio-

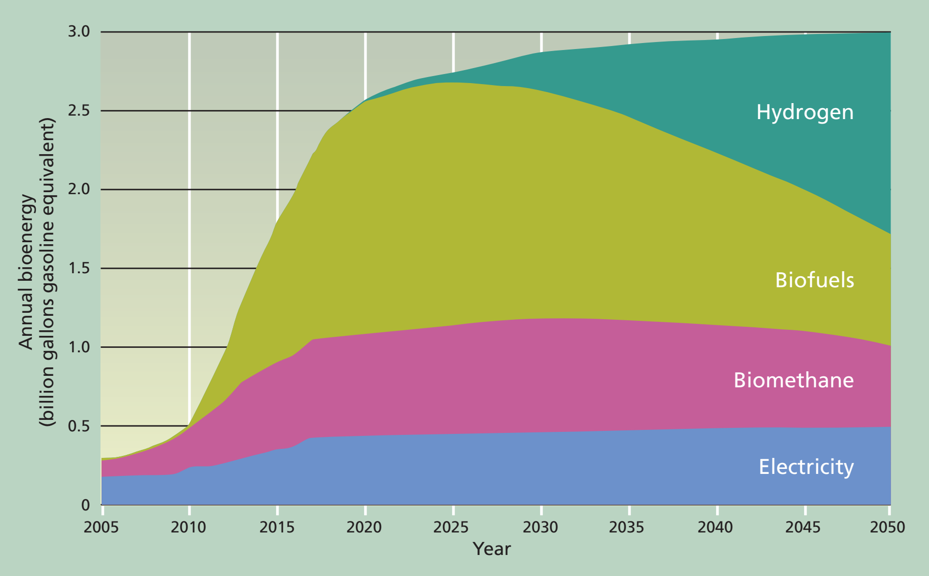


Fig. 3. Speculative development scenario for bioenergy in California. Source: Jenkins et al. 2006.

TABLE 2. Energy potentials from available California biomass feedstocks by energy category (2005 biomass resource base)

Category*	Biomass	Energy in product†	Total capacity‡
	million dry tons/year	*trillion Btu/year*	
Electricity	32	118 (35 TWh/yr)	4,650 MW_e
CHP heat		230	9,050 MW_t
Heat	32	350	11,700 MW_t
Biochemical biofuel	32	188	1.5 billion gge/yr
Thermochemical biofuel	27	250	1.9 billion gge/yr
Biomethane	5	100	0.8 billion gge/yr
Hydrogen (bio + thermal)	32	305	2.1 billion gge/yr

Sources: Jenkins et al. 2006; Williams et al. 2007.

* CHP = combined heat and power (cogeneration). Biochemical conversion is based on fermentation to ethanol. Thermochemical conversion is based on gasification followed by Fischer-Tropsch synthesis. Biomethane is methane derived from anaerobic digestion of biomass.

† TWh = terawatt-hours (billion kWh).

‡ MW_e = megawatt electric; MW_t = megawatt thermal (heat); gge = gallons of gasoline equivalent. Biofuel capacities are based on assumed low yields for dedicated crops. Tonnage for thermochemical biofuel assumed to be constrained by moisture content.

TABLE 3. California annual lignocellulosic ethanol potential

Biomass source	Potential feedstock	Potential ethanol	
	million dry tons	*million gallons*	*million gge**
Field and seed	2.3	160	105
Orchard and vine	1.8	125	83
Landfilled mixed paper	4.0	320	213
Landfilled wood and green waste with alternative daily cover (ADC)	2.7	216	144
Forest thinnings	14.2	990	660
Totals — current California	**24.9**	**1,814**	**1,205**
1.5 million acres dedicated energy crop			
Low yield (5 dry tons/acre, 80 gallons/ton)	7.5	600	400
High yield (9 dry tons/acre, 100 gallons/ton)	13.5	1,350	900
State potentials			
Low yield	32	2,414	1,605
High yield	38	3,164	2,105

Source: Williams et al. 2007.

* gge = gallon of gasoline equivalent.

Roger Milley

Ivars Linards Zolnerovichs

The three main existing biomass resources in California are, *top left*, municipal waste, *bottom left*, agricultural residues and, *center*, forestry residues.

Jack Kelly Clark, UC Statewide IPM Program

More than a million tons of urban wood fuel, mostly construction waste, are currently being burned in biomass power plants statewide.

energy crops on marginal lands, could approach 2 billion gge per year (table 3) (Williams 2007).

In addition to ethanol, other energy types might emerge in competition with liquid fuels for the transportation market, particularly electricity and hydrogen. The demand for electricity from biomass could be much larger than speculated if advances continue in hybrid-electric and battery-electric vehicle design. High-efficiency clean diesel technologies could also shift production capacity away from gasoline substitutes. High-efficiency vehicles that are nearing commercial introduction achieve substantially better fuel economy than the new U.S. 35-mile-per-gallon corporate average fuel economy (CAFE) standard for 2020 under the Energy Independence and Security Act (EISA) of 2007, although similar high-efficiency gasoline technologies are also in development.

Imports of feedstocks and finished biofuels will further increase the share of the state's energy supplied from biomass, but careful attention must be directed toward the sustainability of production, especially in areas outside the state. Nearly all 950 million gallons of ethanol used in California in gasoline blends is imported from other states and countries. Although in-state ethanol biorefining capacity increased to above 100 million gallons per year in 2007, changing economic conditions resulted in industry suspensions of existing operations and new project development of facilities based on imported corn. California is therefore not likely to meet the target of 20% in-state production of biofuel by 2010 under the state's bioenergy action plan.

TABLE 4. Selected biofuel conversion pathways

	Conversion process		
Fuel type	**Thermochemical**	**Biochemical**	**Physiochemical**
Solid	Biomass Chars Charcoal	Biosolids	Densified biomass Other processed fuels
Liquid	Methanol Biomass-to-liquids (BTL) Renewable diesels, biogasolines, other hydrocarbons and oxygenated hydrocarbons Ethanol Mixed alcohols Dimethyl ether Bio-oils (pyrolysis oils)	Ethanol Butanol Other alcohols Mixed alcohols Liquified biomethane (LNG) [Bio]gas-to-liquids (GTL)	Biodiesel (esters from plant, algal and yeast oils) Alkanes (catalytic)
Gas	Producer gas Synthesis gas (syngas) Substitute natural gas (SNG) Hydrogen	Biogas Biomethane Compressed biomethane (CNG) Hydrogen	

Feedstock properties

Feedstock properties also influence the cost and energy conversion potential of the resource (table 4). High moisture contents, above about 50% for example, tend to favor systems where feedstock drying is not required. Much of the animal manure, vegetable, food and municipal green waste is high moisture at the collection point and is often considered for anaerobic digestion, ethanol fermentation or other biochemical conversion. Of the 30 million tons of biomass that California considers technically available for conversion, at least 20% falls into this high moisture category.

Moisture is not the only property of importance, however, and feedstocks vary in composition (Jenkins

***Top*, manure from dairy cattle is used as a feedstock for anaerobic digestion to produce biogas (primarily methane and carbon dioxide), which, *above*, generates electricity at the Castelanelli Dairy in Lodi.**

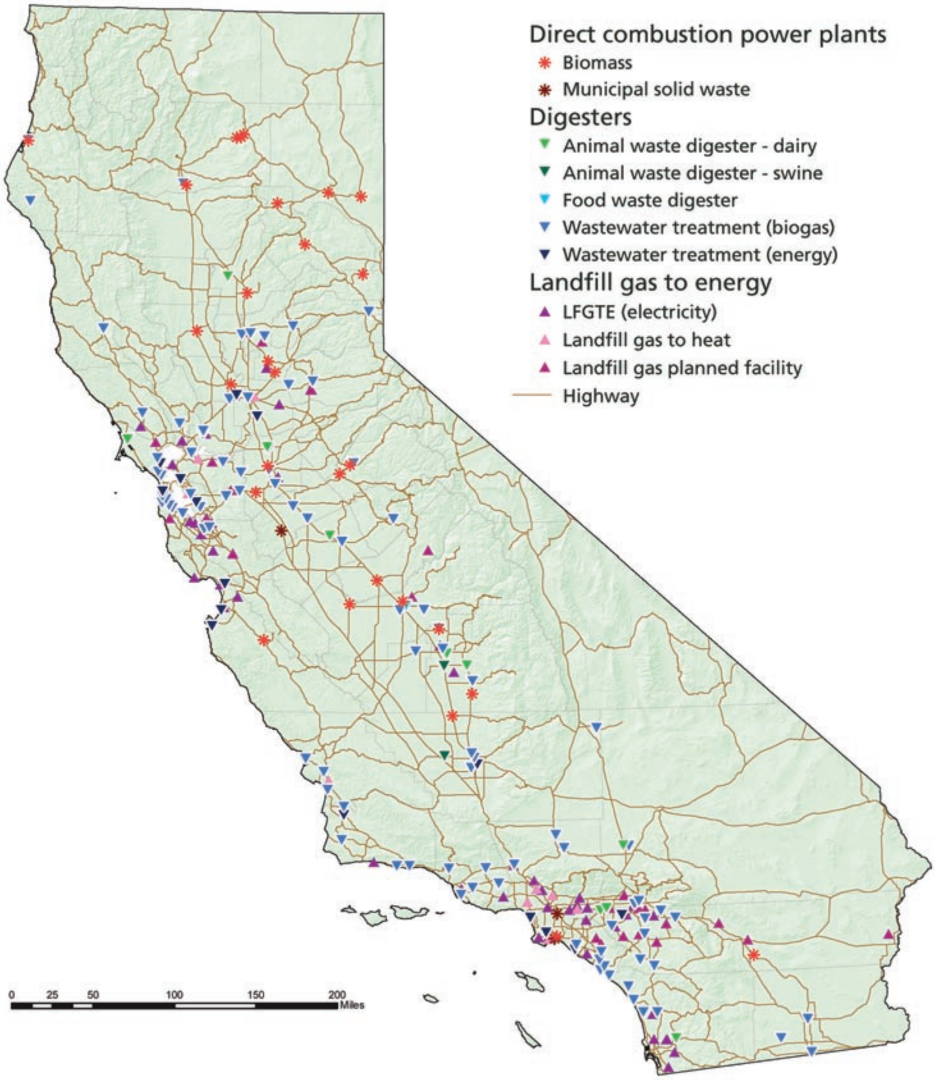


Fig. 4. Biomass power generation facilities in California. Source: Williams et al. 2007.

et al. 1998). Factors that influence the type and design of conversion facilities include the proportions of sugars, starches and lipids; structural components including cellulose, hemicellulose and lignin; inorganic materials in ash; and heavy-metal concentrations. Energy-crop sugar cane trials in the Imperial Valley produced total biomass yields of 65 wet tons per acre per year, with sugar yields averaging 15%, or close to 10 tons per acre per year suitable for ethanol fermentation (Shaffer et al. 2009). Bagasse, the mostly lignocellulosic residue remaining following sugar extraction, accounts for another 18% of the crop, or roughly 11 tons of dry matter per acre per year, although as it leaves the mills the moisture content is about 50%. Bagasse is commonly burned for steam and power generation to support sugar mill or biorefinery operations and for export, but it could also be converted biochemically to increase ethanol yields.

Energy uses for biomass

The complex chemical structure of biomass gives it a tremendous range of uses, but also presents challenges for producing higher-value chemicals and products. Biomass can substitute for fossil resources in virtually all applications, although the various processes are not fully commercialized. Feedstock characteristics influence the technology designed to use it. Ethanol produced from starch and sugar and biodiesel from fat, oil and grease involve well-known commercial processes. The conversion of lignocellulosic biomass such as wood and grasses to high-quality liquid fuels is still precommercial, with large-scale demonstrations under development throughout the United States.

Electricity. In California, electricity-generating capacity from biomass currently exceeds 1,100 megawatts from solid-fuel, landfill gas and digester gas facilities across the state (fig. 4), and annual electrical energy from biomass exceeds 2% of state demand. The prospects for electricity from biomass and other renewable sources were recently enhanced by the state's Renewable Portfolio Standard (RPS), which calls for 20% of the state's retail electricity to come from renewable resources by the end of 2010 (California Public Resources Code, Section 25740) and 33% by 2020. The California Public Utilities Commission (CPUC) currently projects that the 2010 target may not actually be met until around 2013.

The California RPS is resource-neutral and sets no specific target levels or quotas for power generation from particular renewable energy sources. The governor's 2006 Executive Order S-06-06, however, calls for 20% of RPS elctricity to come from biomass. Competition from wind and geothermal sources has so far resulted in biomass lagging behind this goal.

An estimated 14 million dry tons of forestry residues could be sustainably processed in California each year for energy. *Above*, large piles of wood chips are mixed together before being burned in the distant power plant.

Daniel B. Marcum, UCCE Shasta-Lassen

Biogas. The California Energy Commission administers the Dairy Power Production Program (DPPP), created by the California legislature during the state's 2000 and 2001 electricity crisis. Demonstration manure digester projects were installed to generate close to 3 megawatts, but air-quality concerns, mostly over nitrogen-oxide emissions, now limit capacity, and some generators have ceased operations. Upgrading digester gas to meet or exceed natural-gas-pipeline quality standards provides another market, and at least one project is now in operation. One of the dairies participating in the DPPP is now dual-fueling its large milk-delivery trucks with compressed biomethane from a digester. Increasing electricity demand from the transportation sector may also drive improvements in generation technology through improved system efficiency.

The sustainable use of biomass can reduce reliance on imported forms of energy, particularly petroleum, and provide other ecological and economic benefits.

Liquid and gas fuels. Hydrocarbon liquids similar to gasoline and diesel fuels can be produced by thermochemical methods — principally gasification and pyrolysis of biomass by heating under limited oxygen conditions, with secondary refining — through Fischer-Tropsch (FT) synthesis, hydrotreating and other chemical-catalytic techniques. The resulting liquid fuels include methanol, ethanol, mixed alcohols, dimethylether (DME), bio-oils and fuel gases that include synthesis gas (or syngas, a mixture of carbon monoxide and hydrogen with other gases), substitute natural gas (SNG) and hydrogen.

Biochemical methods using microbial conversion in fermentation and anaerobic digestion can produce ethanol, butanol, methane, hydrogen and other fuels. Both landfill gas and digester gas are produced through the natural anaerobic decomposition of the degradable fraction of biomass. The resulting biogas consists principally of methane and carbon dioxide with smaller concentrations of hydrogen sulfide and other trace gases. Lignocellulosic biomass can be converted to ethanol via the pretreatment and hydrolysis of cellulose and hemicellulose to release sugars for fermentation. The lignin fraction is typically considered for use as boiler fuel for steam and power generation in biorefinery operations, although lignin can also be thermochemically upgraded into fuels, and research is continuing on biochemical pathways for converting lignin to biofuel (see page 178). Compared to ethanol, butanol is at present more compatible in the existing pipeline and transportation infrastructure but is still developmental as a fuel.

Biodiesel. Conventional biodiesel is produced through a base-catalyzed transesterification reaction in which a lipid such as a vegetable oil or animal fat is reacted with an alcohol, generally methanol or ethanol. The oil-alcohol reaction is catalyzed using sodium hydroxide or potassium hydroxide to produce a fatty-acid methyl ester, also known as FAME. In the United States, soybeans are the primary feedstock, and in Europe, rapeseed. Glycerol is a coproduct of the esterification, and expanding biodiesel markets will require finding new uses for glycerol. Biodiesel has lower viscosity compared to the original feedstock oil, and as a result has improved atomization and burning characteristics in diesel engines. Biodiesel can be used neat (100% biodiesel or B100) or blended with regular diesel fuel. High feedstock costs are now restricting growth in biodiesel production capacity. It can be produced at lower cost from waste fats, oils and greases such as used fryer oil, but the total resource potential is small compared to fuel demand. Vegetable oils and biodiesel can be deoxygenated to produce upgraded hydrocarbon liquids that are more like diesel fuel, although this level of refining adds to the cost.

Greenhouse-gas reductions

New federal energy legislation mandates substantial increases in the amount of biofuel produced and used in the United States. The nation's Renewable Fuel Standard (RFS) calls for producing 36 billion gallons by 2022. To qualify under the standard, reductions in life-cycle greenhouse-gas emissions must accompany fuel production within defined biofuel categories.

The U.S. Environmental Protection Agency (EPA) estimates that corn ethanol production using coal or natural gas to supply the process energy in biorefineries may have difficulty meeting the RFS for a 20% life-cycle reduction in greenhouse-gas emissions relative to gasoline (fig. 5), although an option to reduce the requirement to 10% might qualify facilities using natural gas. Ethanol from corn using biomass for process energy exceeds the standard, as does sugar cane ethanol. Biodiesel from soybean oil does not meet the mandated 50% reduction in greenhouse-gas emissions, a particular concern for the industry as soy diesel constitutes the majority of biodiesel presently produced in the United States. Biodiesel from waste lipids readily complies. Ethanol production from lignocellulosic feedstocks such as switchgrass and corn stalks exceeds the standard of 60% greenhouse-gas reduction for cellulosic fuels.

California's LCFS requires that by 2020 the state achieve a 10% reduction in life-cycle carbon intensity (greenhouse-gas emissions) of transportation fuels relative to the 2010 baseline. Similar to the federal RFS, estimates by the California Air Resources Board show coal-fired corn ethanol production exceeding the carbon intensity of gasoline when indirect effects from land conversion elsewhere in the world are included. The magnitude of the indirect carbon intensity assigned to different biofuels has been a matter of debate and will receive continuing attention and research.

Logistics and economics

From raw materials to finished product delivered into final demand, bioenergy systems invariably involve extensive logistical supply chains. For purpose-grown energy crops, this includes growing and harvesting as well as transportation, storage, processing, conversion, product distribution, sale and use. These operations can be combined to optimize the system design either by minimizing costs or maximizing profits. In addition, economies of scale in capital costs for the biorefinery, combined with increasing feedstock delivery costs as facility size or production capacity increases, often lead to an optimal facility size. Opportunities exist for greater integration of heat, power and fuel production in distributed generation and advanced biorefinery systems.

Feedstock acquisition costs vary depending on type, location, distribution and alternative uses. In most cases, waste-to-energy facilities are able to charge a disposal or tipping fee for feedstocks such as mixed municipal solid wastes, thereby accruing additional revenue to offset facility capital and operating expenses. Such disposal fees now range from about $50 to $60 per ton in California.

As competition increases for these resources, this trend may reverse. Costs for collecting, transporting and storing agricultural residues in bioenergy applications are typically in the range of $25 to $50 per dry ton. Biomass from forest thinning and stand improvement commonly costs $30 to $50 per ton at roadside and an additional

Jack Kelly Clark, UC Statewide IPM Program

The most common biofuel sources in the United States are corn (shown), which is fermented into ethanol and blended into gasoline, and soybeans, which are converted to biodiesel. However, corn- and soybean-based biofuels may not meet the federal Renewable Fuel Standard for reducing greenhouse-gas emissions.

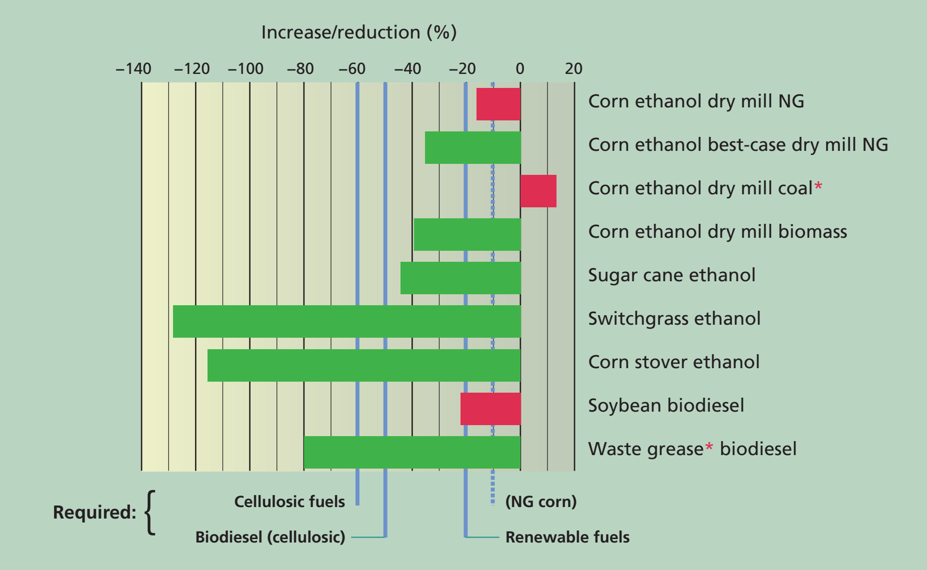


Fig. 5. Estimated life-cycle greenhouse-gas-emission reductions for different biofuel pathways. Red bars show pathways that are estimated not to meet federal reduction requirements under the Renewable Fuel Standard (vertical lines), green bars do. Dry mill = corn-milling technique used in the production of ethanol from corn; NG = natural gas. Source: US EPA 2009.

*Typographical corrections after press run: "coal," not "goal"; and "grease," not "grass."


Terrance Emerson

Gabe Palmer

Energy from the sun can be converted into, *right*, solar power. The search for more sustainable energy sources should include direct solar conversion as well as indirect methods such as, *left*, wind, hydroelectric and biomass.

$0.20 to $0.60 per mile per ton to deliver. Collection costs are higher for smaller trees and on steeper slopes. The development of small-tree-specific equipment may reduce these costs. Intermediate processing such as pelleting, pyrolysis (breaking down using heat) and alcohol synthesis using portable equipment or at satellite facilities has been proposed to reduce transportation costs, although these applications appear to be most economically advantageous beyond about 200 miles.

Component costs depend on yields (tons per acre), equipment capacities (tons handled per hour), type of processing and packaging employed (loose, baled, chopped, chipped, densified), mode of transportation (truck, rail, barge, pipeline), type of storage (short-term, long-term, tarped, permanent structure) and associated input costs (labor, fuel, materials). Costs for purpose-grown energy crops typically range from about $25 to more than $115 per dry ton. The total cost of energy-crop biomass includes growing the crop, which is generally not included for agricultural and forest residues. For example, feedstock costs for switchgrass in the U.S. Midwest are estimated to range from $30 to $70 per ton, of which 40% is attributed to production prior to harvesting (Wright et al. 2000).

Feedstock costs have significant impacts on the cost of finished product from conversion facilities. At conversion efficiencies of 20% for conventional biomass-fueled, steam-cycle power generation, each increment of $10 per dry ton in feedstock cost adds approximately $0.01 per kilowatt-hour (kWh) to the cost of electricity. Total electricity costs from biomass currently range from $0.06 to $0.10 per kWh for new power plants. Capacity payments under some power sales contracts provide additional revenue (typically about $0.02 per kWh) to energy sales. Advanced power plants operating at higher efficiencies, such as biomass integrated gasifier combined cycle (BIGCC) technologies, might realize costs ranging from $0.05 to $0.07 per kWh. Where on-site or nearby heat or cooling demand exists and plants can operate in cogeneration or polygeneration mode, significant economic incentives exist if waste heat utilization can offset natural gas, propane or other fuel purchases.

On an energy basis, corn prices of $4 per bushel ($143 per ton) equate to about $8 per million British thermal units ($8 per MMBtu), roughly equivalent to crude oil at $46 per barrel. At the U.S. average ethanol yield from corn of 96 gallons per ton, this corn price adds $1.49 per gallon to the cost of ethanol, similar to feedstock costs for sugar cane or sugarbeets. The heating value of ethanol is lower than gasoline, so the feedstock cost is equivalent to about $2.33 per gge without accounting for engine optimization on the different fuels (the higher octane of ethanol offsets the energy penalty for optimized engines). Ethanol production costs based on corn dry milling are about $0.52 per gallon, exclusive of feedstock costs (Shapouri and Salassi 2006).

Without coproduct credits (e.g., distiller grains for animal feed) and federal production incentives, corn ethanol costs are close to $3 per gge. Coproduct values and blender's credits reduce this cost by roughly $1 per gge. Volatility in both the petroleum and agricultural commodity markets partially helps to explain why the corn ethanol industry is hesitant to expand capacity in the absence of more-substantial government economic incentives and price-control policies. For biodiesel from soybeans at a price of $235 per ton ($7.05 per bushel) and with a yield of roughly 52 gallons per ton, feedstock adds a cost of $4.52 per gallon to the fuel production cost before coproduct and federal tax credits.

For advanced biofuel production, most cellulosic biomass conversion processes should operate at efficiencies approaching 50%, implying that a $10 per ton increment in feedstock cost will add $0.15 per gge, or for ethanol roughly $0.10 per gallon. Total near-term production costs, assuming enzymatic conversion technology can be sufficiently commercialized, have been estimated at $2.46 per gallon ($3.83 per gge) after taxes for a California facility that produces 70 million gallons per year of cellulosic ethanol with feedstock at $45 per ton (Williams 2007). Operating expenses other than feedstock are $0.57 per gallon or 23% of total cost (partially offset by net electricity exports worth $0.09 per gallon) and capital recovery is $1.02 per gallon or more than 40% of cost.

Feedstock amounts to more than a third of production costs. Improvements in ethanol yield from 70 to 100 gallons per ton of feedstock and decreased enzyme costs from $0.35 to $0.10 per gallon would reduce production costs to around $1.85 per gallon ($2.16 per gge), closer to the federal target for 2012 of $1.33 per gallon of ethanol. Improvement in cellulosic conversion technologies must proceed rapidly if biofuel mandates under the new federal energy legislation are to be met on schedule.

Biomass challenges for California

A wide variety of conversion technologies are currently under development, but large-scale demonstrations of biorefineries producing biofuels from lignocellulosic feedstocks and advanced power-generation options must be completed before commercially successful approaches can be identified and full technical, cost and environmental performance are known. Air emissions will be a dominant concern for new facilities in most regions, especially for power generation, but water supplies, water quality and waste disposal will also be critical determinants in siting and financing. Performance-based sustainability metrics and standards or other instruments providing clear industry guidance will be important over the near term if financing and commercial development are to occur on the scale needed to meet existing state bioenergy targets. Permitting complexity and cost are frequently cited as substantial hurdles, but regulatory processes will increasingly need to address global, state and regional impacts and cross-media effects in addition to local impacts.

Increasing feedstock costs and declining ethanol market prices have resulted in the recent loss of in-state corn biorefining capacity. The longer-term economic prospects for biofuel production are more favorable, however, as long as cellulosic feedstock costs, which are projected to constitute about a third of total production costs, remain less volatile compared with grain and sugar prices. If transportation-fuel costs continue to rise without a concurrent expansion in electric-vehicle capacity in the state or escalation in renewable electricity prices, increasing competition for biofuel feedstocks will occur at the expense of electricity generation. The implications for overall efficiency, greenhouse-gas emissions, and local pollutant emissions and exposures must be considered at the systems level in order to apply incentives to meet existing policy targets and design new policies to encourage development.

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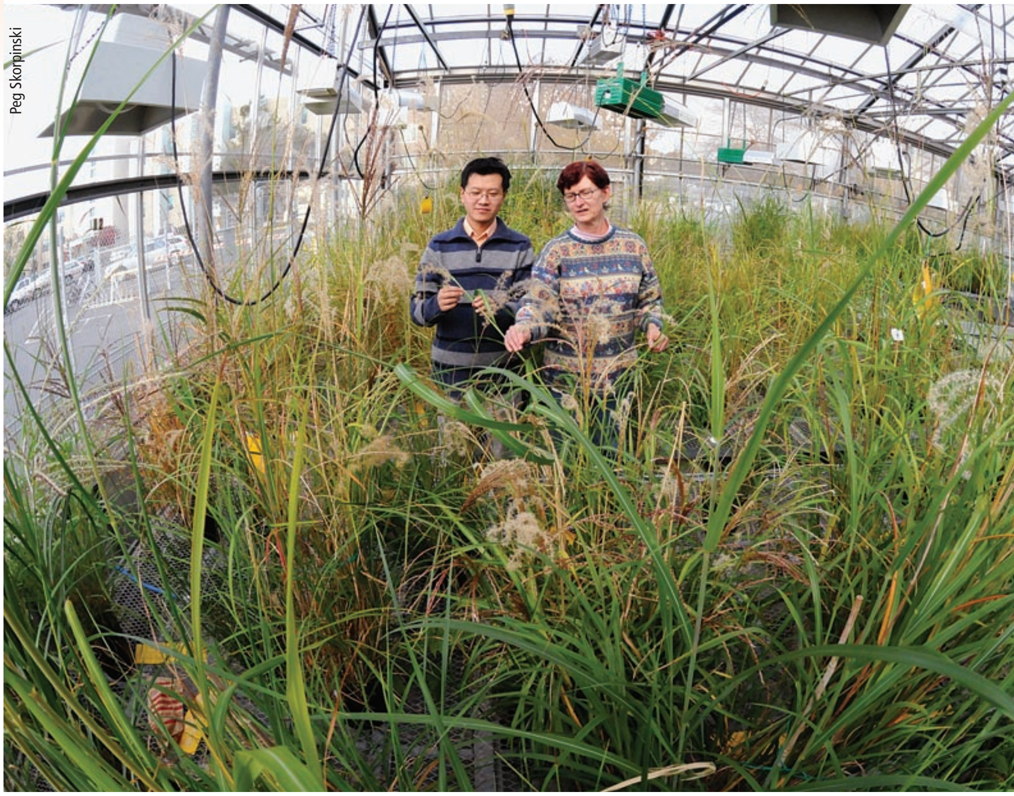
Plant and microbial research seeks biofuel production from lignocellulose

by Laura E. Bartley *and* Pamela C. Ronald

A key strategy for biofuel production is making use of the chemical energy stored in plant cell walls. Cell walls are a strong meshwork of sugar chains and other polymers that encircle each plant cell. Collectively known as lignocellulose, cell wall material represents the bulk of plant dry mass. Biofuels can be made by releasing sugars from lignocellulose and converting them into fuel; however, this is currently an energy-intensive process. We summarize the barriers to efficient lignocellulosic biofuel production and highlight scientific research recently funded by the U.S. Department of Agriculture and U.S. Department of Energy, both to understand and harness the mechanisms by which plants build cell walls, and to further develop enzymes and microbes that facilitate sugar release and biofuel production.



Peg Skorpinski

Lignocellulosic biomass refers to vegetative tissues and plant-derived wastes that can be used to produce liquid transportation fuels. Postdoctoral Researcher Yuegeng Guan (left) and UC Berkeley professor Sheila McCormick of the Energy Biosciences Institute are studying *Miscanthus sinensis* at the USDA Plant Gene Expression Center in Albany.

Burning fossil fuels is inefficient and unsustainable, and it releases climate-changing carbon dioxide into the atmosphere. To ameliorate these problems, business leaders, policymakers and scientists are investigating alternatives such as producing liquid transportation fuels from plants. The production of ethanol and biodiesel fuels from food crops such as corn and soybeans is relatively energy-intensive and could potentially divert land from food production, leading to food price increases (Farrell et al. 2006). Still, these food-based fuels serve as a bridge to a future industry based on the use of vegetative tissues and plant-derived waste products, collectively known as lignocellulosic biomass (Waltz 2008).

Starch vs. lignocellulose

The conversion of both corn grain and biomass to fuels has the same three steps: (1) production of plant material, (2) deconstruction of the material into sugars and (3) conversion of the sugars into fuel (fig. 1). Corn-based ethanol production essentially follows the familiar process of brewing. First, starch is extracted from the corn grain and then cleaved into individual sugars with inexpensive enzymes. The resulting sugar, glucose, is fermented by yeast into ethanol.

Corn grain production, however, is highly inefficient compared with other diverse forms of biomass. Corn ears constitute only half of the aboveground tissue of the maize plant by dry weight, and only about 60% of the grain is starch (Somerville 2007). Thus, by utilizing only kernel-derived starch, more than half of the corn plant's sugar content is wasted. In contrast, lignocellulosic biomass is highly abundant, consisting of essentially the entire plant's dry mass, and including crop, forest and municipal wastes such as rice straw, wood chips and carbon-containing trash (Orts et al. 2008; Waltz 2008).

Additionally, analyses suggest that one of the most efficient and sustainable methods of biofuel production will be harvesting the aboveground portions of densely produced, fast-growing perennial energy crops such as poplar trees (*Populus trichocarpa*) and switchgrass (*Panicum virgatum*) (Schmer et al. 2008; Somerville 2007). The perennials under consideration require less water, fertilizer and management inputs compared with annual crops, and can be grown on marginal lands, including those with erosion-prone, dry or saline soils.

The potentially large energetic and environmental benefits of utilizing bioenergy crops and waste products — compared with fossil fuels and corn or other annual food crops — are greatly diminished by the current expense

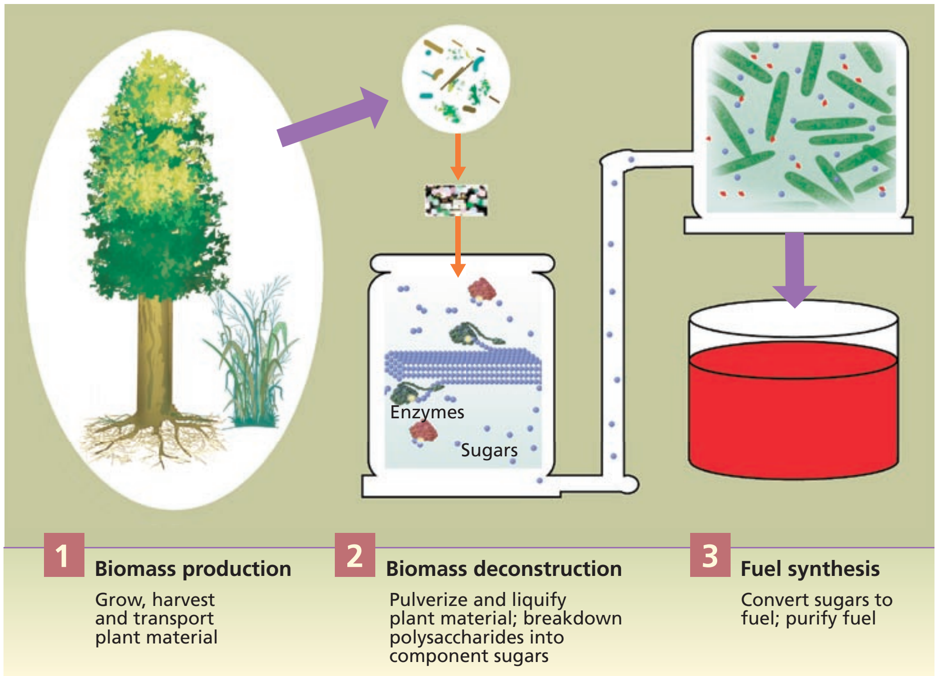


Fig. 1. Stages of converting biomass to biofuel. Images adapted from DOE Genome Programs (http://genomics.energy.gov).

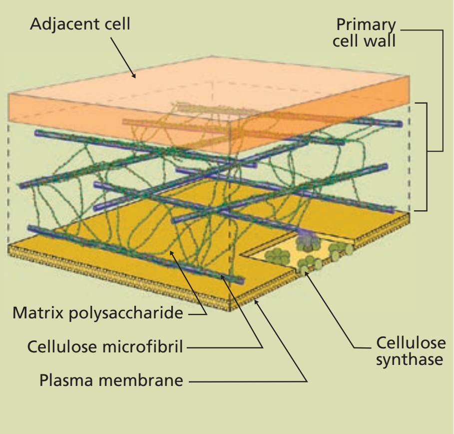


Fig. 2. Primary cell wall. Cellulose microfibrils, composed of multiple linear chains of glucose; matrix polysaccharide, composed of branched sugar chains made of diverse sugar types, especially xylose; the plasma membrane, which composes the boundary of living cells; and a complex of proteins that synthesize cellulose, represented by the ring of spheres embedded in plant cell walls. As the plant grows and ages, primary cell walls become compacted and cross-linked by a dense meshwork of lignin. Graphic courtesy of C.R. Somerville.

of deconstructing biomass into its component sugars (Lynd et al. 2008). Lignocellulosic sugar chains, called polysaccharides, are tightly bound to each other and are difficult to access. To release them, plant matter must be physically pulverized and then dissolved under energetically costly conditions, such as treatment with hot acid or pressurized alkali (Galbe and Zacchi 2007). Next, the polysaccharides are cleaved into individual sugars with enzyme catalysts, which are currently expensive, required in large amounts and do not cleave to completion (Galbe and Zacchi 2007; Lynd et al. 2008). As with current starch-based methods, the sugar water is then fed to yeast to produce ethanol. Yeast is currently unable to metabolize a significant fraction (as much as half) of the diverse sugars that compose cell walls.

Biofuel research goals

For each stage of production (fig. 1), researchers are pursuing technical solutions for the efficient use of lignocellulose to make biofuels, including integrating all steps in the process (Lynd et al. 2008). For research related to biomass production, major goals are to further reduce the environmental and monetary costs and increase the production efficiency of diverse bioenergy crops. High-density sources are necessary to reduce the costs of transporting biomass to processing stations. Another major goal is to understand and control how plants build cell walls in order to improve their deconstruction and synthesis into fuels.

For the deconstruction phase, major goals are to reduce the energy and other costs of pretreatment, as well as of the enzymes that catalyze sugar release. Fuel synthesis researchers are focusing on engineering organisms that can utilize 100% of the diverse sugars released from lignocellulose and tolerate the accumulation of high amounts of fuel product.

Due to the drawbacks of ethanol fuel, researchers are also exploring the synthesis of fuels less mixable (miscible) in water. These include butanol and alkanes, which may be used directly in conventional car engines. Beyond the scope of this review, researchers are seeking ways to utilize the nonsugar components of cell walls (Orts et al. 2008).

Cell wall synthesis

Plant cell walls consist primarily of two classes of polysaccharides — cellulose and diverse types of matrix polysaccharides (fig. 2). In addition, older, weight-bearing walls contain a network of the phenolic polymer, lignin.

Plants use their cell walls primarily for structural support, and gas and liquid transport; walls also participate in defense against fungi, insects and other pests and pathogens. Plant organs and cells with different functions have different cell wall compositions. The selective benefits of different plant taxa having distinct cell wall compositions are less clear (Carpita 1996). In particular, the matrix polysaccharides of grasses and other recently evolved monocots (plants with single seed leaves and parallel veination) are quite distinct from those of dicots (plants with two seed leaves and branched veins) (table 1) (Carpita 1996).

Researchers are investigating which genes are responsible for the synthesis and modification of plant cell walls and the biological function of each wall component. With this knowledge, they hope to manipulate plant walls to increase the efficiency of deconstruction, while still maintaining strong, vigorous plants that can be grown on a large scale. One idea being developed is to genetically engineer plants that express

TABLE 1. Flowering plants and relevant characteristics for lignocellulosic biofuel production

Biomass source	Dicots	Grasses
Waste product examples	Nut hulls, Brassica stalks	Corn stover, rice, wheat or sorghum stalks
Dedicated energy crop examples	Poplar, eucalyptus, willow, alfalfa	Switchgrass, Miscanthus, reed canary grass, prairie cord grass
Reference systems with sequenced genomes	Arabidopsis, *Medicago truncatula*	Rice, sorghum, *Brachypodium*
Cell wall type	Type I	Type II
Cell wall composition	(1) Cellulose; (2) matrix = xyloglucan, glucuranoxylan and minor components w/pectin (galacturonans and rhanmnogalacturonans); (3) S-, G-lignin	(1) Cellulose; (2) matrix = arabinoxylan, mixed linkage glucan and minor components; (3) S-, G-, H-lignin

enzymes for breaking down cell wall components at the end of the growing season (Sticklen 2006).

Microfibrils. Cellulose consists entirely of long, linear chains of the 6-carbon sugar, glucose. Glucose is the same sugar that makes up starch and, when depolymerized, is readily converted into ethanol by yeast. Cellulose typically composes nearly 50% of the cell wall (Pauly and Keegstra 2008). Bundles of 36 cellulose chains, called microfibrils, are laid down in a crisscross manner to form a scaffold — the cell wall equivalent of steel cables. Microfibrils are dense, crystalline structures that exclude water and become chemically cross-linked — and even less degradeable as plants grow and age. Large protein complexes at the cell surface synthesize microfibrils (fig. 2). Elusive for decades due to the difficulty of purifying active protein complexes from plant extracts, the plant genes for cellulose synthesis were finally identified in 1996, based on sequence similarity to bacterial cellulose synthases (Pear et al. 1996). An important remaining question is how plants regulate the synthesis of cellulose to integrate microfibril synthesis with other wall components.

Matrix polysaccharides. Between the microfibrils, shorter, branched matrix polysaccharide chains interlace (fig. 2). Matrix polysaccharides are enriched for the 5-carbon sugar, xylose, and compose about 30% of the cell wall (Pauly and Keegstra 2008). The grass matrix consists primarily of mixed polysaccharides of the sugars xylose and arabinose (Carpita 1996); whereas, the matrix of dicots, like poplar and alfalfa, are mostly polysaccharides of glucose, xylose and glucuronic acid as well as diverse and complex pectin polysaccharides.

Matrix polysaccharide is more easily extracted from the cell wall than cellulose; however, most yeast cannot use the 5-carbon sugars that make up the bulk of the matrix. Moreover, matrix components often contain chemical modifications that inhibit the breakdown of cellulose and other downstream processes. While genes for the synthesis of many of the major matrix components of dicots have been defined (Farrokhi et al. 2006), most of the genes for grass-specific matrix synthases and modifying enzymes have not yet been assigned and characterized. Strategies for identifying the genes responsible for the synthesis of cell wall components include examining the results of introducing the putative cell wall–synthesis genes into living systems that normally lack the genes, and disrupting or increasing the expression of such genes in their plant hosts (Farrokhi et al. 2006). Screening plant populations for natural or induced genetic variation in cell wall structure and function is also a common approach (Brown et al. 2005).

Lignin. As plants grow and require stronger walls, lignin is deposited in the cell wall (15% to 30% in mature walls) (Boerjan et al. 2003; Pauly and Keegstra 2008). Individual lignin monomers — the main portion of which is a carbon ring — react with various wall components, particularly other lignin, to cross-link and reinforce the cell wall. The result is a chemical meshwork that is physically strong and difficult to degrade. Thus, decreasing the strength of the lignin network is a prime target for genetic manipulation in plants (Chen and Dixon 2007).

For example, Clint Chapple of Purdue University and colleagues are analyzing the effect of blocking lignin-

Roy Kaltschmidt/Lawrence Berkeley Nat'l Laboratory

Jay Keasling (left) and Rajat Sapra of the Joint BioEnergy Institute developed a technique that speeds up the search for improved microbes to ferment plant sugars into biofuels.

synthesis genes on cell wall composition and growth in poplar (Coleman et al. 2008). Also, John Ralph and associates at the University of Wisconsin have shown that plant cells can be fed modified lignin monomers (simple compounds), with the result that the lignin they then produce has chemical "zippers" and can be more easily deconstructed or "unzipped" (Grabber et al. 2008). If methods can be devised to develop plants that make such modified lignin, the plants' cell walls might be more easily deconstructed while maintaining their biological functions. Researchers are pursuing this goal at the Joint BioEnergy Institute (JBEI; www.jbei.org) in the San Francisco Bay Area and the Great Lakes Bioenergy Research Center (www.greatlakesbioenergy.org), both with funding from the U.S. Department of Energy (DOE).

Reference plants

A major research strategy to elucidate the synthesis and breakdown of cell wall components is to conduct experiments with well-characterized reference plants. The results can then be applied toward improving species that produce significant amounts of biomass (table 1). The best-characterized plant at the molecular level is a diminutive species from the mustard family, *Arabidopsis thaliana*, which has a short generation time of 6 to 8 weeks. The research community has developed abundant resources and methods to support examination of Arabidopsis gene functions. Arabidopsis was the first plant to have its DNA fully sequenced (AGI 2000). This has allowed scientists to identify Arabidopsis plants with mutations in almost every gene, so that the effect of deleting most genes of interest can be rapidly examined (Alonso et al. 2003). Currently, the U.S. National Science Foundation is supporting the collection of significant functional information for every Arabidopsis gene. The basic knowledge gained from gene function studies in Arabidopsis can often be applied to other plant species, especially broad-leaved dicots such as poplar (table 1).

In addition to Arabidopsis, the grass-family member rice (*Oryza sativa*) has also been developed as a reference plant. It also has short generation times (9 weeks for some varieties) and is easily transformed (Jung et al. 2008). Grasses share a high degree of similarity in the arrangement and, in many cases, the function of their genes (Devos 2005). This suggests that rice data will greatly assist with understanding other grasses, including the many being developed as energy crops in the United States (table 1). The rice genome, smallest among the cereals, has been fully sequenced, and rice mutant collections are being developed to facilitate gene function studies (Goff et al. 2002; Krishnan et al. 2009). Genes that have high sequence similarity between Arabidopsis and rice are generally expected to function in a similar, though not identical, manner. However, only 50% of rice genes are closely related by sequence similarity to an Arabidopsis gene (Goff et al. 2002). For example, grasses possess distinct groups of genes likely involved in cell wall synthesis that are not represented in the genomes of Arabidopsis and other dicot plants (Cao et al. 2008).

In an example of model plant studies, JBEI researchers are determining how particular genes contribute to the cell wall structures in rice and Arabidopsis. Their strategy includes isolating enzymes involved in cell wall synthesis from rice and Arabidopsis to determine their biochemical effects on purified sugars (Jensen et al. 2008). The results of these studies will provide information relevant to the two major classes of flowering-plant cell walls, those of dicots and grasses (table 1).

Genomic data

The identification of part or all of the genetic sequence of a species provides invaluable information for improving yield and other characteristics. The DOE's Joint Genome Institute, located in Walnut Creek, Calif., has collaborated with other researchers to sequence the genomes of the potential energy crops sorghum (*Sorghum bicolor*) and poplar (Paterson et al. 2009; Tuskan et al. 2006). Given the expected importance of grasses as biomass producers, DOE is also sequencing the genome of the small, dryland grass *Brachypodium distachyon*, which is being developed as a reference species like rice and Arabidopsis (Opanowicz et al. 2008). A complementary approach to sequencing the full genome is to sequence just the expressed genes (messenger RNA) isolated from different tissues. The U.S. Department of Agriculture (USDA) and DOE have sequenced about 500,000 segments of expressed genes from switchgrass (Tobias et al. 2008), and progress is now under way to sequence its complete genome.

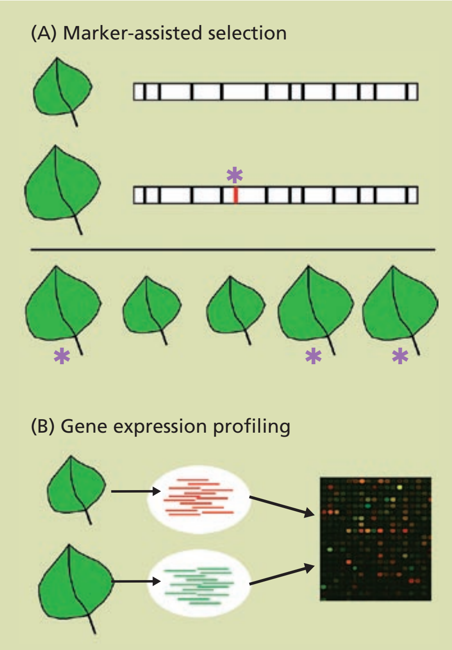


Fig. 3. Uses of DNA sequence data. (A) In marker-assisted selection, long rectangles represent a segment of genomic DNA from a plant; vertical lines represent DNA markers. The red mark (*) correlates with a trait of interest, e.g., large leaves. (B) In one method for RNA profiling, RNA is extracted from two biological samples, e.g., a small leaf and a large leaf. The RNA is used to make red- and green-dye-labeled probes. These samples are added to a spotted surface on which each spot represents a gene in the genome. The color and intensity of the dye at each spot provides a profile of the expression of each gene by indicating the amount of corresponding RNA in each of the samples, e.g., red spots indicate genes expressed in small leaves, and green spots genes expressed in large leaves.

The uses of sequence data are many. We highlight just two techniques that researchers are using for energy crops, marker-assisted selection and biomolecule profiling analysis (fig. 3).

Marker-assisted selection. Marker-assisted selection accelerates the development of improved plant varieties by taking advantage of DNA sequences


James H. Miller, USDA Forest Service, Bugwood.org

Miscanthus, a potential biofuel.

that vary slightly among different plants in a population (fig. 3) (Robins et al. 2007). Each sequence variant is known as a genetic "marker." Plant geneticists examine a particular trait of interest, such as large leaves, for association with DNA markers. In the ideal case, a DNA marker (or markers) might be found to occur in every plant that has the trait but none of the plants that lack it. Thus, breeders can quickly screen large numbers of plants with a simple assay for the marker rather than conduct more time-consuming tests for the actual trait, for example by manually measuring leaves at a particular growth stage.

In recently funded work, scientists initiated a number of marker-assisted selection programs for potential bioenergy crops. Researchers led by Edward Buckler at Cornell University and Christian Tobias at the USDA Western Regional Research Center in Albany, Calif., are looking for markers associated with biomass production traits, such as plant height, tiller number and photosynthetic rate in switchgrass and reed canary grass. William Rooney of Texas A&M University and E. Charles Brummer of University of Georgia are conducting similar studies in sorghum and alfalfa, respectively (Murray et al. 2009; Robins et al. 2007). These researchers will also be looking for markers associated with the quality of the biomass for biofuel production, in terms of sugar availability. Because many dedicated bioenergy-crop species have not previously been the subject of intensive breeding efforts, researchers expect that significant improvements can be made relatively quickly.

Optimizing the efficiency of lignocellulose breakdown is a major goal.

Profiling analysis. Another application of sequence data is to develop large-scale profiling approaches to simultaneously measure the participation of many gene products in a biological process (fig. 3) (Jung et al. 2008). For example, cell wall synthesis is carried out by only a subset of plant proteins. At the appropriate time and plant tissue, the cell wall genes are read out (expressed) as messenger RNAs that are then translated into proteins, such as the enzymes that synthesize cellulose and other polysaccharides. Profiling approaches monitor which RNAs or proteins are present in a particular biological sample such as an expanding poplar leaf. Such approaches require sequence data because usually only a small fragment, or tag, of each RNA or protein is revealed during profiling, and sequence data allows this tag to be equated with the full-length gene (fig. 3).

A recently funded consortium project involving University of Mississippi, UC Davis and The Ohio State University entails RNA and protein profiling of rice cells as they regenerate their stripped-away cell walls. Having identified potentially important genes for cell wall synthesis via profiling, these researchers are characterizing mutant plants in which the identified genes have been disrupted, in contrast to other mutants in which the identified genes have increased levels of expression (Brown et al. 2005).

Cell wall deconstruction

Microbiology research to support biofuel production primarily addresses the deconstruction and fuel synthesis stages of biofuel production (fig. 1). JBEI seeks to help lead the development of improved enzymes for the more effective breakdown of lignocellulose. That consortium is focusing on enzymes to break down lignin, the cross-linking polymer that greatly reduces the availability of cellulose in mature plant tissue. The JBEI strategy begins by developing improved assays for monitoring the cleavage of various cell wall components simultaneously. These improved measurement methods will allow screening of potential sources of new lignocellulose-degrading enzymes from environments where cell wall degradation occurs, such as compost heaps and rainforest floors.

Samples that provide effective cleavage of key wall components can be analyzed by DNA sequencing, as, for example, has recently been performed on the community of organisms inhabiting the hindgut (stomach) of a termite species (Warnecke et al. 2007). Such sequencing of whole communities, as opposed to single organisms, is known as metagenomics. With such an approach, deconstruction enzymes can be identified without the requirement to be able to isolate and grow the organism that makes them. Full genome sequencing of important organisms from lignocellulose-degrading environments is another strategy for identifying genes for deconstruction. In this vein, researchers have recently sequenced the genome of a key cellulose-degrading bacterium, again from the guts of termites (Hongoh et al. 2008).

Newly discovered and formerly characterized enzymes will be further studied and subjected to directed evolution to develop improved enzymes that are more effective under commercial conditions. Directed evolution generates new variants of the enzymes of interest through repeated cycles of mutation and selection. Variation can be introduced into the enzyme target by numerous methods, including gene shuffling, which results in replacement of pieces of the enzyme with pieces from other similar enzymes (Shibuya et al. 2000). The new enzyme variants are then screened for improvements in the desired activity. Any variants that pass the screen can then be fed back through the cycle of mutation and further screened with increased stringency or different criteria.

Conversion of sugars to fuel

The currently employed, yeast-based method of sugar conversion to ethanol has a number of shortcomings for fuel synthesis. The fermentation of sugars by yeast does not proceed to completion nor does it utilize two of the major carbon sources in lignocellulose — the 5-carbon sugars that are abundant in matrix polysaccharides and phenolic lignin. Furthermore, ethanol as a fuel is not optimal; it has low energy content (67% less than gasoline), requires energy to separate from water and is corrosive (Somerville 2007). Therefore, the major goal for biofuel production is to develop an organism or community of organisms that utilizes all of the major components of lignocellulose and produces a more gasoline-like fuel. Ideally, this organism(s) would also produce cell wall–degrading enzymes, incorporating many of the deconstruction functions of cleaving polysaccharides and lignin networks in the fuel synthesis phase.

Many of the biochemical processes required for the conversion of lignocellulose into diverse fuels have already been identified in various organisms, though the search for improved or alternative chemistries continues. Engineering or selecting for high yields is a crucial area of research. Another major challenge is to bring together all of the processes in a single organism, or a few coordinated organisms, that perform well under industrial conditions. For example, some anaerobic bacteria can ferment 5-carbon sugars. Based on the pathways in those organisms, laboratory yeast strains that are intolerant of industrial conditions have been engineered with this ability (Jeffries and Jin 2004). Other organisms have been described that produce alternative fuel products. For example, the bacterium *Vibrio furnissii* converts glucose to alkanes, long hydrocarbon chains similar to those found in petroleum (Park 2005). In a recent elegant example of combined metabolic engineering and directed evolution, the commonly used bacterium *Escherichia coli* has been engineered to produce relatively high yields of butanol (Atsumi et al. 2008). Butanol is a 4-carbon alcohol that can be directly substituted for gasoline in unmodified car engines, though it still lacks beneficial characteristics compared with less water-miscible alkanes such as hexadecane.

JBEI and other groups will be working on moving the necessary enzymes into yeast and other organisms for use on an industrial scale. Using such techniques as RNA, protein and small-molecule profiling similar to those described here for examining plants, the biological state of the engineered organisms will be monitored to evaluate how to make improvements. These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Seeking an alternative to yeast, Veronica Fok of the Joint BioEnergy Institute in Emeryville is engineering new microbes that can quickly and efficiently ferment complex sugars into advanced biofuels.

studies will build on progress in understanding microorganism biology, which has already advanced to using mathematical models that accurately describe the flow of sugars and small molecules through the series of enzymes that convert sugars to fuels (Suthers et al. 2007).

The biofuel future

Significant creativity is now being focused on the challenge of developing sustainable biofuel production. Optimizing the efficiency of lignocellulose breakdown is a major goal. Researchers also seek to improve bioenergy crop production and develop improved fuel synthesis methods. With such advances, biofuel production has the potential to fit into a near- to midterm future in which transportation fuels are efficiently generated with little greenhouse-gas production from municipal and agricultural waste products and low-input, extremely high-yielding perennial energy crops. The current DOE goal is that by 2030, 30% of U.S. transportation fuels will come from from such alternative sources (Perlack et al. 2005).

L.E. Bartley is a postdoctoral scholar in the Grass Genetics Group, Joint BioEnergy Institute (JBEI); and P.C. Ronald is Vice President of Feedstocks and Director of Grass Genetics, JBEI, and Professor of Plant Pathology, UC Davis. We thank Sang Won Lee, Matthew Peck and David Doyle for commenting on the manuscript. This work was funded in part by JBEI, which is supported by the U.S. Department of Energy Office of Science and Office of Biological and Environmental Research, via contract DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory. L.E. Bartley was supported by a UC President's Postdoctoral Fellowship.

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Cellulosic biomass could help* meet California's transportation fuel needs

by Charles E. Wyman *and* Bin Yang

Cellulosic biomass, which includes agricultural and forestry residues and woody and herbaceous plants, is the only low-cost resource that can support the sustainable production of liquid fuels on a large enough scale to significantly address our transportation energy needs. The biological conversion of cellulosic biomass to ethanol could offer high yields at low costs, but only if we can improve the technology for releasing simple sugars from recalcitrant biomass. We review key aspects of cellulosic ethanol production, including pretreatment and enzymatic hydrolysis technologies that present the greatest opportunities to lower processing costs. Although several companies seek to introduce cellulosic ethanol commercially, innovative measures are needed to help overcome the perceived risks of first applications.

Laboratories at the Center for Environmental Research and Technology at UC Riverside focus on understanding and improving pretreatment, enzymatic hydrolysis and fermentation technologies for the biological conversion of cellulosic biomass into ethanol and other products.

Cellulosic biomass, a structural material in plants that can be converted into ethanol, is the only large-scale sustainable resource for producing alternative liquid fuels that can be integrated with our existing transportation infrastructure. Cellulosic biomass includes agricultural residues such as corn stover (the corn plant minus kernels and roots), forestry residues such as sawdust and paper, yard waste from municipal solid waste, herbaceous plants such as switchgrass, and woody plants such as poplar trees. Because a dry ton of cellulosic biomass could provide about three times as much energy as a barrel of petroleum, cellulosic biomass would be worth about $200 per dry ton when crude oil sells at $65 per barrel. It can be purchased for about a third of that amount. To utilize this abundant resource, we must develop low-cost technologies for transforming biomass into fuels that can compete with petroleum (Lynd et al. 1999).

The U.S. Department of Agriculture and Department of Energy (DOE) project that nationwide about 1.3 billion dry tons of cellulosic biomass (equivalent to 1.5 billion barrels of petroleum) could be available annually nationwide, enough for a major impact on energy use (Perlack et al. 2005), and that large-scale biomass use is possible without threatening food supplies (Lynd et al. 2007). Overall, the conversion of cellulosic biomass into ethanol and other organic liquid fuels can improve energy security, reduce trade deficits, enhance global competitiveness and create rural employment. In addition, biotechnology can be harnessed to further reduce costs and realize the high yields vital to economic success (Wyman 1994). Perhaps of greatest importance, when appropriately utilized, cellulosic ethanol can release very little if any net carbon dioxide, because carbon dioxide released during processing and combustion only slightly exceeds the amount sequestered by cellulosic biofuel feedstocks such as trees and grasses. This provides a powerful and not readily matched mechanism to cut greenhouse-gas emissions due to transportation, the largest U.S. contributor with about a third of the total (Farrell et al. 2006).

Both President Barack Obama and his predecessor in the White House have identified production of ethanol from cellulosic materials such as switchgrass and wood as vital to overcoming the U.S. "addiction" to oil. In recent years, California also adopted several bold new initiatives, including: (1) AB32, The Global Warming Solutions

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*Author's typographical correction after press run; addition of the word "help."

Act of 2006, which caps greenhouse-gas emissions at 1990 levels by 2020, (2) an executive order establishing the first Low Carbon Fuel Standard and calling for a reduction in the carbon intensity of passenger-vehicle fuels by at least 10% by 2020, and (3) an historic agreement with Arizona, New Mexico, Oregon and Washington to reduce greenhouse-gas emissions through a market-based approach. Meeting these targets will be challenging for a state with a transportation fuels market that dwarfs that of other states. Transportation fuels account for about 40% of California's total energy use; the state is the largest transportation fuels market in the country. Additionally, about 40% of California's greenhouse-gas emissions come from transportation, a higher fraction than the country as a whole.

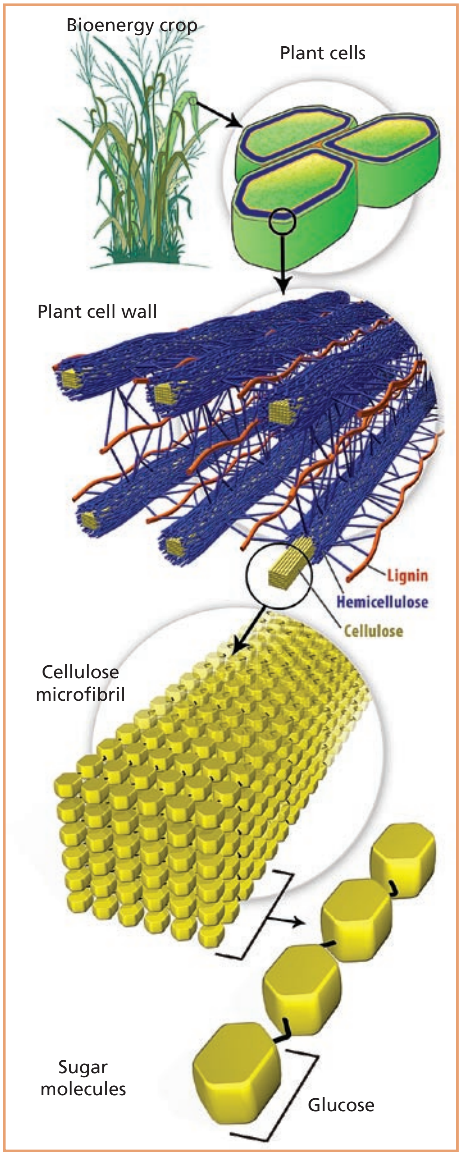


Fig. 1. Lignocellulose, the most abundant organic substance on Earth, is composed of three major constituents — cellulose, hemicellulose and lignin — that combine to protect energy-storing sugars and give the plant cell wall strength and structure. Source: Genome Management Information System, Oak Ridge National Laboratory.

At present, cellulosic biomass is the only environmentally sustainable resource for producing liquid transportation fuels to meet these goals. California has large quantities of agricultural residues, forest thinnings and residues, and municipal waste. The California Biomass Collaborative estimates that the state produces about 24.2 million dry tons of cellulosic biomass annually, with enough of this available for the sustainable production of fuels displacing about 1.1 billion gallons of gasoline each year (http://biomass.ucdavis.edu).

Cellulosic biomass composition

Cellulosic biomass has three major components: hemicellulose, cellulose and lignin. Hemicellulose is an amorphous, branched polymer that is usually composed primarily of five sugars (arabinose, galactose, glucose, mannose and xylose); it typically comprises about 15% to 30% of cellulosic biomass. Cellulose is a large, linear polymer of glucose molecules typically joined together in a highly crystalline structure due to hydrogen bonding between parallel chains; it typically comprises about 35% to 50% of cellulosic biomass. Lignin is a complex phenyl-propane polymer that often comprises about 15% to 30% of cellulosic biomass. Although lignin cannot be converted into fermentable sugars, this component has high value as a boiler fuel and could also be useful as a raw material for making aromatic compounds such as benzene and toluene.

Turning biomass into fuel

The biological processing of cellulosic biomass involves first using enzymes as catalysts to release sugars, as in from hemicellulose and cellulose by hydrolysis (in which water reacts with these fractions to release simple sugars), and then using microorganisms to ferment the sugars into ethanol (fig. 1). In laboratory studies, the enzyme-catalyzed hydrolysis of cellulose into glucose is promising for making fuel or other commodities because high glucose yields, considered vital to economic success, are possible (US DOE 1993).

The costs of processing cellulosic biomass have already been reduced by about a factor of four in the last 25 years, making them competitive with costs for producing ethanol from corn (Wyman 2001). Many of the advances needed to lower costs further are achievable through the application of powerful, evolving tools of biotechnology (Lynd et al. 2008). In addition, the high selectivity of biological processing, particularly of enzymes that catalyze reactions, minimizes waste generation and related disposal problems.

Acid processing. Dilute acids can also break down cellulose into simple sugars. However, they have two drawbacks: (1) in commercially practical processes, glucose yields are limited to 50% to 60% of those theoretically possible, and (2) the degradation products cause operational problems. (Cao et al. 1997). Concentrated acids achieve more commercially attractive yields because hydrolysis occurs at relatively low temperatures and pressures. However, acid recovery is expensive, and must be improved to attain competitive costs with plentiful feedstocks (Cao et al. 1997).

Enzymatic processing. To overcome the natural resistance of cellulose to biological degradation, biomass is milled and pretreated. Pretreatment with dilute acid often achieves hemicellulose sugar yields of up to 90% and makes the cellulose left in the solids highly digestible by enzymes. The resulting liquid is treated to remove inhibitory compounds such as acetic acid, which would otherwise interfere with enzymes such as cellulase. Inhibitory compounds are naturally released from biomass, as in acetic acid, or may be formed by its degradation, as in furfural, a chemical used to make plastic materials. This sugar stream is fermented using technology developed to convert the five 5-carbon hemicellulose sugars into ethanol.

The second sugar stream is derived by adding the enzyme cellulase to pretreated solids. This catalyzes cellulose breakdown with glucose yields of over 90% for appropriate cellulase formulations and pretreatment conditions; many organisms, including common yeast, can ferment glucose into ethanol at around 90% of theoretical yields.

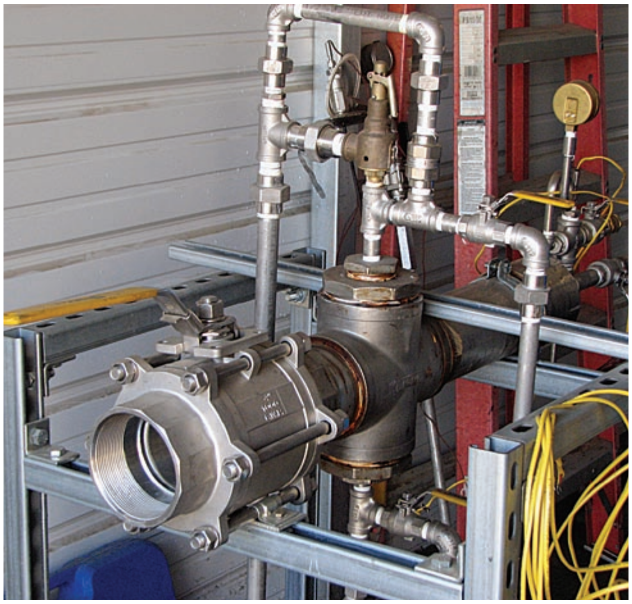
Cellulosic biomass is the only known resource for the sustainable production of liquid transportation fuels on a large scale and at low cost.

Ethanol and other products. Finally, the fermentation broth from both sugar streams is transferred to distillation columns, then to molecular sieves to concentrate and recover the ethanol. Lignin, water, enzymes, microorganisms and other nonethanol components are left in the column bottoms, and are concentrated to feed a boiler that provides heat and electricity for the entire process. Finally, excess electricity is sold. Liquid not retained with the solids is treated, and the resulting clean water is discharged or recycled. The sludge is disposed of, any methane produced is fed to a boiler, and ash is landfilled. Coupling the use of lignin for boiler fuel with the low levels of fertilizer needed to grow cellulosic crops, fossil energy inputs are minimal, and the net release of carbon dioxide is low (Farrell et al. 2006).

Pretreatment options

Pretreatment can provide two vital functions: recovering sugars from the hemicellulose, and improving the enzyme digestion of cellulose into glucose. Innovative pretreatments could also recover lignin, protein, minerals, oils and other materials in biomass to enhance revenues (Lynd et al. 1999). Pretreatment is projected to be the most costly operation in the conversion of biomass to ethanol, representing about one-third of total processing costs, and it substantially affects upstream and downstream operations (for instance, if acetic acid or furfural build up and inhibit biomass degradation or fermentation). However, costs are even higher without pretreatment; we believe that the only operation more expensive than pretreatment is no pretreatment (Wyman 2007).

Our understanding of how pretreatment technology deconstructs biomass is confounded by the fact that a hemicellulose-and-lignin shield surrounds cellulose, limiting its accessibility (Hsu 1996). Yet, little effort has been spent on thoroughly understanding pretreatment, resulting in trial-and-error approaches and impeding progress toward lower costs.



Researchers at UC Riverside invented this novel steam chamber, which heats up the reactors used to pretreat biomass more quickly and uniformly, and, conversely, cools down the material more rapidly than previous technology allowed.

Over the years, various biological, chemical and physical pretreatments have been applied to enhance the susceptibility of cellulose to attack by enzymes, and to recover hemicellulose sugars with high yields (Hsu 1996). Ammonia, lime, controlled pH, sulfur dioxide and dilute sulfuric acid are cost-effective pretreatments, and they are being studied by the Biomass Refining Consortium for Applied Fundamentals and Innovation (a national consortium of universities and the DOE National Renewable Energy Laboratory) for applications to corn stover, poplar wood and switchgrass (Wyman et al. 2005).

Dilute sulfuric acid hydrolysis has been the subject of considerable research and development, particularly targeting fuels production. Hemicellulose sugar yields from uncatalyzed steam explosion are limited to about 65% (Heitz et al. 1991), but adding dilute sulfuric acid can enhance yields by 50% and produce more digestible cellulose at relatively low cost (Knappert et al. 1981). The technology is also effective for a variety of feedstocks. For example, sugar yields of 85% to 90% or even more can be recovered from hemicellulose with temperatures of around 320ºF (160ºC), reaction times of about 10 minutes and acid levels of about 0.5% (Lloyd and Wyman 2005). About 85% to 90% of the remaining cellulose can then be enzymatically digested into glucose (Lloyd and Wyman 2005). The National Renewable Energy Laboratory in Golden, Colo., and others favor dilute sulfuric acid hydrolysis for near-term applications.

Because it is corrosive, however, dilute sulfuric acid hydrolysis is still expensive, requiring costly construction materials for processing equipment. Its degradation products (such as furfural and lignin fragments) and solubilized biomass compounds (such as acetic acid) must be removed before fermentation by processes such as overliming or ion exchange. In addition, acid neutralization and hydrolyzate conditioning with lime both form gypsum, which causes downstream difficulties. Furthermore, the cost of sulfuric acid and lime mount when accounting for disposal costs following neutralization.

Hydrolysis and fermentation

Enzymatic hydrolysis. A major challenge for cellulosic ethanol has been improving the technology for hydrolysis of recalcitrant cellulose, with high glucose yields made possible by the synergistic action of three classes of fungal cellulase components: endoglucanase, cellobiohydrolase and beta-glucosidase. Classical mutations of the cellulase-producing fungus *Trichoderma reesei*, which was discovered during World War II, improved the enzymes by, for example, enhancing beta-glucosidase activity for converting cellobiose, a powerful inhibitor, into glucose. (Cellobiose is two chemically bonded glucose molecules that slow further breakdown of cellulose.) In addition, cellulase evolved from earlier strains of *T. reesei* such as QM9414, to improved varieties such as Rut C30 (Kadam 1996; Montencourt and Kelleher 1980) and Genencor 150L

Cellulosic biomass includes a range of plant materials that can be converted into ethanol for use as liquid transportation fuel. *Right*, a border of switchgrass, an herbaceous plant that shows promise as a biofuel.


ARS/Chung-Ho Lin

(Wyman et al. 1986). Genencor and Novozymes announced significant progress in reducing enzyme costs through DOE support (CEN 2005; CEP 2004). Although uncertainty remains regarding the actual commercial price, several new projects are being funded by DOE to drop costs even further.

Saccharification and fermentation

The glucose released when cellulose is broken down by cellulase is a powerful inhibitor of this enzyme. To reduce glucose accumulation during cellulose breakdown (or saccharification), yeast or another fermentative organism can be added to convert the released sugars into ethanol. This configuration is called simultaneous saccharification and fermentation (SSF). Compared to hydrolysis alone, SSF offers better rates, yields and concentrations of ethanol, although at lower temperatures than are optimal for enzymes.

Following identification of the SSF configuration in the mid-1970s (Takagi et al. 1977), fermentative organisms were sought to tolerate the combined stresses of (1) higher temperatures, to increase hydrolysis rates by enzymes, (2) low glucose levels, due to rapid sugar metabolism by the fermentative organism and (3) high ethanol concentrations, which are lethal to fermentative organisms (Wyman et al. 1986).

SSF performance was improved by the yeast *Brettanomyces custersii*, which ferments cellobiose directly into ethanol, or by coculturing the less-ethanol-tolerant yeast *B. claussenii* with the more robust *Saccharomyces* yeast (Spindler et al. 1992). Similar benefits are provided by bacteria genetically engineered to ferment xylose (one of the sugars derived from hemicellulose) into ethanol, bacteria that ferment cellobiose into ethanol either naturally or through genetic modifications, and organisms that also make cellulase components (Wood and Ingram 1992). The search continues for temperature tolerance and other traits that better match the operating conditions preferred by cellulase.

Since the early studies, SSF has been applied to a wide range of feedstocks pretreated under various conditions (Ballesteros et al. 2002), including a few applications in fed-batch and continuous processes for the conversion of paper sludge and wood. SSF has been combined with hemicellulose sugar fermentation (simultaneous saccharification and cofermentation) to lower costs, and has been studied for making products other than ethanol (Thomas 2000). Other approaches are still being considered (Alkasrawi et al. 2002), but SSF technology is a leading candidate for near-term applications and will likely remain so until cellulases can act much faster (that is, make it possible to perform two steps as fast as SSF performs one) with minimal product inhibition at high temperatures (Wright et al. 1987).

Numerous laboratory experiments are focusing on batch operations for enzymatic hydrolysis or SSF, as well as limited fed-batch or continuous systems. Surfactants can improve performance (reduce the amount of enzyme needed to yield the same amount of ethanol) (Castanon and Wilke 1981), and the addition of protein can enhance glucose yields by reducing the nonproductive binding of enzymes to lignin (Yang and Wyman 2004, 2006). This approach can also reduce or eliminate the current practice of supplementing cellulose processing with beta-glucosidase to keep cellobiose concentrations from inhibiting enzyme activity. Nonetheless, even at costly enzyme doses of 15 international filter paper units per gram (IU/g) of cellulose, typical SSF reaction times are about 5 to 7 days to achieve modest ethanol concentrations (Kadam et al. 2004)

Economics of cellulosic ethanol

Projected costs. Although estimates always suffer from inaccuracies, economic models can track progress, identify promising options and define lower cost paths. Researchers project that cellulosic ethanol costs have dropped from about $4 to $5 per gallon of ethanol in 1980 to be competitive with corn ethanol (which today costs close to $1 per gallon to produce), and commercial projects are now under way (Wyman 1999). These cost reductions can be attributed to progress in two areas: (1) overcoming biomass recalcitrance through advances in pretreatment, cellulases and fermentation integration (SSF) (Wyman 2001), and (2) overcoming biomass sugar diversity by fermenting all five hemicellulose-derived sugars into ethanol with high yields (Ho et al. 1998; Ingram et al. 1999). Cellulase enzymes have historically been a key cost, because of the large amounts required. Major cellulase cost reductions have been claimed by producers, but the current purchase price for initial applications is unclear, clouding decisions on commercial status and research needs. One way to reduce enzyme costs would be to produce cellulase on-site (Himmel et al. 1999).

Commercial challenges. Several companies are attempting to commercialize cellulosic ethanol in the United States, including Broin, BlueFire, Dupont, Iogen, Mascoma, SWAN Biomass and Verenium (CEN 2007). Because the technology is unproven commercially and is capital intensive, strategies such as capitalizing on low-cost waste materials, integrating with existing facilities, utilizing tax-free bonds and developing higher-margin coproducts (such as succinic acid) are needed to overcome risk concerns (Wyman and Goodman 1993). The three most-expensive process steps are projected to be pretreatment, enzymatic hydrolysis and enzyme production, in that order, which means that enhancing performance and reducing costs will depend on integrating these steps more effectively.

Reducing costs

Of the total cost of cellulosic ethanol production, the four most expensive elements are projected to be feedstocks (33%), pretreatment (18%), enzymatic hydrolysis (12%) and enzyme production (9%) (Wooley et al. 1999). However, because biomass unit energy costs are equivalent to those of oil at about $20 per barrel (Lynd et al. 1999), these factors are the major drivers for large cost reductions in unit operations to overcome the recalcitrance of biomass (Wyman 2007). Consequently, total cellulosic ethanol costs could be competitive with other fuels without subsidies via further advances in pretreatment and the integration of enzyme production, enzymatic hydrolysis and fermentation (Lynd et al. 2008). Biomass at $60 per dry ton realistically yields about 100 gallons of ethanol, which translates into a feedstock cost of only 60 cents per gallon. The challenge is to advance technologies so that feedstock represents more than two-thirds of the final product cost, as is typical for mature commodity businesses, resulting in a cellulosic ethanol cost of about 90 cents per gallon or less. Other keys to reducing costs are minimizing processing vessel sizes, reducing the cost of construction materials, reducing the number of process steps, avoiding high pressures and temperatures, improving thermal integration (using residual heat from one process step to meet the needs of another step of the process), and lowering power requirements and water use.

Heather McKenzie

UC Riverside Ph.D. student Qing Qin uses a pipette to measure enzymatic hydrolysis samples into vials, in order to determine sugar concentrations. This research ultimately seeks more efficient ways to break down plant cellulose into sugars that can be fermented into transportation fuel.

“Consolidated bioprocessing” is a promising approach — organisms produce powerful enzymes anaerobically and ferment all of the sugars released into ethanol, with high yields. Modern biotechnology offers great potential for the development of new organisms to accomplish such feats, and great strides have already been made (for instance, in the genetic engineering of microorganisms to ferment arabinose and xylose into ethanol). Pretreatment costs could also be decreased with advances such as lower chemical use and milling demand, less-expensive construction materials, decreased sugar degradation, lower inhibitor formation, and higher hemicellulose and cellulose sugar yields (Lynd et al. 2008).

Refining coproducts

A range of fuels, chemicals and natural materials could be derived biologically from the sugar intermediates used to make ethanol in a biorefinery, as is done with petroleum, corn and other commodities (Lynd et al. 1999). Several analyses point out that the biological conversion of cellulosic biomass benefits from economies of scale, with all unit costs going down as scale increases — and boiler, power generation and waste treatment costs dropping fastest (Wooley et al. 1999). Furthermore, although the costs to transport feedstock increase with distance, capital cost reductions are projected to outweigh these until more than about 10,000 dry tons per day of feedstock is used. Few chemical markets can currently support such large facilities, but ethanol has the huge market demand for which they are appropriate.

Coproduction of small-volume chemicals would increase the profitability of a large-scale biomass facility because side streams of low-cost sugars resulting from cellulosic ethanol production could be converted into products such as succinic acid that have greater margins. Similarly, the excess power produced from burning lignin and other residues could be sold into the grid at lower prices than are possible for a dedicated power plant. Lignin could also be used as a precursor for the production of aromatic compounds and various natural materials. Cellulosic biomass contains valuable constituents including oils, proteins, minerals and complex materials valuable in processing (Dale 1983), and the extraction of such components through biorefining could enhance the range of products and associated financial benefits. On the other hand, introducing multiple products increases the technical risks of a venture and provides additional marketing challenges. Focusing on a single product first is prudent, with add-ons later to diversify the product slate and increase profitability.

Commercial production

The need for sustainable energy production to address mounting security and environmental problems is finally being recognized, and cellulosic biomass is the only known resource for the sustainable production of liquid transportation fuels on a large scale and at low cost. Cellulosic fuels such as ethanol would be particularly beneficial for California to meet its bold new initiatives to reduce greenhouse-gas emissions, and the state has abundant cellulosic resources.

Substantial advances in the enzymatic hydrolysis of cellulosic biomass into sugars and their fermentation into ethanol make the technology attractive now, and even lower costs are forecast as the technology matures, although particular attention is needed to advance pretreatment systems and assure that low-priced enzymes are available. The primary challenge for the first commercial market entries is overcoming the perceived risk for such capital-intensive projects, and innovative approaches will be needed for success. Once in place, the low-cost sugars from making ethanol at a large scale can support the profitable production of other products from cellulosic biomass, including sugar intermediates, residue-based power, lignin derivatives and natural materials.

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Biofuel policy must evaluate environmental, food security and energy goals to maximize net benefits

by Steven Sexton, Deepak Rajagopal,
Gal Hochman, David Zilberman *and*
David Roland-Holst

The biofuel industry has received billions of dollars in support from governments around the world, as political leaders respond to new environmental and energy-security imperatives. However, a growing body of research highlights nontrivial costs associated with biofuel production, including environmental destruction and diminished food security, and questions the magnitude of perceived benefits. We discuss the ability of biofuels to accomplish climate change, rural development and energy-security objectives, and consider possible impacts on food production and environmental conservation. We also review methods for judging biofuels, consider how well they contribute to policy objectives, and compare policies that support biofuels.

Beatrice Murch

Biofuels have been promoted as a means to enhance energy independence, promote rural development and reduce greenhouse-gas emissions, but policymakers must also weigh impacts on the environment and food security. *Above*, biodiesel powers a Mercedes Benz.

Governments in industrialized countries have promoted the production of ethanol and biodiesel in order to mitigate climate change, boost income in the rural sector and reduce dependence on imported oil. The total outlays for these policies are measured in tens of billions of dollars per year. As the world emerges from the first global food crisis in three decades and controversy surrounds the greenhouse-gas savings of biofuels, policymakers have begun to question their promotion of a technology that takes land away from two predominant uses — food production and environmental preservation.

Governments that seek to introduce alternative fuel policies do so despite a lack of consensus among researchers as to the costs and benefits of biofuel production. Impacts are mostly predicted through complex economic models based on numerous assumptions, many of which are open to critical review. Furthermore, the impacts of biofuels on climate change, food prices, deforestation and energy security vary by feedstock, and method and location of production, making it difficult to draw general conclusions, and complicating policy development.

Why biofuels?

The biofuel industry has benefited from government policy since the energy crisis of 1973, which disrupted a half-century of cheap oil and awakened oil-importing countries to their dependency on oil-rich nations. In recent years, concern has grown about global climate change as well as national security during an era of increasing energy demand and rapidly rising energy prices. As a result, the United States, European Union (EU), Australia, Canada and Switzerland spent at least $11 billion on biofuel subsidies in 2006 (GSI 2007).

Rural and agricultural development. Because bioenergy creates additional demand for crop production, biofuels may increase farm income and enhance development. Economic theory predicts that an increase in demand for a commodity increases its price, all else being equal. Farmers will enjoy higher prices, even if producers boost supply in response to higher prices, so long as supply increases less than demand. This theory is confirmed by rising world prices for several staple agricultural commodities (fig. 1). U.S. corn prices, for instance, averaged $4 per bushel in 2008, up from $3.40 in 2007 (USDA 2008b).

World prices for staple agricultural commodities have risen considerably in recent years (fig. 1). Rising crop prices can contribute to improved welfare on the farm, but may also be capitalized

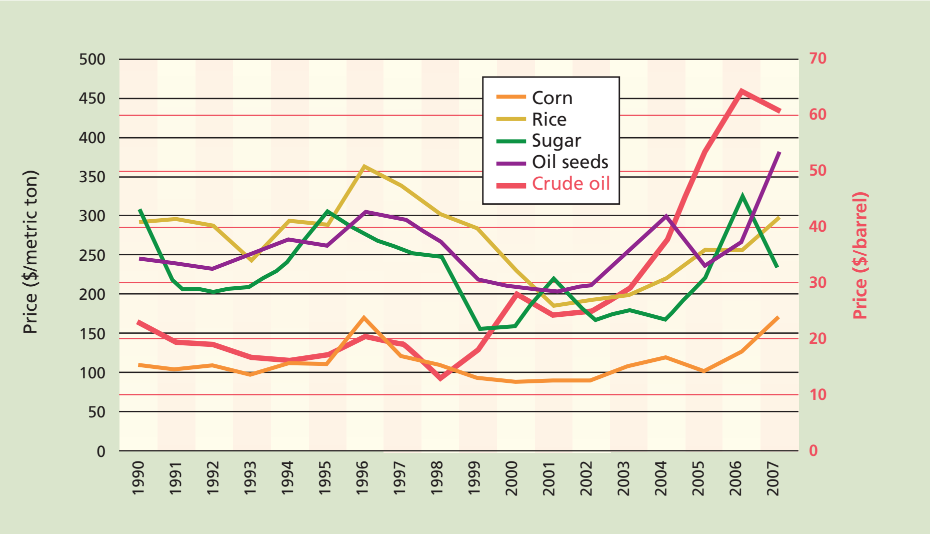


Fig. 1. Agricultural commodity prices and crude oil prices since 1990. Source: Msangi 2008.

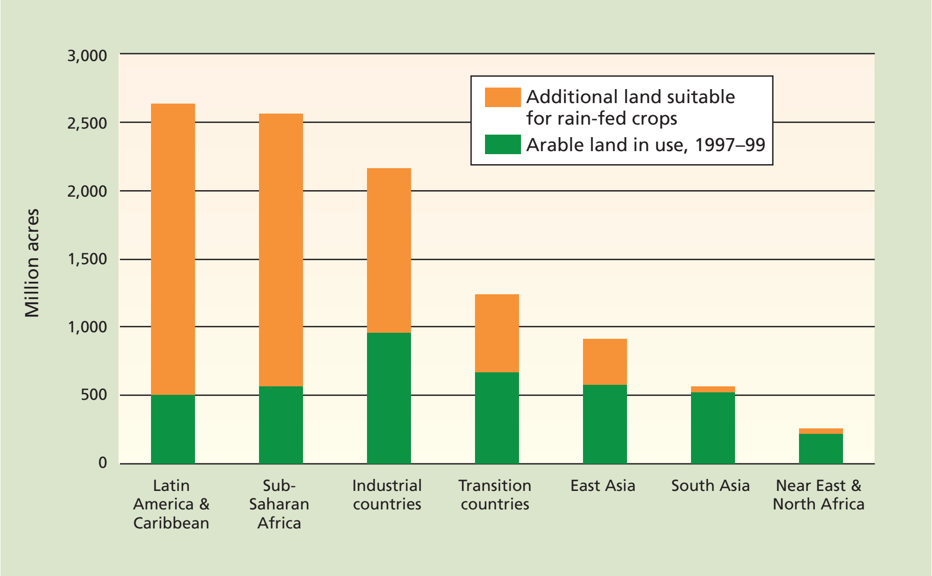


Fig. 2. Agricultural land use and potential expansion by region. Source: Wiebe 2008.

into land rents and the price of other inputs (from machinery to chemicals), reducing the benefit to farmers. Nevertheless, U.S. farm income was an estimated record $89.3 billion in 2008, up roughly 50% from its 10-year average. Average farm household income was an estimated $89,434, nearly 20% above the 5-year average from 2001 to 2006 (USDA 2008a). Benefits will not be uniformly distributed among farmers, however; while row-crop producers will benefit from higher commodity prices, livestock farmers, in particular, are expected to suffer from rising feed costs.

Biofuels may help developing countries transition from subsistence farming. Many poor countries are unable to farm major food crops profitably due to poor climate and soil, but they can produce existing and second-generation bioenergy crops. Eighty developing countries, for instance, grow and process sugar cane, the most efficient feedstock used today in commercial ethanol production (IFPRI 2005). A second generation of biofuels will yield feedstocks that grow on marginal and degraded lands.

For example, Miscanthus can be grown on marginal land and irrigated with saline water and still yield significantly more ethanol per acre than existing feedstocks. Jatropha, an oil-bearing plant used to produce biofuel, can be grown on infertile soil and under drought conditions. An estimated 74 million acres (30 million hectares) of land could be planted to Jatropha in India (IFPRI 2005). Developing countries could have a comparative advantage in producing biofuel feedstocks largely due to lower opportunity costs of marginal land; bioenergy crops would not be displacing crops for food and feed (fig. 2). Notably, countries in South America and sub-Saharan Africa could quadruple their agricultural land base to accommodate bioenergy crops. This transition from subsistence farming could greatly boost welfare in poor countries, but the net welfare effect of biofuel on the poor hinges on the impact of rising food prices. The landless poor would not benefit from energy cash crops, but would suffer from higher food prices.

Energy security. Since biofuels can be produced domestically in many countries, they may improve the energy security of oil-importing countries. With oil prices exceeding $130 per barrel in 2008 and much of the world's oil production occurring in politically unstable regions, governments aim to ensure that their economies are not held hostage. In theory, biofuels can serve as a substitute for fossil fuels and reduce oil imports.

Based on current production methodologies, however, most countries will be unable to displace any significant share of their oil consumption, and can, at most, hope to marginally reduce prices by increasing the supply of liquid fuels. For example, the United States, Canada and EU-15 (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom) could displace only 10% of their gasoline consumption with biofuels if they recruit between 30% and 70% of their respective croplands (Rajagopal and Zilberman 2007). The diversion of such significant shares of cropland is unlikely and would entail significant increases in food prices. Unless biofuel productivity improves, more cropland will be needed to displace the same share of gasoline as energy consumption rises.

Greenhouse-gas mitigation. Concern about global warming has driven interest in fuels that emit less greenhouse gas than oil. The primitive view of biofuels, which has proven quite misleading in recent years, is that carbon is stored during energy-crop growth and later emitted during the combustion of biofuels in a carbon-neutral cycle. This simplistic analysis has been replaced with life-cycle analysis, which considers the greenhouse-gas emissions of an energy source throughout the entire process, including production (soil tilling, gas and diesel-powered farm equipment, emissions from fertilizer production and other inputs), conversion of the energy crop to biofuel, transportation of fuel to market, and fuel consumption.

While analyses differ, the literature suggests modest greenhouse-gas savings associated with the first generation of biofuels, primarily ethanol from corn and sugar cane, and biodiesel from soy and palm oil. Farrell et al. (2006) estimated that corn ethanol provides greenhouse-gas savings of 13% relative to fossil fuels. Hill et al. (2006) reported greenhouse-gas savings from biodiesel of 41% relative to traditional diesel fuel. Life-cycle analysis has generally shown that biofuels are not the global warming panacea many believed they would be, but they can constitute a partial solution. These analyses, however, typically do not account for "scaling up" effects, such as the conversion of land in its natural state, with its existing carbon sequestration functions, to biofuel feedstock production.

The aim of policy should be to temporarily promote biofuel technologies that will one day be competitive with fossil fuels and other alternatives, if externalities are corrected.

Negative implications of biofuels

While biofuels provide benefits, they are also associated with significant costs. First, they can be damaging to the environment — they may actually increase greenhouse-gas emissions, increase car travel, reduce biodiversity, consume scarce water supplies and degrade water quality. Second, as energy production competes with food for harvests and land, food production declines and prices go up. Biofuels are surely responsible, in part, for the food crisis of 2008, during which three decades of declining food prices abruptly gave way to dramatic price increases as food inventories were drawn down to historic lows and food-producing countries imposed export controls to protect domestic markets. The blame for the food crisis attributed to biofuels from media reports is, however, likely overstated.

Greenhouse gases. Even the life-cycle analyses that reported only modest carbon savings from biofuels relative to fossil fuels (for example, Farrell et al. 2006 and Hill et al. 2006) may have overstated the climate change benefits. They ascribed a carbon credit to biofuels to account for sequestration that occurs during energy-crop growth, but failed to account for the loss of carbon sequestration in forests and grasslands destroyed to make room for energy crops.

Searchinger et al. (2008) were the first to analyze the carbon emissions of corn ethanol and account for land-use changes. In particular, biomass sequesters carbon in forests and grasslands and stores it in plant material. If such lands are cleared and the biomass is burned or left to decompose, then the carbon is emitted back into the atmosphere. Because biofuels create additional demand for land, they theoretically lead to the expansion of cropland and the loss of natural lands. Searchinger et al. (2008) found that a 15-billion-gallon (56-billion-liter) expansion of U.S. corn ethanol production would bring an additional 26.7 million acres (10.8 million hectares) of land under cultivation and actually double carbon emissions relative to fossil fuels over 30 years. It would take 167 years for corn ethanol to overcome the carbon debt it incurs from land-use changes and start providing carbon savings (relative to fossil fuels). Switchgrass, which yields more ethanol per acre, could provide carbon savings within four decades (Searchinger et al. 2008).

Similar analysis by Fargione et al. (2008) concluded that the production of food-crop biofuels in the United States, Brazil and Southeast Asia would induce land-use changes that increase carbon emissions from 17 to 420 times the annual carbon savings of biofuels, depending on assumptions about land-use changes. Corn ethanol produced on abandoned U.S. cropland would repay its carbon debt after 48 years. Producing corn ethanol on converted grasslands would double the repayment time. Palm diesel produced on converted rainforest in Malaysia and Indonesia would not repay its carbon debt for more than four centuries.

Car travel. Because biofuels reduce the price of transportation fuel by increasing supply (Rajagopal et al. 2007), they encourage additional car travel by gasoline consumers (Khanna 2008). In other words, biofuels increase vehicle miles traveled, which increases carbon emissions, worsens traffic congestion on roadways and can lead to additional traffic accidents (Khanna 2008; de Gorter 2008).

Biodiversity. The 26.7 million acres of land that Searchinger et al. (2008) predicted would be newly cultivated for the production of 15 billion gallons of corn ethanol would not only increase greenhouse-gas emissions but also destroy natural lands and reduce biodiversity (Mooney and Hobbs 2000). De Fraiture et al. (2008) estimated that an additional 74 million acres of cropland would be needed to meet food and biofuel demand in 2030. Even without biofuels, agricultural production is considered the biggest source of nonclimatic environmental change. It is responsible for loss of habitat and introduction of invasive alien species, for instance (Tilman et al. 2001). Already, 70% of farmland in South Dakota that had been enrolled in the U.S. Conservation Reserve Program will not be re-enrolled as farmers seek to capitalize on high commodity prices.

The loss of natural lands inhibits the environment's ability to provide essential services, including waste assimilation, water purification, fire suppression, soil restoration, nutrient recycling, flood protection, drought

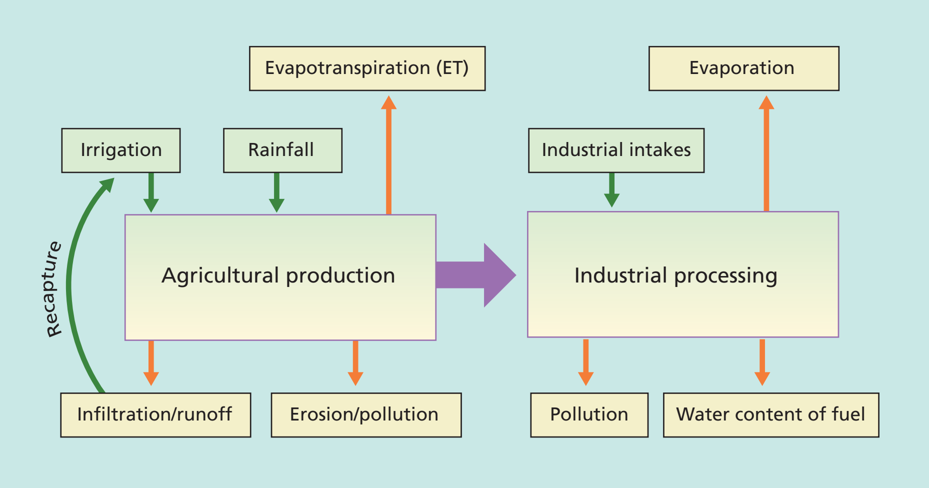


Fig. 3. Water use in biofuel production.

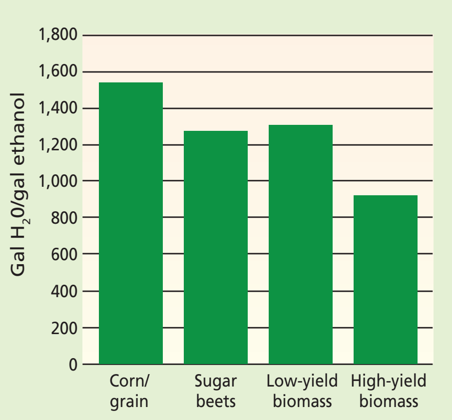


Fig. 4. Water embedded in biofuel for four feedstocks. High-yield biomass = second-generation biofuels. Source: Fingerman and Torn 2008.

prevention and carbon sequestration. Biodiversity also provides value associated with the opportunity to use resources in the future and value associated with the existence of species. Many breakthroughs in science, medicine and agriculture are the result of genetic discoveries in natural habitat (Balick 1996). The loss of biodiversity is costly and irreversible. And while there is hope that climate change can be reduced, there is no way to bring back an extinct species.

Water availability. Water is needed to produce feedstocks as well as convert plant material into fuel (fig. 3). The conversion process is water-intensive and has sparked conflict among biorefineries and growers within watersheds. A recent study commissioned by the California Air Resources Board to investigate the water-resource implications of an increase in California's bioenergy production found impacts to be highly dependent on feedstocks (Fingerman and Torn 2008) (fig. 4).

On average, ethanol produced from feedstocks such as corn and sugarbeets consumes from 925 to 1,527 gallons of water per gallon of ethanol. In contrast, the amount of water required to produce the average daily diet in North America is 1,320 gallons, but less than 500 gallons in sub-Saharan Africa (Serageldin 2001). Evapotranspiration by energy crops constitutes much of the water consumed in biofuel production. By some estimates, the water consumed by energy crops through evapotranspiration could by 2110 meet and even exceed the total water used for evapotranspiration by global croplands in 2002 (Fingerman and Torn 2008).

Water quality. Because agricultural production typically causes some environmental harm, such as soil erosion and pollution from chemicals, to the extent that biofuels increase the stock of productive land, they will increase the magnitude of these damages. Furthermore, as prices for agricultural commodities rise because of biofuel-induced demand, farmers will also find it profitable to use more chemicals per unit of land. Higher input prices could also induce the adoption of precision pest-control technologies, but unless such conservation is considerable, more chemical use will lead to increased pollution of water resources from farm runoff and groundwater percolation. Generally, however, biofuels cause increased environmental damage on both the intensive (more chemicals and erosion per unit of land) and the extensive (more pollution and erosion) margins.

Food security. Perhaps the direst consequence of biofuel production is the pressure that it imposes on the food system. Whereas elevated carbon emissions have negative effects that will play out over decades and centuries, rising food prices and reduced food production mean that people today will potentially go hungry. To some extent, biofuel policies trade food in the stomach for fuel in the tank (see page 199).

A key rationale for biofuel policy is economic development in underdeveloped countries and rural development in industrialized economies. But the food market impacts of biofuels constrain the welfare benefits to the poor. Higher output prices do not universally benefit even the rural poor (Wiebe 2008). For example, the rural poor suffer from higher food prices in countries like Bangladesh and Guatemala, while those in Madagascar and Ghana are better off because they grow more of their own food. The effect of food price increases is even worse for the urban poor, who suffer welfare losses across countries (Wiebe 2008).

Factors affecting biofuel impacts

Feedstocks. Not all biofuel feedstocks are created equal. They vary in the amount of energy yielded per acre of land; the amount of inputs such as fertilizer, pesticides and water required in production; and the extent to which they compete with traditional agriculture for land. By all of these criteria, the second generation of biofuels (high-yield biomass) will fare better than existing biofuels. Plants like Miscanthus, switchgrass and Jatropha can greatly improve the carbon accounting of biofuels because they are less input-intensive and yield more biofuel per unit of land. Cellulosic ethanol from Miscanthus, for instance, can yield as much as three times the biomass per acre as traditional corn ethanol (table 1) (see page 185). Because they are less land-intensive, second-generation feedstocks reduce pressure for the conversion of natural lands, which greatly reduces the carbon debt estimated by Searchinger et al. (2008).

Technology. In the past half-century, growth in agricultural productivity has permitted gains in per-capita food production even as world population doubled. This achievement is even more remarkable considering that the agricultural land base shrank during that time. These gains are the result of mechanization, modern irrigation, chemical fertilizers and pesticides, and the Green Revolution, which capitalized on hybridization to create "super crops," which have freed land for environmental conservation. Such success, however, may have bred a complacency about crop science that the world community can ill afford; there are 852 million undernourished people around the world and food production per capita is decreasing (FAO 2004). Though political considerations and distribution may be to blame for hunger, the situation will not improve as food becomes scarce.

The 2008 food crisis and slowing advances in crop productivity generally are likely the result of underuse of technology that permits the transfer of genes across plant species in a more rapid and deliberate process than conventional hybridization techniques. Whereas rice and wheat yields (fig. 5) have experienced slow growth in recent years, soybeans, corn and cotton have experienced consistent growth due to the adoption of agricultural biotechnology, which greatly improves yields and reduces pesticide use (Qaim 2009).

Fuel production. Though demonstration projects are producing cellulosic ethanol on a small scale, more work must be done before such production can be scaled up (see pages 178 and 185). The challenge is to identify genes, culture them and determine an industrial method of replicating what is already occurring in nature. This challenge creates an imperative for additional advances in biofuel technology so that the world can transcend the use of corn and soy and develop liquid fuels from more productive sources.

The carbon consequences of biofuels are also closely tied to production methods. To the extent that energy-efficient technologies are developed and deployed, and cleaner energy is used in production, the net carbon benefit of biofuels can be improved. For example, nitrogen fertilizer used on corn fields is produced from energy that is 90% gasoline and 10% coal; if fertilizer production were to rely entirely on coal power, the carbon benefit of the resultant corn ethanol would be 61% less (Zilberman 2008). In addition, reducing the distances that feedstocks are transported to refineries and that refined ethanol is transported to market will minimize carbon emissions.

Price and policies. Biofuel impacts are a function of market conditions and policies that determine the prices perceived by market participants. Higher fuel prices and lower prices for agricultural commodities will tend to increase the land devoted to biofuels. If the price of cleaner fuels is less than the price of fossil fuels (perhaps because of policy), then consumption will shift to cleaner fuels — a "green-green" solution. Rising transportation fuel prices may lead to a reorganization of the industry to minimize transportation costs. As transportation costs are reduced, so too are carbon emissions, and the carbon balance of biofuels improves. The conversion of natural land can also be reduced by policies that provide payments for environmental services. Food impacts can be reduced by policies that tie biofuel support to food supply. For instance, subsidies and mandates used to promote biofuel production could be reduced when food inventories fall or food prices rise.

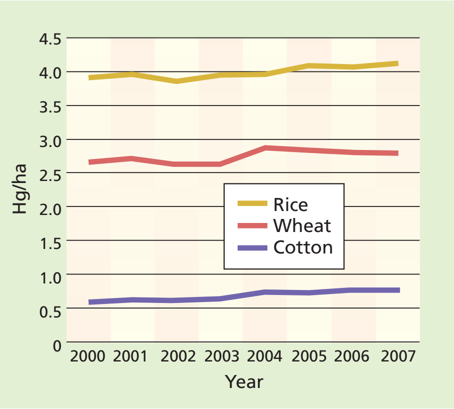


Fig. 5 Growth in yields for wheat, rice and cotton; 1 hectogram = 0.22 pounds; 1 hectare = 2.47 acres. Source: Qaim 2009.

TABLE 1. Feedstock yields and their land-use implications

Crop	Harvestable biomass	Ethanol	Acres needed for 35 billion gallons ethanol	2006 harvested U.S. cropland
	tons/acre	*gal/acre*	*millions*	*%*
Corn grain	4	500	70	25.3
Corn stover	3	300	105	38.5
Corn total	7	800	40	15.3
Prairie	2	200	210	75.1
Switchgrass	6	600	60	20.7
Miscanthus	17	1,700	18	5.8

Source: Long 2008.

Climate-change policy options

Biofuels have wide-ranging implications for the environment, food production, energy markets and economic growth, complicating the development of welfare-maximizing biofuel policies. In addition, biofuel impacts vary by feedstock, location, time and production process, further complicating the work of policymakers. Because the successful development of a robust biofuel industry requires coordinated adoption across a number of sectors and market participants (from farmers who must plant crops to fuel retailers who must develop capacity to sell new fuels and blends), government intervention may be needed at various stages of the supply chain. The aim of policy should be to temporarily promote biofuel technologies that will one day be competitive with fossil fuels and other alternatives, if externalities are corrected.

Carbon and land-conversion taxes. In economics, policies are categorized based on their efficiency. First-best policies are those that achieve socially desirable outcomes with the least cost. Economists nearly universally agree that the first-best response to anthropogenic (human-caused) climate change is the imposition of a global carbon tax

Some industrialized nations seeking to reduce their dependence on imported oil have required that a percentage of biofuel is blended with fossil fuels each year. *Above*, an oil refinery in Southest Asia.

on each unit of emissions equal to the marginal externality cost (i.e. the climate change cost) of carbon emissions. Such a tax internalizes the externality (the harm to society above and beyond the harm to the emitter) associated with carbon emissions to the one who emits the carbon; it essentially corrects a market failure that does not require people to pay for releasing carbon into the atmosphere. Such a tax, known as a Pigouvian tax, would improve social welfare by reducing carbon emissions while creating no distortions in the economy. It would also generate government revenue that could be used to reduce other taxes that do cause distortions (deadweight loss), such as income, payroll and capital gains taxes.

Equivalent to a Pigouvian tax under certain conditions, "cap-and-trade" systems have been favored by governments in the United States, Europe and elsewhere. The European Union implemented a cap-and-trade program in order to meet its Kyoto Treaty obligations. In June 2009, the U.S. House of Representatives passed a carbon cap-and-trade bill that the U.S. Senate was set to consider in fall 2009. If the quota of emissions permits is set so that the price of a permit is equal to the Pigouvian tax, and if government auctions the permits, then the efficiency and distribution implications of cap-and-trade are identical to a first-best carbon tax.

A carbon tax or equivalent cap-and-trade program would induce a greater supply of clean energy by shifting production from fossil fuels to biofuels (assuming biofuels are at least somewhat cleaner) (Hochman et al. 2008). This, in turn, would induce land conversion and a loss of biodiversity as energy-crop production expands. Without proper valuations of natural habitat, a carbon tax would lead to more environmental destruction than is socially optimal. A carbon tax could actually reduce social welfare depending on whether biodiversity is more valuable to society than carbon emissions reductions. To ensure a welfare-maximizing outcome, a policy to price carbon emissions must be paired with one to price environmental services and biodiversity, such as a land-conversion tax or system to pay landowners for the environmental services they provide.

Furthermore, these policies should be adopted globally. Otherwise, a tax system in any one country will suffer "leakage" of carbon emissions and biodiversity loss outside its jurisdiction. Because carbon emissions are a global public "bad," emissions anywhere harm people everywhere in the world. If a carbon tax makes emissions more costly in the United Kingdom, for instance, then emissions-intensive activities like industrial production will shift to countries that have not imposed such taxes or other regulations. As a result, carbon emissions would be reduced in the United Kingdom but not necessarily on a global level.

Fuel taxes. A fuel tax is the second-best way to regulate carbon emissions. Because it is costly for regulators to monitor all sources of carbon emissions, a fuel tax may be preferred — fuel purchases are relatively easy to observe. Many countries and states already impose fuel taxes, though the taxes often are not set equal to the marginal externality cost of fuel consumption. A fuel tax should vary according to the class of fuel, with dirtier fuels taxed more heavily. Life-cycle analysis should be used to classify fuels according to carbon costs. A fuel tax, however, is inferior to a carbon tax because it targets an input (fuel) when it is the output (carbon emissions) that causes damage. Because carbon emissions are not strictly determined by fuel consumption, a fuel tax is inefficient. For instance, it does not provide incentives for the adoption of cleaner burning technologies that reduce carbon emissions per unit of fuel consumed.

Subsidies and mandates

Carbon and land-conversion taxes have not materialized in the United States because of political considerations and lack of coordination with other countries. Given the political difficulties associated with imposing first-best policies, we consider a class of policies that could be used to develop a renewable fuels industry — subsidies and mandates. Assuming greenhouse-gas savings from biofuels relative to the next-best alternative fuel, these policies can serve as an indirect and third-best (after carbon and fuel taxes) method of reducing greenhouse gases.

Economists generally prefer subsidies as a more market-oriented approach, but mandates may be preferable for biofuels. The United States has pursued both policies, offering a tax credit for blending biofuels in fossil fuels (a subsidy) and requiring certain quantities of biofuel blending each year (a mandate).

Biofuel mandates can be preferable because they create a certain market for biofuels — producer profits are not tied directly to market forces in food and energy, such as fluctuating oil prices. By removing uncertainty about profits, they encourage innovation and capital investment. Mandates make demand for biofuels unresponsive to price. This means that rising food and energy prices induce agricultural intensification and productivity gains rather than the land expansion that is costly in terms of climate change and biodiversity (Babcock 2008). Because land expansion releases considerable carbon emissions, this is not a minor issue — it is critical to the carbon balance of biofuels. Finally, mandates are revenue neutral, whereas subsidies are deducted from the treasury. The cost of mandates is borne by producers and consumers, depending on the responsiveness of fuel supply and demand to prices. The cost of carbon-emissions reductions would be greater under mandates than under a carbon tax because mandates do not permit reductions in the least-cost way.

Biofuel subsidies, whether paid to producers or consumers, increase biofuel use, decrease gasoline use and have an ambiguous effect on greenhouse-gas emissions — arguably the main motivation for biofuels policy. In addition, subsidies create a less-certain market environment because the demand for biofuels is tied to their cost relative to oil. The cost of biofuel production is likewise dependent upon food market conditions because food and biofuels compete for land and harvest.

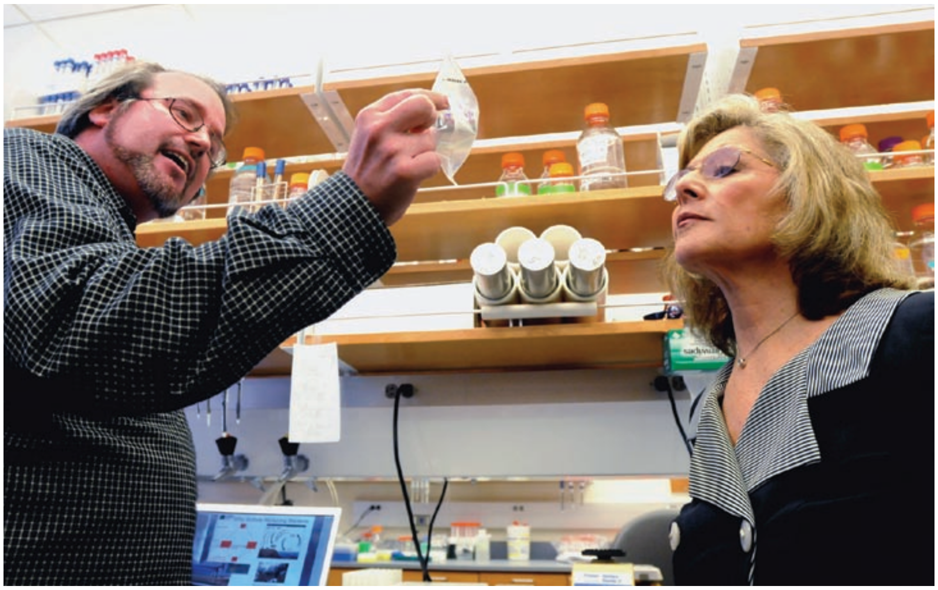
Any biofuel policy, whether based on taxes, mandates or subsidies, should take into account and vary according to the sustainability of biofuels in terms of carbon emissions, biodiversity, water and air pollution, and food availability. This means government support could be tied to net carbon benefits, yields per acre, the use of dedicated energy crops (as opposed to food crops) or crop residues and waste, and input-intensity of the feedstock conversion process. Life-cycle analysis can determine the net carbon benefits of biofuels, but it ignores other attributes of production that determine the sustainability of biofuels, such as impacts on food markets, the environment and natural resources. While more sustainable biofuels should receive larger mandates, regulators should recognize that transition technologies, such as corn ethanol, may be needed in the short run to ensure a transition to better-performing biofuels.

Investing in technology

Economic theory predicts underinvestment in biofuel and food technology for several reasons. Research and development are associated with spillovers, whereby others benefit from the innovation of an individual or firm, but do not pay a price for the benefits they enjoy. Innovating firms, therefore, do not capture all the benefits of their investment and will consequently underinvest in research and development relative to the optimal level (Naidiri 1993). Regulatory uncertainty creates further doubts as to whether private institutions will be able to capture sufficient benefits to compensate for their investments. Government intervention can essentially eliminate markets, and uncertain policy direction can slow innovation among risk-averse firms. Regulation and uncertainty have affected research and development in biofuels and agricultural biotechnology.

Private investment in agricultural biotechnology has fallen off considerably since the 1990s, in part because of a de facto ban on genetically modified organisms in the European Union that severely limited the market (Graff and Zilberman 2004). In addition, the emergence of some genetically modified organisms has been stalled because farmers can reproduce the seed, limiting the potential for firms to benefit from research and development. Finally, research is lacking to develop traits and seeds for developing countries because many of the countries cannot afford to pay for the innovations. Underinvestment in crop science creates a role for public investment in agricultural productivity, not just for the sake of bioenergy, but also human hunger. Public research universities have partnered with private companies for both biotechnology and biofuel research, leveraging public dollars with private dollars and capitalizing on the comparative advantage of university scientists in basic research. UC Berkeley, for instance, has entered into a 10-year, $500 million commitment with the oil firm BP to develop new fuel technologies.

Ensuring food security. The ability to mitigate the food impacts of biofuels will be crucial to their future, and investment in crop and biofuel science should be viewed as policies to enhance food security. Agricultural productivity gains like those seen over the past half-century could free significant farmland for energy-crop production and still feed a world growing to 9 billion people by 2050.



Peg Skorpinski

The U.S. House of Representatives passed a carbon cap-and-trade bill in June 2009, which the U.S. Senate was scheduled to consider this fall. *Above*, UC Berkeley professor Adam Arkin showed a bacterial sample to California Senator Barbara Boxer at the Energy Biosciences Institute in late 2008.

▶ **On the San Joaquin Valley's West Side, certain biomass crops could be grown in salt-damaged oils.**

Fuel technology that develops cellulosic ethanol can reduce pressure on food markets by permitting the use of agricultural waste products in biofuel production and by producing energy crops that yield more fuel per acre and can be grown on lands not suited for food crops. Food security also demands that biofuel policies be flexible and adjust to food market conditions. Subsidies and mandates could be tied to food inventories, for instance, in order to prevent food crises. This would, however, create a less certain market for biofuels and could slow innovation. Because the poor will most acutely be affected by pressure on the food system, biofuel policy should perhaps be coupled with mechanisms, such as a global food fund, to provide for vulnerable populations during periods of high food prices.

Balancing green energy needs

Biofuel policies should balance the demand for a green energy source today with efforts to improve biofuels in the future and the need to address food security concerns. Policy must address ways to improve the greenhouse-gas benefit of biofuels, reduce impacts on food markets and develop a biofuel industry. Policy is complicated by heterogeneity in biofuel costs and benefits — not all biofuels are created equal.

Current biofuels are far from perfect. But if the world turns its back on biofuels based on the impacts of transition technologies, then we must wonder what other fuels will be introduced to meet the growing demand for transportation energy (for fuel). These alternatives, like oil shale, may well be dirtier than traditional fossil fuels and existing biofuels.

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Model estimates food-versus-biofuel trade-off

by Deepak Rajagopal, Steven Sexton, Gal Hochman, David Roland-Holst *and* David Zilberman

Biofuels have been criticized for raising food prices and reducing food production. While biofuels have rightly been blamed for contributing to reduced food security at a time of record-high food prices in 2008, they have not been credited with reducing the cost of gasoline, also at a time of record-high prices. We discuss the food-versus-biofuel trade-off associated with biofuel production and model the effects of biofuel production in markets for key crops and gasoline, showing that food consumers lose from biofuels but gasoline consumers enjoy substantial benefits. We also suggest ways to address the food-versus-biofuel debate.

Simone D. McCourtie/World Bank

Some researchers and policymakers blame biofuel production mandates for the food crisis of 2008, which caused record-high prices and political unrest in some developing countries. *Above*, a food market in Kaski, Nepal.

IN 2008, the world entered a food crisis amid record-high commodity and energy prices that induced hunger and political unrest in developing countries, thefts of food from farms and food-aid caravans, and export restrictions in top grain-producing countries. The food crisis struck as biofuel production, driven largely by state mandates and subsidies, reached its pinnacle. The link between first-generation biofuels and food, which compete for land and harvest, was clear to researchers and policymakers, who blamed biofuel production mandates in developed countries for the 2008 food crisis (Traynor 2008).

The degree to which biofuels contributed to high food prices is likely overstated in the popular press, but even researchers don't agree on how much blame rests with biofuels. At the same time that food prices climbed, energy prices, particularly for oil, rose considerably, increasing the costs of transportation and further constraining household budgets. Amid the firestorm over the role of biofuels in the food crisis, their role in reducing transportation energy costs has largely been overlooked. It is, nevertheless, substantial.

We present a model that quantifies the effects of biofuel production on food and gasoline consumers in the United States and the rest of the world, and show that gasoline consumers benefit significantly from reduced prices whereas corn and soy consumers lose from higher prices.

Multimarket framework model

The introduction of biofuels affected both food and fuel markets. Biofuels utilize resources used to grow food crops and thus reduce food supplies. Hence, the introduction of biofuels increases the price of staple crops, especially corn and soybeans consumed by livestock, people and biofuel producers. At the same time, biofuels increase fuel supplies, reducing fuel prices and increasing fuel consumption.

While theory can predict the qualitative effects of biofuels on food and fuel, quantitative measures are also required to derive policy recommendations. We build on a partial-equilibrium multimarket framework to model the interactions between supply and demand in several markets. This structure estimates the impact of biofuels, particulary on prices and quantities in food and fuel markets, and on buyers and sellers in these markets.

Key parameters in these analyses are the price elasticities of supply and demand — the responsiveness of quantities supplied or demanded to a given change in prices. Both food and fuel markets are characterized by low demand elasticities. Therefore, even a small increase in the supply of food or fuel induces a large drop in the price of food or fuel, respectively. For example, if biofuels increase the availability of fuel by 1% and prices go down by 2%, then the demand elasticity is −0.5 (−0.5 = 1%/−2%).

U.S. ethanol production alone reduced gasoline prices as much as 2.4% in 2007.

We extended the model described in Rajagopal et al. (2007) to estimate the potential effects of U.S. biofuel production on welfare and simulate a global multimarket equilibrium comprising markets for corn, soybeans, ethanol and gasoline. We considered two regions: the United States and the rest of the world. We assumed that the “own” price elasticities (responsiveness of demand and supply of a crop to change in its price) and the cross-price elasticities (responsiveness of supply and demand for a crop to changes in the relative prices of other crops) did not vary across regions. The equilibrium prices and quantities were then computed assuming two scenarios: no biofuel production and biofuel production at 2007 levels.

The simulation results are reported for three distinct sets of assumptions about price elasticities for food and gasoline: (1) a “high” scenario characterized by highly elastic crop markets and an inelastic gasoline market, (2) a “low” scenario that assumes the opposite, a low elasticity for food and an elastic gasoline market and (3) a “mid” scenario that assumes moderately elastic markets for both food and gasoline (table 1). Biofuel production has the greatest benefit to consumers in the high scenario.

Research suggests that gasoline elasticities tend to be less than 0.3 in the short run. Similarly, for corn and soy, short-run elasticities tend to be less than 0.3. If so, our high scenario provides a conservative estimate of the net consumer benefits from biofuel production. Even long-run gasoline elasticities are less than 0.5.

To reduce the complexity of simulations and for ease of exposition, we assumed fixed cross-price elasticities between corn and soy across all scenarios. The cross-price supply elasticities of corn with respect to soy, and vice versa, are −0.076 and −0.13, and the demand elasticities are 0.123 and 0.027, respectively (Shideed 1987).

In our analysis, we included the impact of biodiesel on the soy market, but did not estimate its impact on the diesel market, which makes our assessment of fuel-market benefits even more conservative. Including the diesel-market equilibrium would increase gasoline (or “transportation fuel”) consumer benefits.


ARS/Keith Weller

The authors’ model estimated that biofuels were responsible for approximately 25% of the food-price inflation in 2007 and 2008. Conversely, U.S. ethanol production lowered gasoline prices by about 2.4%. *Above*, at the USDA’s Henry A. Wallace Agricultural Research Center in Beltsville, Md., the visitor center bus, powered by soy-based biodiesel, passes a soybean field ready for harvesting.

Impacts on food and gas prices

Without ethanol supplies, gasoline prices would be between 2.4% (high scenario) and 1.4% (low scenario) higher (table 1). By increasing petroleum supplies, ethanol production reduces prices for fossil fuels, benefiting consumers of transportation fuels. Biofuel production, however, raises the price of food commodities by reducing the supply of crops for food processing. In our model, biofuel production caused the price of soy to increase 10% to 20% and the price of corn to increase 15% to 28% in 2007. In contrast, much lower biofuel production in 2006 caused the price of soy to increase between only 2% and 7% and the price of corn to increase between only 5% and 13%, according to the model. Though not expressly modeled in this analysis, the effects on soy and corn consumers can be expected to carry over to other agricultural commodities, particularly coarse grain (Zilberman 2008).

Given our simulated price effects, we estimated the welfare effects of ethanol production. In figure 1, we present the

TABLE 1. Elasticity assumptions of three supply-and-demand scenarios

Own price elasticities	Scenarios High	Mid	Low
Supply			
Corn	0.5	0.4	0.3
Soy	0.5	0.4	0.3
Gas	0.3	0.4	0.5
Demand			
Corn	−0.5	−0.4	−0.3
Soy	−0.5	−0.4	−0.3
Gas	−0.3	−0.4	−0.5

Sources: Gasoline, FTC 2005; corn and soy, Shideed et al. 1987.

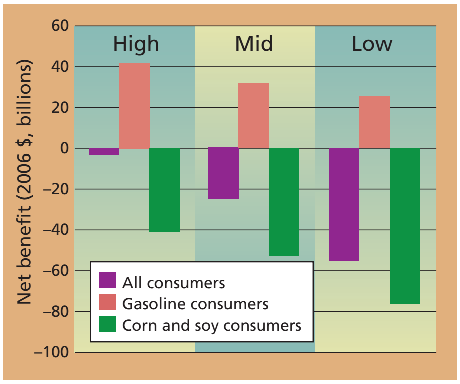

Fig. 1. Net benefits to world gasoline and food consumers from ethanol supply in 2007.

benefits to world gasoline and food consumers under each of the three scenarios considered in our analysis. In the mid scenario, we find that gasoline consumers worldwide benefited from 2007 U.S. biofuel production by about $31.3 billion because of 1.8% lower gas prices. The total cost to food consumers and U.S. taxpayers (in the form of subsidy payments), however, was $52.8 billion. The net gain to corn and soybean producers was about $27 billion. Under plausible conditions and partial-equilibrium analysis, ethanol production was associated with a net benefit worldwide of $1.7 billion. Overall, the rest of the world gained $4.7 billion, whereas the United States lost $3 billion (net of taxes).

In the United States, under the mid scenario, gasoline consumers gained approximately $7.2 billion, whereas the total cost to corn and soy consumers was $17.4 billion, and the cost to taxpayers from the U.S. Volumetric Excise Tax Credit was $2.2 billion. Higher food prices benefited U.S. corn and soy producers by $11 billion (producers in the rest of the world gained $27 billion).

Some have argued that the cost of ethanol subsidies should not be counted against biofuel production in welfare analysis because it displaces traditional farm-policy payments. Our simulations, however, revealed that corn prices would likely have remained above specified loan rates for 2007 without ethanol-induced price increases. The cost of ethanol subsidies, therefore, is not likely to have been offset by reduced subsidies to corn.

This analysis ignores the loss to oil producers worldwide from lower oil prices. Considering rhetoric from political leaders in oil-importing countries, these losses may not be of great concern from a policy standpoint. It should be emphasized that the foregoing analysis is partial. It does not consider the impacts of biofuels on other markets that are directly affected, such as sugar, or indirectly affected, such as wheat. We ignored potential market distortions apart from the ethanol production subsidy. We have not estimated the consumer benefits resulting from changes in carbon emissions and other pollutants due to ethanol or the welfare effects of tariffs on ethanol imports.

Despite these limitations, this analysis is useful to determine the orders of magnitude of biofuel price effects. It suggests that U.S. ethanol production alone reduced gasoline prices as much as 2.4% in 2007. To the extent that biofuels do reduce oil imports and prices, they can also be a mechanism for improving countries' terms of trade (i.e., net exports).

Food-versus-biofuel debate

Several reports have examined the factors responsible for the global food-price inflation in 2008 (Abbott et al. 2009; IFPRI 2008; IRRI 2008; Mitchell 2008). While there is generally consensus among researchers that forces such as economic growth, rising energy prices, adverse weather, devaluation of the U.S. dollar and biofuel policies contributed to the 2008 food crisis, the magnitude of these effects is a source of debate. Whereas U.S. Department of Agriculture chief economist Joe Glauber estimates the biofuel impact on a global food index to be 10% (USDA 2008), Mitchell (2008) puts it at around 75%. The various attempts to quantify these effects are based on different assumptions, data and study periods, which explains the variations and complicates the development of consensus among academics (FAO 2008).

In contrast to existing literature, we used a multimarket approach to characterize the impact of biofuels on two prominent food markets, corn and soy. Biofuels indirectly affect other food markets by raising demand for farm inputs, including land, labor and chemicals. But for corn and soy, biofuel production competes for harvest, diverting production from its other predominant uses in food and feed. We show that, on average, the introduction of biofuels was responsible for one-quarter of food-price inflation in 2007 and 2008.

In future research, we plan to extend this methodology and include crop inventories in addition to policies such as biofuel subsidies and mandates. Whereas biofuel subsidies and mandates increase the current demand for staple crops, low inventories reduce future demand. Both effects reduce food availability and increase food prices. We also plan to introduce noncompetitive behavior to the energy market, in contrast to the competitive behavior assumed in the existing literature.

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Can feedstock production for biofuels be sustainable in California?

by Stephen R. Kaffka

The use of crops and crop residues as feedstocks for biofuels increases domestic and global supplies, creates new industries, and may result in reduced greenhouse-gas emissions. Uncertainty about the best crop and residue sources, technologies for manufacture, future public policy, and the global supply and price of oil make it difficult to predict the best approach. California growers can produce feedstocks from grain, oilseed and woody crops and, in the Imperial Valley, from sugar cane. If the technology for making ethanol or other liquid fuels from cellulose becomes cost-effective, then saline and other wastewaters may be used in biofuel feedstock production of salt-tolerant crops, particularly perennial grasses. However, recent global increases in biofuel production have raised questions about their impacts on food and feed prices, climate change and deforestation. New state laws affecting energy use and mandating greenhouse-gas reductions require that the sustainability of all biofuels be assessed. Sustainability should take into account factors at both the global and local scales, including resource-use efficiency, cropping-system adaptability and the potential of biofuels to remediate agriculture's environmental effects.

Peggy Greb/USDA-ARS

While corn grain has been the primary feedstock for ethanol in the United States, sugarbeets have a higher per-acre ethanol yield, especially given the high root yields achieved in recent years in California.

Use of crops for biofuels has developed rapidly in the United States since the U.S. Congress passed federal energy bills emphasizing biomass in 2005 and 2007. The Energy Independence and Security Act (EISA 2007) provides targets for bioenergy use in transportation and other sectors, and subsidies to increase the domestic manufacture and supply of ethanol and biodiesel for transportation. Current federal fuel mandates call for 15 billion gallons annually of corn ethanol, 1 billion gallons of biodiesel (primarily soy) and another 20 billion gallons from advanced (noncorn grain) biofuels, chiefly cellulosic sources.

California has mandated the use of alternative transportation fuels in AB32, the Global Warming Solutions Act of 2006 (CARB 2009a), and created guidelines for qualifying fuels through the Low Carbon Fuel Standard (LCFS) (CARB 2009b). The LCFS requires that greenhouse gases (GHG) from combusting petroleum-based transportation fuels decline over time, primarily through substitution and blending with less carbon-intensive alternative fuels, including those from biomass.

These and other policies have resulted in substantial investment in corn-grain-based ethanol manufacturing in the United States, although current economic conditions have slowed or idled new facilities. At the same time, oil price volatility makes investment in alternative biofuels uncertain. While price volatility will continue, the demand for corn grain for ethanol likely will remain high as long as federal policies continue to encourage ethanol use and the price of oil is high (Tokgoz et al. 2007).

As petroleum reaches its practical limits, the importance of biomass as a transportation-fuel feedstock will increase. California scientists from UC and other institutions are now working to develop clear metrics and goals for sustainable biofuel production. This discussion has been spurred by the LCFS and subsequent California Air Resources Board resolution 09-31 (CARB 2009c), which call for — among other things — a science-based definition of sustainability, and provisions to incentivize sustainable fuels. The deadline for these provisions is December 2011.

Evaluating agricultural efficiency

The definition of "sustainability" in agriculture has been, and continues to be, the cause of much controversy and debate. Montieth (1990) formulated one of the simplest, most relevant ways to evaluate agricultural sustainability. His sustainability ideal is a farming system that creates ever-greater outputs for ever-fewer inputs on a per-unit product basis. An unsustainable situation occurs when inputs increase or are static as output declines. Increasing resource-use efficiency, and sustainability, is correlated with a decline in cost per-unit product. Resource-use efficiency is important because it takes energy to produce energy crops. The larger the difference between the energy used for feedstocks and that returned from the feedstock, the greater the net energy yield. High-energy yield per acre of cropland is a critical factor affecting sustainability (Liska and Perrin 2009). Many of the adverse greenhouse-gas effects of current biofuel production are attributed to the crop production component (Zah et al. 2008). Acquiring crops and residues from fewer acres at high efficiency allows other agricultural lands to be used for conservation, as well as natural systems such as forests, which may also accumulate significant amounts of carbon (Robertson et al. 2000).

Research to support increasing agricultural efficiency, including new technologies such as precision agriculture (Kaffka et al. 2006) and reduced tillage (Mitchell 2009), remains essential (Alston and Zilberman 2003). The challenge is to achieve both efficient and low-polluting cropping systems, because intensive practices involving irrigation, fertilizer and pesticide use may be more damaging locally, even if large-scale resource-use efficiency is enhanced (de Wit 1992). Reconciling these concerns remains an open issue in developing performance standards for sustainable production, and is an essential objective for adaptive agricultural research.

California is the most productive agricultural state in terms of income, due to farmers' ability to produce diverse, high-value crops. In addition, the state has a nearly year-round, frost-free growing season, high levels of solar radiation, good soils, irrigation capacity (largely avoiding crop water stress), pest and disease management, and high yields. In the absence of water and nutrient stress, crop yields are limited primarily by solar radiation and tend to be more consistent than in rainfall-dependent areas. Because yields are high, efficiency also can be greater.

Data from California demonstrates this process. From 1950 to 1990, the productivity of field crops was estimated to increase by a factor of 2.4 while inputs increased by only about 0.6. This increase was due more to technological change than to an increase in inputs, although both occurred. However, the rate of increase in crop productivity was less during the 1990-to-2002 period for most crops than it was elsewhere in the United States (Alston and Zilberman 2003).

Defining sustainability

Sustainability has many definitions, which usually include more than just efficiency considerations. Efforts are under way to develop practical standards to satisfy diverse aspects of sustainability. For about a decade after the oil shock of 1973, there was widespread discussion about energy-use efficiency in agriculture (Stanhill 1985). Since then, discussions have focused on soil quality, pesticide use, the relative benefits or disadvantages of organic farming, and social aspects of farming (Francis et al. 2007), as well as direct and indirect effects on global land use, greenhouse-gas emissions and other sustainability attributes.

The Biomass Roadmap prepared by the California Biomass Collaborative, to provide guidance on the sustainable development of biomass energy in California, calls for enforceable, performance-based standards that are locally relevant and internationally consistent (http://biomass.ucdavis.edu). New state laws like California's AB32 and AB118 (CEC 2009) support the development of alternative transportation fuels and include requirements to address and ensure sustainability.

Many groups around the world are writing sustainability standards for biofuel production (van Dam et al. 2008). Some are goal-proscribing and focus on motivating change, based on ideas about what would be best for agriculture (Francis et al. 2007). Other definitions are descriptive and focus on either the ability of agriculture to fulfill a set of goals or standards, or more simply on an agricultural system's ability to continue through time.

The Roundtable on Sustainable Biofuels (RSB 2009), a nonprofit based in Lausanne, Switz., recently published an updated draft of sustainability principles and criteria, derived from a broadly consultative process. The draft is an attempt to protect environmental conditions and human welfare as biofuels are brought into global trade and use, and to create international consensus. However, optimum or best management practices are locally developed and interact with highly diverse social circumstances, making the formulation of an international standard a formidable challenge. Also, since all agricultural systems lead to some level of ecosystem change, principles that minimize landscape alteration — or resource depletion — may inevitably stifle biofuel development.

Standards for energy crops must be based on a clear definition of sustainable agriculture. Hansen (1996) provided a still-useful categorization of differing definitions, arguing for (1) a literal definition of sustainability — the ability to continue over time, (2) the quantitative assessment of properties associated with sustain-


Some biofuel crops may help remediate environmental problems. UC researchers and a grower evaluate bermudagrass pastures in Kings County that were produced on saline soils and irrigated primarily with recycled, saline drainage water.

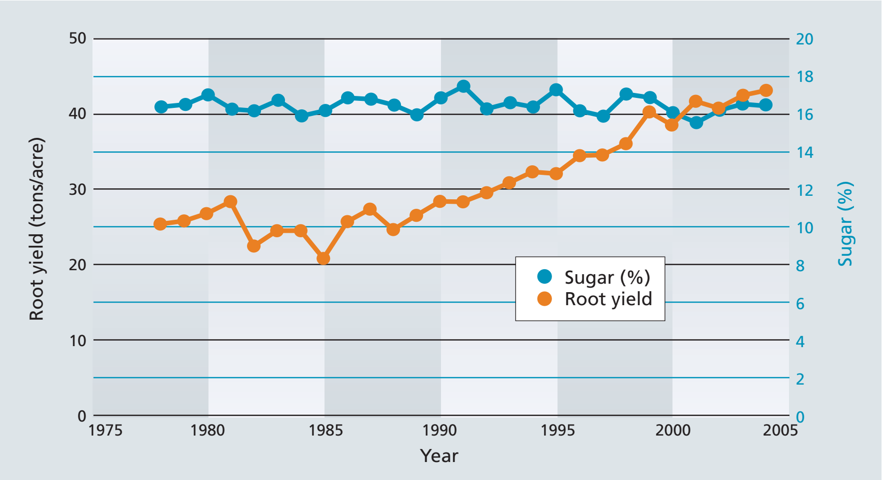

Fig. 1. Sugarbeet yield increases from 1978 to 2004. Data courtesy of California Beet Growers Association, Stockton, Calif.

ability, measured as continuous variables within well-defined systems and (3) an accounting for the variation that inevitably occurs with time.

Sustainability standards should include requirements for the measurement and prediction of relevant biophysical processes, such as changes in soil organic matter, crop yield and environmental effects. Agricultural research institutions are generally responsible for these measurements, not individual farmers or vendors. The best way to develop these measurements is dedicated, long-term research closely integrated with simulation modeling, but neither alone is sufficient (Tubiello et al. 2007). Specific measurements cannot define sustainability, but rather are objective considerations essential for its definition. Since the measurement of long-term trends and environmental effects is difficult and expensive, sufficient public support for high-quality agricultural research focused on these public objectives is necessary for regulatory programs to be effective.

Social and environmental concerns reflect the multiple roles played by agriculture in human society, but they are also difficult to define and measure (Francis et al. 2007). No one best policy can result from such considerations; diverse views about the character of the productive landscape, the appropriate place for wildlife, measurable and perceived consequences from pesticide use, and the distribution of benefits and costs must be considered. A dynamic, ongoing and broadly inclusive consultative process to guide public policy may be the only legitimate way to combine such considerations together with more quantitatively measurable phenomena.

Innovation occurs continuously in agriculture. Consequently, best management practices constantly evolve in response to new research discoveries, technological advances and changing economic circumstances. To be useful, sustainability standards must account for and encourage innovation. The optimum mix of farming practices varies locally and is guided by applied research and farmer adaptation; one good example is the UC integrated pest management guidelines (UC IPM 2009), which are updated continuously. Rigid concepts of sustainability will stifle innovation, and lead to less-than-optimal management locally. In a fundamental and seemingly contradictory sense, sustainability involves flexibility and adaptation, that is, the ability to change. Achieving this is a significant challenge for the regulatory community.

Best biomass crops and uses

Which agricultural feedstocks will be best in the future remains uncertain, and a number are being investigated. Many analyses indicate that rather than grains or seeds, crop residues and purpose-grown crops that produce large amounts of biomass per acre will be more efficient and have the greatest environmental benefits (Schmer et al. 2008; Adler et al. 2007). Some estimates for the conversion of cellulosic feedstocks approach the efficiency of newly developed petroleum supplies (table 1). But compared to calculations for grain, sugar and oilseed crops, biofuel yields from cellulosic sources are still theoretical and have not yet been realized commercially (Liska and Perrin 2009). It is difficult to break down tough, resistant, plant cell walls into sugars that can then be fermented into ethanol, other alcohols or carboxylic acids (US DOE 2006), and much related research and development is under way (see pages 178 and 185).

TABLE 1. Estimated average and range for energy return on investment (EROI)* of various biofuel feedstocks

	Corn ethanol	Sugar cane ethanol	Switchgrass and other cellulosic sources	Biodiesel	Petroleum†
Average	1.3:1	9:1	6:1	3:1	15:1
Range	0.84–2.96	6.0–11.0	0.69–15.0		

Sources: Hammerschlag 2006; Cassman et al. 2007; Schmer et al. 2008.

* EROI = Energy out/energy in (nonrenewable). The larger the EROI, the more renewable energy is delivered per unit of fossil fuel used in its production.

† Value for new petroleum recovery in the United States, from Cleveland (2005), is provided for comparison.

Biomass may also be an efficient petroleum substitute for uses other than transportation fuel. For example, Hermann et al. (2007) and Ragauskas et al. (2006) reported that bio-based bulk organic chemicals offer clear environmental and energetic advantages compared to petroleum as a feedstock. This comes in part from avoiding expensive oxygenation and catalytic steps to convert petroleum into alcohols, carboxylic acids and esters. About 5% of the petroleum entering a modern refinery goes toward the manufacture of such precursor chemicals (Ragauskas et al. 2006), and replacing this use of petroleum may be a more valuable use for biomass than producing transportation fuels. For both these markets, sourcing sufficient, reliable and sustainable supplies of feedstock is an essential but unmet challenge.

Sustainable feedstocks

Crops produced with increasing resource-use efficiency will be better candidates for biofuel feedstocks. For example, sugarbeets have been grown in California since 1870, and in recent years yields have risen substantially (fig. 1). With increased fertilizer efficiency, the Imperial Valley has had the highest sugarbeet yields globally for the last several years. In July 2007, Desert Sky Farms produced about 11 tons (22,000 pounds) of sugar per acre for a July-harvested field, substantial yield progress over the last decade. Researchers and farmers have learned that lower amounts of fertilizer nitrogen per unit yield can be used (fig. 2). Similar efficiency gains are needed if traditional crops are to be used for biofuels. In recent life-cycle comparisons of biofuel crops (Sharpouri et al. 2006; Zah et al. 2008), sugarbeets were among the most efficient ethanol feedstocks, even at much lower yields than in California.

Worldwide, the most important crops used for biofuel feedstocks are sugar cane (in Brazil and other tropical locations) and corn for ethanol, and oil palm, soybean and canola or rapeseed for biodiesel. Europeans also use wheat and sugarbeets for ethanol production. Soybeans are the principal crop feedstock used for biodiesel, followed by canola. Soybeans have never been produced on a commercial scale in California because older varieties were not well adapted to the state's climate, and because the value of the oil produced has been too low compared to other alternative crops. Canola grows well in California but is not widely produced here. It is reported to be a selenium accumulator and may help remediate selenium accumulation problems in San Joaquin Valley soils (Stapleton and Banuelos 2009). Like wheat, canola grows in the winter and can take advantage of winter rainfall, minimizing the need for irrigation.

The oilseed crop grown most widely in California for the last 60 years is safflower, which is well adapted to California's semiarid climate (Kaffka and Kearney 1998). Its fatty-acid composition makes it one of the most suitable oilseed feedstocks for biodiesel production using the fatty-acid methyl ester or FAME process, resulting in a high-quality biodiesel fuel. It is also relatively easy to grow and if irrigated properly does not have many pest or disease problems.

Finally, several groups are attempting to develop ethanol production from sugar cane in the Imperial Valley. Initial evaluations suggest that productivity will be high and water use will be approximately in line with that of alfalfa (Bazdarich and Sebasta 2001). Additional quantification is needed to substantiate these claims. If obstacles to its development can be overcome, sugar cane can provide ethanol for fuels, electricity from the combustion of residual biomass (bagasse) and other possible secondary products.

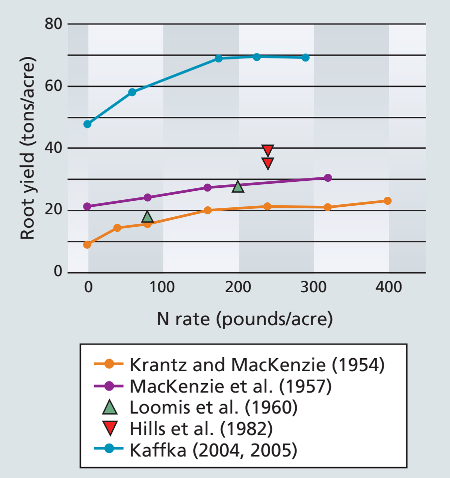

Fig. 2. Sugarbeet root yields and nitrogen fertilizer levels in a series of trials, 1954 to 2005, UC Desert Research and Extension Center, Holtville, Calif., and the author's research.

Biofuels in agronomic systems

There are concerns that biomass crops should be restricted because of an inherent conflict between their use for food or for fuels, especially affecting the poor (see page 191). A more useful way to think about the production of crops for energy, however, involves considering individual crops in cropping systems.

Biofuel feedstock crops can serve useful roles in California in rotation with other more valuable crops. For example, safflower may be the deepest-rooting annual crop, allowing farmers to use water stored in well-drained soil from winter rainfall or the previous season's irrigation, and to recover nitrogen fertilizer from soils at greater depths than other crops (Bassil et al. 2002). Safflower is also moderately salt-tolerant, so it can be grown on soils with some salt limitations or partially irrigated with saline water (Bassil and Kaffka 2002a, 2002b).

In rotation with higher value crops that are not as deep-rooted such as tomatoes or cotton, safflower can remediate some environmental effects of intensive agriculture. Because nitrogen fertilizer is usually the most energy-intensive input in crop production, this in turn improves the potential energetic efficiency of biodiesel made from safflower. Efficiencies of this sort are not recognized in large-scale surveys of costs and benefits (Zah et al. 2008).

More generally, diversifying cropping systems provides a number of agronomic and economic benefits. Since there is constant pressure for farms to specialize (de Wit 1992), biofuel crops may provide economic incentives to capture the positive agronomic benefits from more diverse cropping systems.

Landscape-scale management

Another way to think about efficiency is to consider potential biofuel crops at the regional landscape scale, where they may help manage environmental problems. Salts and salt disposal are a problem in all irrigated agricultural regions of the world with semiarid climates. In California, salinity is a particular problem in the western San Joaquin Valley, where naturally occurring salts and trace elements like selenium are mobilized and concentrated by irrigation practices (Stapleton and Banuelos 2009). Some fields in the region have been retired due to salt accumulation and a lack of sufficient water or drainage to sustain crop production. In addition, even irrigation at better locations produces salts that find their way into underlying aquifers (Schoups et al. 2005). Some crops can grow on salt-affected land or can use lower-quality water sources without yield losses, and could help intercept this saline drainage water.

Several perennial forage grasses in particular are salt-tolerant and easy to manage (Corwin et al. 2008). Various species have been suggested as good sources for cellulosic material for biofuel. Among the grasses, switchgrass is most commonly mentioned in the United States (Schmer et al. 2008). A perennial indigenous to large regions in the Plains states, switchgrass does not require annual tillage and planting, and is grown on conservation reserve lands that have uneconomic yields of annual crops or are too erosive. But variable climate in that part of the United States makes switchgrass supplies uncertain

Cattle graze on a bermudagrass pasture grown on saline soils in Kings County; the fast-growing grass could also be harvested as a biomass feedstock if suitable markets were available nearby.

in dry years, potentially limiting production levels in biorefineries using it as a feedstock. In contrast, the production of a salt-tolerant perennial grass in California using moderately saline water for irrigation could provide reliable, predictable supplies of biomass to a factory sited near the point of production. If yields are high, the distance biomass must be moved would be reduced because the area needed to produce it would be smaller and biorefineries could be centrally located.

Likewise, the author and others (Corwin et al. 2008) have grown bermudagrass on a severely salt-affected site in Kings County since 1999, using a mixture of saline drainage water, wastewater from the town of Lemoore, and King's River irrigation water, while maintaining soil quality. This forage was grazed but could also be harvested as a biofuel feedstock, given suitable markets.

The use of saline land and water may seem like an exception to the idea that the most efficient response to inputs occurs on better quality land, and the most efficient use of agricultural inputs occurs at higher yield levels (de Wit 1992). But if a crop is unaffected or marginally affected by salinity because it is tolerant, or if it is produced when salt stress is reduced (winter production), then the crop's response to inputs could still be efficient (Bassil and Kaffka 2002a, 2002b). In these and other ways, biofuel cropping systems in California could help manage waste resources and related environmental problems, and improve overall system sustainability. Further, the cost of feedstock production is subsidized by reductions in the cost of managing related environmental problems.

Reducing greenhouse gases

Even if crop production is efficient, biofuels also should reduce the global warming potential of transportation fuel. Because fuel made from plant materials recycles atmospheric carbon dioxide captured by plants, biofuels can potentially reduce greenhouse gases (Farrell et al. 2006). However, more complete analysis may uncover effects that reduce or eliminate that benefit. The federal Renewable Fuel Standard specifies minimum levels of life-cycle greenhouse-gas emissions reductions for diverse types of biofuels (US EPA 2009). California's Low Carbon Fuel Standard also mandates reductions in such emissions through changes in the carbon intensity of fuels.

Life-cycle analysis calculates all the energy costs and benefits of a biofuel production process, from field to final use (Wang et al. 2007). Even the most careful life-cycle analysis, however, involves assumptions and decisions about qualitative criteria used in making quantitative assessments (Zah et al. 2008). Life-cycle analysis cannot anticipate future conditions and technical breakthroughs, so it is best used for comparison rather than setting absolute standards. Transparency and ease of use of life-cycle analysis models is needed to legitimize them as a basis for important public policy decisions (Liska and Perrin 2009).

A complete accounting of all greenhouse gases is required for life-cycle analysis. While crops absorb greenhouse gases, producing crops also generates them. Nitrogen fertilization results in increased nitrous oxide (N_2O) emissions from soils. Because nitrous oxide has a global warming potential that is 297 times that of carbon dioxide, heavy use of nitrogen fertilizer with energy crops may in some cases negate the effects of atmospheric carbon uptake in the biomass. Nitrous oxide is one of the most important greenhouse-gas emissions from agriculture (Snyder et al. 2007), and there is significant uncertainty about its measurement (Adler et al. 2007; Snyder et al. 2007). High-quality agricultural research is also needed to ensure accurate analysis of the greenhouse-gas costs of biofuels.

Implications for California biofuels

The sustainable use of crops for biofuels will depend on ever-increasing efficiency in crop production and improving the returns for all energy-containing inputs in farming systems. Without this, there is no reasonable basis to use crops for biofuels. Similarly, adequate supplies of irrigation water are necessary for any crop production in California, including biofuel crops. Sustainability standards must include the measurement and robust prediction of trends in important biophysical characteristics of farming systems. Standards must account for and encourage — not inhibit — innovation, while seeking the least environmental perturbation. A means of valuing incommensurable social values must be included in the standard-setting process. Lastly, any useful sustainability standard for biofuel production from crops must include adequate investment in public agricultural research, and a continuous commitment to broadly inclusive consultative processes in setting and maintaining standards.

Biofuel cropping systems in California could help manage waste resources and related environmental problems, and improve overall system sustainability.

California's agricultural economy provides opportunities for biomass production, ranging from the large-scale industrial production of energy crops such as sugar cane in the Imperial Valley and the use of salt-affected lands and saline water in the western San Joaquin Valley, to the smaller scale, integrated production of biomass to help meet individual on-farm energy demands. The amount and extent of potential biofuel production in California are difficult to predict because of uncertainty associated with changing technology and public policy. Foreseeable increases in the price of oil, regulatory requirements, increased efficiency in crop production and supportive standards will make possible the production of crops for biofuels in California. The best and most sustainable choices will be based on the interaction of these factors and locally varying production conditions.

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Survey explores teen driving behavior in Central Valley, Los Angeles high schools

by Ramona M. Carlos, John A. Borba,
Katherine E. Heck, Keith C. Nathaniel
and Carla M. Sousa

Teenage drivers, particularly new drivers, have higher crash rates than adults. We surveyed 2,144 teenage drivers in California about their driving practices, factors influencing driving behavior, and views on driver education and resources. Teens wanted updated driver education courses and more behind-the-wheel training while learning to drive. They identified parents as their most important resource when learning to drive and also reported that parents were less likely to enforce the rule prohibiting driving with teen passengers than other driving rules. Teens described behavior by teen passengers that distracted them while driving. The findings indicate that new drivers benefit greatly from graduated driver licensing laws.

Teenagers are now required to practice driving for 50 hours with a licensed adult over age 25. Such legal restrictions help keep young drivers safe while they gain skills. In Fresno, Micheline Golden and daughter Chelsea Beeson review her driving records with 4-H advisor Dave Snell.

The rate of automobile accidents involving teenage drivers nationwide is of great concern to public safety officials, families and educators. Teenagers have a higher rate of car crashes, including injuries and deaths, than do adults. Crash rates among 16-year-olds are more than double that of 18- and 19-year-old drivers and 10 times the rate of those ages 30 to 59 (Baker et al. 2006). In 2006, California drivers ages 15 to 19 were involved in 526 fatal collisions and 33,174 collisions that resulted in injury. The motor vehicle death rate in California for all drivers is 12.7 per 100,000, compared to an average of 15 per 100,000 for the United States (SWITRS 2006). Northern counties and those in the middle to lower Central Valley have the highest crash rates in California (CDC 2006).

Driving laws for teenagers

Factors contributing to higher crash rates for teenagers, particularly 16-year-olds, include inadequate skills and lack of experience, risk-taking behaviors, distractions and poor judgment (AAP 2006; Williams 2003; Arnett 2002). Increased concern about teen driving behaviors has led many states to implement graduated driver licensing laws, which have shown encouraging results in lowering the number of teen injuries and deaths due to car accidents (McKnight and Peck 2002).

California's first modified licensing program for new drivers under age 18 was implemented in 1983. In July 1998, California became the first state to implement a graduated driver licensing law that included passenger restrictions for teen drivers. Other enhancements to the 1983 program included a 1-year driving curfew between 12 a.m. and 5 a.m. (expanded to 11 p.m. in 2007); an increase in the mandatory provisional period from 1 to 6 months (since expanded to 1 year); and a requirement for parent certification of 50 hours of supervised practice, including 10 hours at night.

Masten and Hagge (2003) evaluated California's enhanced 1998 program by examining monthly crash rates from January 1994, well before implementation of the graduated licensing law, through December 2001. Parameters for the time-series analysis included whether the impact on teen crash rates was a gradual one that became permanent, a sudden one that was temporary, or a sudden change that became permanent. Their results indicated no overall reduction in total crashes or fatal/injury crashes immediately following program implementation or beginning 6 months later, but the program was associated with a 19.45% gradual-permanent increase in total crashes for 18- and 19-year-olds 6 months after the program was implemented. This increase suggests that the program's positive effects may not continue into later years or may be due to a higher percentage of teens waiting until age 18 to be licensed as a way to avoid the program.

Furthermore, the nighttime restriction was associated with a sudden-permanent small reduction in total crashes (0.44%) and fatal/injury crashes (0.45%) for 15-to-17-year-olds, starting 1 year after program implementation. The 6-month passenger restriction was associated with approximately 73 fewer crashes per month (or 878 fewer per year) for 15-to-17-year-olds, representing a 2.52% decrease in total crashes (whether or not they involved passengers) (Masten and Hagge 2003).

Influences on teen driving behavior

Our goal was to explore the factors influencing teen driving behavior by asking teens about their perceptions of driver education and training, and about their driving practices. In particular, we focused on youth in rural Central Valley areas, who tend to have higher crash rates (CDC 2006). A second goal was to identify determinants of high-risk driving among California high-school students and learn about influences on teen driving behaviors. This research project was co-led by UC Cooperative Extension 4-H youth development advisors and the 4-H Center for Youth Development at UC Davis.

Survey. We surveyed high-school seniors because they are most likely to have accrued some driving experience. To develop the questionnaire, focus groups were conducted with 48 high-school students and their parents. From the resulting information and a literature review, we developed a four-page survey with both multiple choice and open-ended questions. The survey focused on various issues relevant to driving including training and education, most-helpful learning resources, parental expectations and reasons for driving. Students were asked about driving with friends, as either drivers or passengers; if they participated in risky behaviors while driving; and, if their friends exhibited risky behavior while in the car with them or as drivers, whether they spoke up. Students were also asked about their involvement in automobile accidents and the circumstances. (The full survey is available from the authors.)

The survey, in either English or Spanish (most students chose to take it in English), was approved by the UC Davis Human Subjects Internal Review Board. Prior to survey administration, parents received letters (in English, Spanish, Russian and Hmong, depending on the school population) allowing them to opt their children out of participating. Letters were sent to more than 3,000 parents, and 12 requested that their children not participate.

Chi-square analysis was used for calculations. Additionally, since students were sampled within their schools, SUDAAN (Research Triangle Institute 2001) was used for analysis to adjust for the nested-cluster sample design. Results for all comparisons are statistically significant when $P < 0.05$.

Schools. During the 2005–2006 and 2006–2007 school years, we surveyed high schools in seven California counties, most in the Central Valley (Fresno, Kern, Madera, Sacramento, Tulare and Yolo) as well as urban Los Angeles County. Twelve comprehensive public high schools and one parochial high school participated. The student populations ranged from a few hundred per school to more than 2,000, and were ethnically diverse. Of the students who completed the survey, 19% attended rural schools in towns or areas with fewer than 10,000 people, 49% were in suburbs or towns with populations between 10,000 and 75,000 and 32% were in urban areas with populations of 75,000 or more.

TABLE 1. Survey sample (n = 2,144) compared with all California high school seniors (n = 423,289)

Characteristic	Survey sample	California seniors
	%	
Race/ethnicity*		
Hispanic/Latino	34.2	39.0
White	42.0	37.0
Asian	8.6	9.9
Pacific Islander†	3.1	3.7
African American	5.8	8.0
Native American	2.7	0.9
Male	46.1	50.4
Female	53.9	49.6

Sources: California Department of Education (CDE) enrollment for seniors in 2005-06 school year; survey taken during 2005-06 and 2006-07 school years.

* About 9% of study sample did not report race/ethnicity, and 4.6% reported more than one race group.

† CDE separates Pacific Islander and Filipino, which are combined here as Pacific Islander.

Schools were classified by income level based on California Department of Education data on the proportion of students who received free or reduced-price meals; students in three schools were higher-income (fewer than 20%), six schools were moderate income (between 20% and 49%) and four schools were lower-income (50% or more).

Student sample

Demographics. The survey was administered on a single school day in each school, in an English class that all seniors were required to take. A total of 2,144 enrolled seniors (68%) completed the survey. The respondents were 46% male and 54% female. The majority (76%) were 17 years old, 17% were 18, and 5% were 16. Students in the sample were 41.9% white/non-Hispanic; 34.2% Latino/Hispanic, 11.7% Asian/Pacific Islander, 5.8% African American and 2.7% Native American (table 1).

Relatively few youth reported that their parents did not allow them to drive with teenage friends in the car, even though this is a risk factor for crashes.

Licensure and driving habits. Of the respondents, 54% had licenses, 11% had permits and 34% had neither. Among those without licenses or permits, 22% did not drive and 12% drove anyway. These numbers are similar to data in the 2007 Motor Vehicle Occupant Safety Survey, a national telephone survey of more than 6,000 people aged 16 and older, in which 45% of 16-and-17-year-olds reported driving nearly every day, 18% drove a few days a week and 31% were nondrivers (Block and Walker 2008). In our study, while students reported a wide range of hours driving, the average was 5 hours per week. Of those who drove, 820 (39.7%) had driven for 12 months or more, 404 (19.6%) had driven between 6 and 11 months, and 316 (15.3%) had driven for less than 6 months.

Nondrivers. Students who did not have a license or permit were asked to identify reasons why they did not drive. About 14% said no car was available, and 13.5% said that the cost of driving or becoming licensed was too high. About 10% said they were not allowed by either parents or the state to receive a license; some of these students (0.9%) indicated they were undocumented and not eligible. Students had the option of listing other reasons; these included not wanting to drive (10.7%), waiting until they turn 18 when they would no longer be subject to graduated driver licensing laws (8.6%), and feeling that driving is too much trouble (5.4%) or that the driving laws for teenagers are too restrictive (4.6%).

Unlicensed drivers. Approximately 12% of respondents ($n = 265$) reported not having a license or a permit but responded positively to questions regarding driving, indicating that they drove regularly. The unlicensed drivers were primarily male (56%) and Latino (67%) (fig. 1). The association between race/ethnicity and driving with or without a license was significant ($P < 0.008$). Latino and African-American youth were more likely to drive without either a license or permit than white, Asian or Native-American youth.

Most unlicensed drivers attended a school with a lower-income population, and most lived in urban areas. Economic factors were cited by 12% of unlicensed drivers and 14% of nondrivers for why they did not have a license. The costs of licensure and insurance for a teen driver are prohibitive for some families. Unlicensed drivers reported several reasons, including having no car to use regularly, not being allowed by parents or the state (or being an undocumented immigrant), waiting until they turn 18, and logistical reasons such as no time to obtain one.

Unlicensed drivers drove approximately the same number of hours per week as licensed drivers, but the two groups differed significantly in several respects. Unlicensed drivers had been driving for less time, and as their main reasons for driving they were less likely to report getting to school ($P < 0.0001$); going to clubs, sports practices and other activities; and going out with friends. They were also slightly more likely to report running errands and helping with family responsibilities as reasons for driving.

Considering their licensure status, it is not surprising that unlicensed drivers were statistically more likely than licensed drivers to report always following the rules of the road ($P < 0.0001$). They were less likely to drive after 11 p.m. and with friends in the car ($P < 0.0001$), and were more likely to report having been a passenger in a car with a driver who drank alcohol ($P < 0.0001$). Licensed and unlicensed drivers were equally likely to report driving after alcohol and drug use.

Reasons for driving. Students stated that their primary reason for driving was to get to school (72%). This was true for all students, regardless of school location, gender, ethnicity and whether or not they were licensed. About 39% reported getting to work as a main reason for driving, and 37% said they ran errands or helped with family responsibilities.

The reasons for driving varied significantly across race/ethnic groups ($P <$

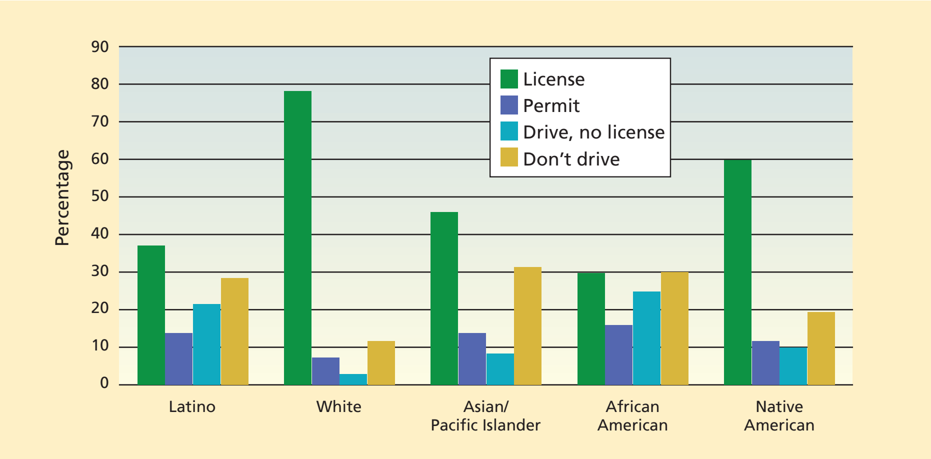

Fig. 1. Licensed and unlicensed drivers, by race and ethnicity.

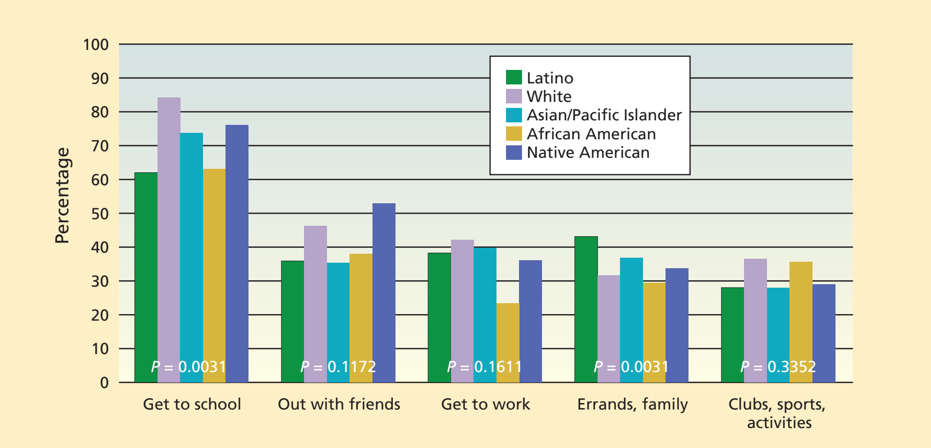

Fig. 2. The main reasons teens drive, by race and ethnicity. *P* values measure the significance of differences across ethnic groups, where *P* is significant at < 0.05.

0.003), with Latino students more likely than others to report running errands or helping with family responsibilities (fig. 2). For all drivers, going out with friends (40%), or getting to work, helping with family errands or responsibilities, and going to clubs, sports practices or other activities (32%) were the other principal reasons for driving.

Cars. Just under half of the students who drove had their own cars, while 40% shared with parents and about 20% shared with siblings or other family members. These numbers are similar to Williams et al. (2006), in which 41% of teenage drivers indicated that they owned a vehicle. In that study, parents were generally agreeable to letting teens have their own cars from the start, after being licensed.

Influences on teen driving

Parents. Our results indicated that parents are a strong influence on young people's driving. When asked about the most helpful resource they had available when learning to drive, almost half (47%) of the students cited their parents, significantly greater than driver training (25%), driver education classes (11%), other relatives (5%) and friends (4%). Youth who indicated their parents as the most helpful resource when learning to drive were significantly less likely to drive after drinking.

The majority of youth indicated that their parents set rules and/or responsibilities concerning driving and these appear to have an influence on their driving behavior. About half said their parents required them to pay for their own gas, and 48% had to maintain the car. About 44% reported having to keep their grades up (often a condition of youth receiving less-expensive auto insurance), and a similar number had a curfew. A substantial fraction (39%) reported having to run errands as a condition of their driving, while smaller numbers reported having to pay for their own insurance (20%), buy their own car (16%) or drive others around (17%).

Boys were significantly more likely than girls ($P < 0.0001$) to report having to cover expenses and take responsibility for the car (buy the car, pay for gas or insurance or maintain the car) as a condition of driving, while girls were statistically more likely than boys ($P < 0.0017$) to report having a curfew. We also found an interaction between gender and parental rules with respect to driving after alcohol use.

In general, youth who indicated they had to pay for either gas or insurance or maintain the car were more likely to drive after drinking ($P < 0.02$). However, this result is due to the fact that parental rules on maintaining and paying costs were not associated with drinking and driving among boys, whereas there was an association for girls. Girls who were required to pay for gas were more likely to report driving after drinking than those without such a rule. Youth who had any of these responsibilities were also more likely to report driving with friends in the car. However, youth who were expected to keep grades up and/or had a curfew were less likely to report driving after drinking or drug use.

Relatively few youth (less than 15%) reported that their parents did not allow them to drive with teenage friends in the car, even though this is a risk factor for crashes. Teens who reported they were not allowed to drive with friends in the car were statistically less likely ($P < 0.0001$) to have driven after drinking alcohol and less likely ($P < 0.010$) to report having been in a crash.

Driver education and training. The graduated driver licensing system in California is similar to that of many other states and countries. Teens are required to go through a supervised learner's period (with a learner's permit) for at least 6 months before receiving an intermediate license. There is a minimum 50-hour requirement of supervised driving with a parent or other adult over age 25 during this period (including 10 hours at night), as well as a nighttime restriction.

During this learner's period, drivers under age 18 must enroll in and complete a driver education and driver-training course, including 6 hours of behind-the-wheel practice with an instructor. Often these training courses take place in three 2-hour sessions. The driver education course can be taken online, with students reading and taking quizzes independently; or as an instructor-led course, either through a private company or, in some cases, at school. The California Education Code requires school districts to offer driver

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In a survey of more than 2,100 teenagers in the Central Valley and Los Angeles, nearly 50% said that the quality of teaching and driver education should be improved, and about 20% wanted more practical, hands-on training.

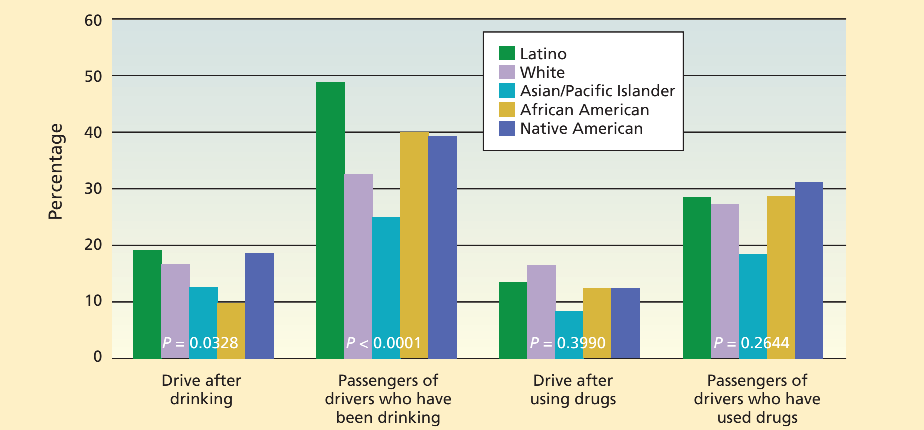

Fig. 3. Percentages of teens, by ethnicity, who reported driving after drinking or using drugs; and teens who report being passengers of teen drivers who have been drinking or using drugs.

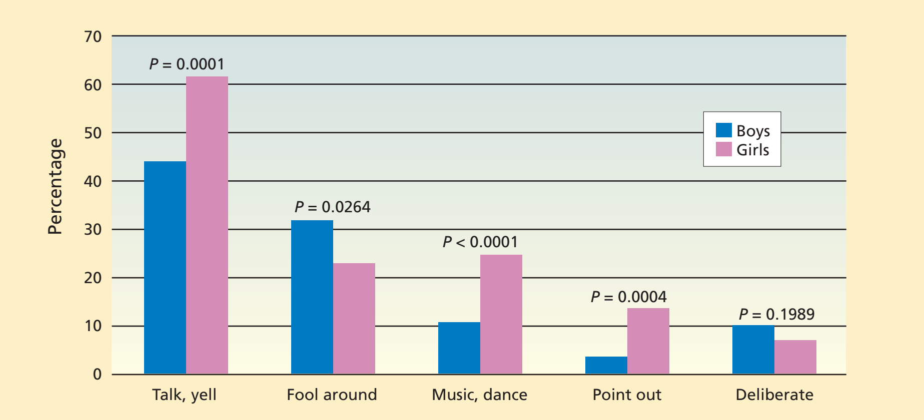

Fig. 4. Teens who reported being distracted while driving, and the causes. Talk, yell = passenger talking or yelling. Fool around = passenger fooling around, messing around. Music, dance = passenger dancing in car, changing radio station or CD. Point out = passenger pointed something out to driver. Deliberate = passenger caused an intentional distraction, such as hitting or tickling driver or attempting to use the vehicle's controls. *P* values measure the significance of difference between genders, where *P* is significant at < 0.05.

education classes for free, but this is not enforced. Less than one-third of schools in California offer driver education classes, and even fewer provide behind-the-wheel training (Quan 2007).

In an open-ended question about how driver education or training could be improved, 48% indicated that they felt teaching quality should be improved. Nearly 20% said driver education should be more practical or hands on, while more than 12% suggested changing the amount of time for training, whether longer or shorter (most wanted it to be longer). Approximately 12% said driver education or training was "ok as it is."

Risk factors for teen drivers

Alcohol or drug use. Students were asked about dangerous driving behaviors (fig. 3). About 17% reported that they had (ever) driven after drinking alcohol, and 15% had driven after using drugs. For experiencing these risks as a passenger, the numbers were even higher: 39% had been in the car of a driver who had been drinking, and 27% with a driver who had been using drugs.

Friends in the car. In California, youth who have been driving less than 12 months are not allowed to drive with other teens in the car unless a licensed driver over age 25 is present. Among students who reported that they had been driving for less than a year, 73% had driven with friends in the car, compared with 95% of students who had been driving for 12 months or more.

Late-night driving. We found that students who had been driving for less than 12 months were significantly less likely to report driving after 11 p.m. (and to report driving with friends) than those driving 12 months or more ($P < 0.0001$). However, 53% reported violating the driving curfew at least once. The data suggests that the graduated driver licensing laws are reducing violation rates for novice drivers, yet a fair number continue to break one or more laws.

Passenger-related distractions. Distraction is a key cause of accidents for both teenagers and adults. In many cases, distraction results from driver behavior, such as changing the radio, eating, talking on the phone or putting on makeup. Teen drivers are subject to these types of distractions, but research shows they are at particular risk from traveling with other teenage passengers (Heck and Carlos 2008). Specific reasons for this elevated risk have not previously been explored.

In our study, teens were asked whether they had been distracted while driving by things passengers had done. Overall, 38.4% of the young drivers ($n = 623$) reported such distractions, with females slightly more likely than males ($P = 0.0523$) (fig. 4). While there were no significant differences across racial or ethnic groups or urban, rural or suburban schools, students at lower-income schools were significantly less likely to report being distracted by passengers than those who attended moderate- or upper-income schools ($P = 0.0002$).

The most common distraction reported was a passenger talking, yelling, arguing or being loud (nearly 45%). However, more than 22% of the teenage drivers said they were distracted by passengers "fooling around," "wrestling" or otherwise behaving playfully or foolishly. About 16% of drivers reporting distractions said passengers played music, danced or changed the CD or radio station. About 3% reported accidental distractions such as spilling things. Overall, 7.5% of the students reported passenger-related distractions that appeared to be intentional, such as hitting, poking or tickling the driver, or attempting to use the vehicle's controls. This number may be an underestimate because for some of the comments, particularly those referring to “fooling around,” it was not possible to determine whether the distractions were intentional.

Reporting being distracted by a passenger was strongly associated with driving after alcohol use ($P = 0.0003$); this suggests that high-risk driving behaviors may tend to cluster among certain youth. Also, youth who reported having had a crash as a driver and those who reported having ridden with a dangerous driver were more likely to say they had been distracted as a driver.

Passengers of unsafe teen drivers. More than 59% of students had been passengers when a friend was driving dangerously, indicating that this is a common experience. However, over 83% said they would speak up if they felt unsafe because a friend was driving dangerously.

Car crashes. One of the risks to novice drivers is the greater possibility of being involved in a serious motor vehicle accident. California crash data indicates that drivers 15 to 17 years old were at fault in 68% of fatal car crashes in which they were involved (ACSC 2006). When asked if they had been in any car crash as a driver, 328 teens (20.5%) responded positively (148 males, 180 females). The majority of crashes occurred during daylight (63%). Speeding or reckless driving was the contributing factor most often identified (29.7%). Other contributing factors included bad weather (18%), car problems (11%), cell-phone use (11%) and alcohol or drug involvement (10%). Among additional responses, about 10% said a lack of attention contributed to the crash.

There were no significant ethnic differences among students indicating that they had been in a car crash as a driver, but girls were more likely than boys (fig. 5). Almost half of students surveyed (47%) said they had been in a crash as a passenger. This finding is similar to data reported by the National Highway Traffic Safety Administration that 47.2% of 17-year-olds (per 1,000 drivers) had been involved in an injury or fatal crash (NHTSA 2003).

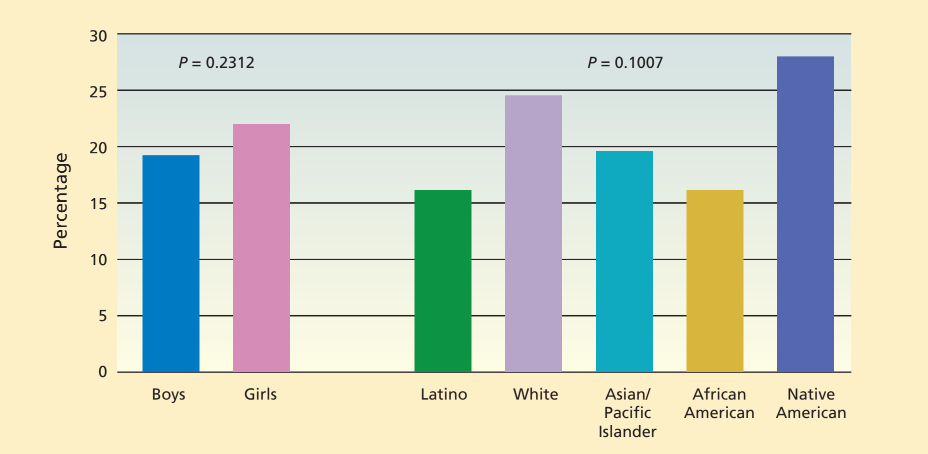

Fig. 5. Teen drivers who reported being in a crash while driving, by gender and ethnicity.

Keeping teen drivers safe

Our results underscore the need for graduated driver licensing laws, which clearly address the most important issues facing teen drivers: risky driving behaviors; driving situations that may require greater experience or judgment, such as night driving; and distractions by passengers in the car. These laws place legal boundaries on new drivers, not only helping to save lives, but also offering an “out” to teens who feel pressured to drive friends around. Legal restrictions help keep novice drivers safe as they continue to develop cognitively into the late teens/early twenties and gain more driving experience.

Teens expressed frustration about driver education and training. They indicated that they would prefer updated, less-boring teaching methods. A noteworthy comment by more than a few students was that during in-car driver training, some driving instructors did not always appear to be focused on instruction, but rather on personal issues and tasks. Another important comment was the need for more hands-on, practical driving experience, with more than 6 hours of total instruction behind the wheel. Students clearly said

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Teenage drivers as a whole have significantly higher crash rates than adults, and drivers 16 years old are twice as likely to crash as 18- and 19-year-olds. The riskiest behaviors are using drugs and alcohol, driving late at night and not using seatbelts.

they wanted as much driving experience as possible when learning. This is addressed in the graduated driver licensing laws, which require 50 hours minimum supervised driving during the learning period.

Teens indicated how important their parents were as resources when learning to drive. By placing expectations on their children and through teaching and guidance, parents provide boundaries for teens that allow them to safely develop skills and learn the responsibilities that come with the privilege of driving. The fact that most students did not report having rules about teen passengers suggests that parents may be less concerned about this risk, a somewhat curious but not isolated finding.

Williams et al. (2006) found that parents thought the highest risks to teen drivers were drugs and alcohol, post-midnight driving and seatbelt nonuse, and the lowest risks were 9 p.m.-to-midnight driving and driving with one passenger. (When the Williams et al. [2006] survey was administered, driving with a teen passenger was legal for novice drivers.) There are several reasons why California parents may not enforce the no-passenger rule as vigorously as others. For one, there are exceptions to the restriction. The California Department of Motor Vehicle Web site states that a novice driver may drive other teenagers when other reasonable transportation is not available (DMV 2009). In these cases, a signed note must be kept in the driver's possession explaining the necessity and the date that it will end. This exception can apply to sports events, school transportation and other school activities, as well as the need to drive younger siblings to their activities or school. If novice drivers can legally drive in certain situations with other teens in the car, these exceptions may lead parents to believe the rule is not as important as others.

This particular rule may also be viewed as irrational. If two teens plan to attend the same nonschool event yet neither has driven for more than 1 year and both have their licenses, neither can legally drive the other in the same car. It may be perceived as wasteful for them to go in two separate cars. This is one area for future research and education; parents clearly have a powerful influence on their teens, but the message of how risky teen passengers can be to the safety of all in the car must be strengthened, clarified and better understood by parents (Williams et al. 2006).

It is difficult to know for certain how many unlicensed drivers are on the road at any time. Our study clearly indicates that teens do drive without licenses, for various reasons. These drivers appear to be involved in fewer crashes and are more likely to follow other driving laws, but everyone faces the risks of unlicensed driving. Licensure status was strongly related to income, with almost two-thirds of unlicensed drivers attending lower-income schools, as were 40% of nondrivers. While the costs of driving (e.g., insurance and fuel) may remain prohibitive, finding ways to make driver education and training more affordable for all teens would result in better-educated and better-trained drivers on the road.

To our knowledge, there have been few if any studies that focused specifically on California youth and their driving behaviors and perceptions. All new teen drivers are influenced by peers and are susceptible to distractions, as a normal part of their maturation process. For the most part, young people try to be good drivers and follow the laws of the road. Our study sheds light on the regulated aspects of driving that are difficult to enforce. We found that students place a high value on driving and enjoy the opportunities that come with it, but also that they need more legal and adult guidance so that they can learn safely.

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Member record books are useful tools for evaluating 4-H club programs

by Larry Forero, Katherine E. Heck, Pat Weliver, Ramona M. Carlos, Thi Nguyen *and* Audra Lane

We used data from 4-H record books to evaluate the 4-H programs in Shasta and Trinity counties. These books are completed annually by youth participants throughout California to describe and quantify their experiences in the program and reflect on their involvement in citizenship, leadership and life-skills activities. Quantitative and qualitative data from the reports was coded according to the Targeting Life Skills model developed at Iowa State University. Most club participants reported life-skill activities in each component of the model (Head, Hands, Heart and Health), in accordance with established 4-H goals. This method is applicable to other counties wishing to perform 4-H program evaluations using club participants' record books.

Participants in the Shasta County 4-H program exhibit their project lambs at the Shasta District Fair.

4-H is a youth organization in which young people are given opportunities to build confidence, learn responsibility and develop life skills. Youth make friends and share interests, ranging from building robots to raising rabbits, from designing Web pages to landscape design; and they undertake volunteer projects in their communities.

The 4-H programs in many states use record books as a tool to teach youth about record keeping, improve their projects and reflect on their achievements. The record book format varies by state, and in most cases it is a personal description and reflection of their own experiences rather than a public record.

Along with personal data such as age, grade level and years in the 4-H program, the California record book includes a personal development report (PDR) with a quantitative page documenting participation in a variety of 4-H projects and activities, such as the number of meetings and events attended, projects completed, presentations given and awards received. The record books include project pages and a personal narrative written by the member describing his or her 4-H participation. This open-ended narrative is intended to describe the totality of one's history and experiences in the program in a sequential fashion.

These record books represent a large commitment of time by youth and adult volunteers. As a collection of personal information describing program experiences, the record books also provide a potential data source for program evaluation that has been heretofore untapped in California and elsewhere. Since the record books contain personal reflections, most are not shared beyond the club level, which may be the reason that they have rarely been used in evaluation.

Little has been published regarding the use of record books in 4-H program evaluation. Diem and Devitt (2003) examined 89 record books of New Jersey 4-H members and reported on what youth recorded learning (such as goal-setting, subject matter knowledge, organization and public speaking). Previous 4-H evaluations have primarily used survey data for program evaluation, rather than record books (Astroth and Haynes 2002; Howard et al. 2001; Lerner et al. 2008; Seevers and Dormody 1995).

The goal of this project was to use available record book data to evaluate how well the 4-H programs in Shasta and Trinity counties were achieving the statewide 4-H goals and mission, "to engage youth in reaching their fullest potential while advancing the field of youth development" (www.ca4h.org).

TABLE 1. Personal development report (PDR) categories coded to Targeting Life Skills model items, 2005–2006 (n = 341)

PDR category	Youth reporting	Targeting Life Skills model items
	%	
Local club meetings attended	71.8	(No skills coded)
Project meetings attended	71.2	(No skills coded)
4-H camp (planned)	5.6	Planning/organizing, teamwork
Field days: club, county, region, state	54.6	Marketable skills, self-motivation, self-responsibility, keeping records, planning/organizing, goal-setting
State leadership conference	0.8	Communication, leadership, sharing, teamwork, self-esteem, planning/organizing
Committee chair	27.6	Communication, cooperation, social skills, nurturing relationships, leadership, responsible citizenship, contribution to group effort, marketable skills, teamwork, self-motivation, planning/organizing, problem solving, decision making, self-esteem, self-responsibility
Judging contest	54.8	Communication, keeping records, critical thinking, decision making
Wrote and submitted news-club paper	9.1	Communication, leadership, marketable skills, self-motivation, planning/organizing, critical thinking, learning to learn, self-discipline
Represented 4-H in other way	60.7	Contribution to group effort, responsible citizenship
Committee member	49.6	Communication, cooperation, social skills, sharing, nurturing relationships, contributions to group effort, marketable skills, teamwork, planning/organizing, goal-setting, problem solving
Junior or teen leadership	16.7	Communication, cooperation, sharing, leadership, contributions to group effort, self-motivation, planning/organizing, goal-setting, problem solving, decision making, self-esteem, social skills
Prepared and gave talk	32.3	Communication, marketable skills, keeping records, planning/organizing, critical thinking, learning to learn, self-discipline, sharing
Held an office	27.9	Communication, social skills, nurturing relationships, leadership, responsible citizenship, contributions to group effort, marketable skills, teamwork, keeping records, planning/organizing, goal-setting, decision making, self-esteem, self-motivation
Radio or TV appearance	2.9	Communication, leadership, marketable skills
Medalist	27.0	Self-motivation, self-responsibility, planning/organizing, goal-setting, sharing, marketable skills
Project exhibit	73.9	Sharing, marketable skills, self-motivation, planning/organizing, self-esteem
Participation other than 4-H	0.0	(No skills coded)
Demonstration	55.1	Communication, sharing, self-motivation, planning/organizing, critical thinking, self-esteem, self-discipline, social skills
Number of projects completed	87.4*	Self-motivation, keeping records, goal-setting, self-responsibility, self-discipline
Planned group activity	38.7	Communication, cooperation, social skills, concern for others, sharing, nurturing relationships, leadership, contributions to group effort, marketable skills, teamwork, self-motivation, planning/organizing, goal-setting, problem solving, decision making, self-discipline
Attended event	0.0	(No skills coded)
County winner	0.0	Self-motivation, self-responsibility, planning/organizing, goal-setting, sharing, marketable skills
Other: individual achievement	48.7	Self-motivation
Other: group achievement	31.7	(No skills coded)
Community pride service	70.4	Cooperation, concern for others, empathy, sharing, nurturing relationships, community-service volunteering, responsible citizenship, contributions to group effort, teamwork, character
Project showing contest	68.6	Communication, sharing, planning/organizing, self-responsibility

* Percentage who completed at least one project.

This mission is lofty but challenging as the basis for evaluation at the county level. It is difficult to determine whether youth have reached their "fullest" potential, and advancing the field of youth development is an important mission but unrelated to members' personal reflections. To facilitate the evaluation, a more concrete set of goals was needed.

For many years, the 4-H program has focused on the development of citizenship, leadership and life skills. The specific life skills cultivated were identified in the Targeting Life Skills model developed by Patricia Hendricks of Iowa State University (Hendricks 1996). The model, also known as the Iowa wheel, includes 35 skills related to "Heart" (relating to and caring about others), "Head" (managing and thinking), "Hands" (giving and working) and "Health" (living and being) (fig. 1). Life skills included in this model represent a diverse range of characteristics, from personal qualities such as empathy, self-motivation and resiliency, to specific skills such as planning and organizing, problem solving and keeping records.

These 35 life skills were used as the basis for our evaluation of quantitative components in record book data from Shasta and Trinity counties describing the types of activities in which young people participated. Qualitative narrative data describing personal program experiences was coded and analyzed according to a statement from the 4-H Web site summarizing the 4-H experience: "4-H enables youth to have fun, meet new people, learn new life skills, build self-confidence, learn responsibility and set and achieve goals!"

Questions we sought to answer with this project included: (1) are record books usable as a data source for program evaluation? and (2) how well is the 4-H program helping young people to develop citizenship, leadership and life skills? To answer the first question, we had to examine the record books available to see whether they contained the kind of information that could be used to provide data on the success of the program. Once the first question was answered affirmatively, we could analyze the data to learn about young people's experiences in 4-H.

Fig. 1. Targeting Life Skills model. Source: Hendricks 1996.

Coding record book data

Record books were submitted to the 4-H youth development program representatives in Shasta and Trinity counties on a volunteer basis, with the knowledge that they would be used for this project. We used data from the 2005–2006 4-H year (4-H runs from July 1 to June 30, with most youth enrolling at the beginning of the school year). From 919 members who participated, 341 record books were collected, 330 of which included narratives. The sample represented 37.1% of all youth in the 4-H programs in Shasta and Trinity counties, and the narrative data represented 35.9% of all participants. We used two components of the record books for evaluation, the personal development report (PDR) and the personal narrative, "My 4-H Story."

Personal development report. The PDR includes tables that are filled in to quantify participation in 26 types of activities or honors, for the current year and previous years. For this analysis, we used the data simply to indicate whether the youth had participated in the activity or not, rather than to determine how many times they had participated (i.e., as a binary rather than a continuous model).

We compared the activities listed in the PDR to the life skills described in the Targeting Life Skills model and identified which life skills each PDR item would help develop (table 1). The individual PDR items were coded with more than one of the Targeting Life Skills model items in most cases. For example, having a radio or television appearance was coded as developing communication, leadership and marketable skills.

Not all of the Targeting Life Skills items relate to the categories defined in the PDR. Therefore, not all of the skills could be identified and coded; of the 35, 25 were coded to one PDR category or more. Conversely, 21 of the 26 PDR items received Targeting Life Skills model codes, while five items received no code (participation in activities other than 4-H, attended event, other group achievement, and attending local club and project meetings).

Ten of the Targeting Life Skills model items (accepting differences, conflict resolution, resiliency, wise use of resources, service learning, managing feelings, healthy lifestyle choices, stress management, disease prevention and personal safety) may be developed through a variety of 4-H activities, but were not coded because the PDR categories were not adequate to definitively say that the young person had developed these skills. For example, a young person participating in a rocketry project may develop personal safety skills. However, no PDR item is exclusive to such a project, so it was not possible to say using the PDR data how many young people developed personal safety.

Personal narrative. To examine qualitative experiences in the program, the personal narratives were coded according to the Web site statement of 4-H goals. After the research group reviewed and agreed upon the codes, three researchers individually coded the youth narratives. To ensure consistency, the group discussed any items about which a team member was uncertain. Data from coding the narratives was entered into a spreadsheet.

For example, if a narrative reported that the youth had fun, had a good time or enjoyed the program, he or she was coded as "having fun." "Meeting new people" included meeting buyers for their animals, meeting people at places where youth volunteer, and making new friends through program participation. "Learning new life skills" included learning any of the 35 life skills listed in the Targeting Life Skills model. Youth who reported increased self-confidence as a result of their participation in the program were coded as having developed "self-confidence." "Responsibility" included learning responsibility or becoming more responsible through 4-H participation. "Set/achieve goals" included youth who reported that they had set one or more goals during that 4-H year or reported achieving one or more goals.

Statistical analysis. The narratives were hand-entered into Microsoft Word and then coded using Excel. Data were analyzed using SAS Institute software for quantitative and NVivo software (QSR International) for qualitative data analysis.

Demographics. Participants ranged from 9 to 18 years old, with a median age of 13 (table 2). Most record books came from youth who had participated in 4-H for fewer than 4 years, although 40% had been in the program 4 years or longer. The majority of participants were female (57%). Eighty percent lived in Shasta County, while the remainder lived in Trinity County.

TABLE 2. Demographics of 4-H study participants, Shasta and Trinity counties, 2005–2006

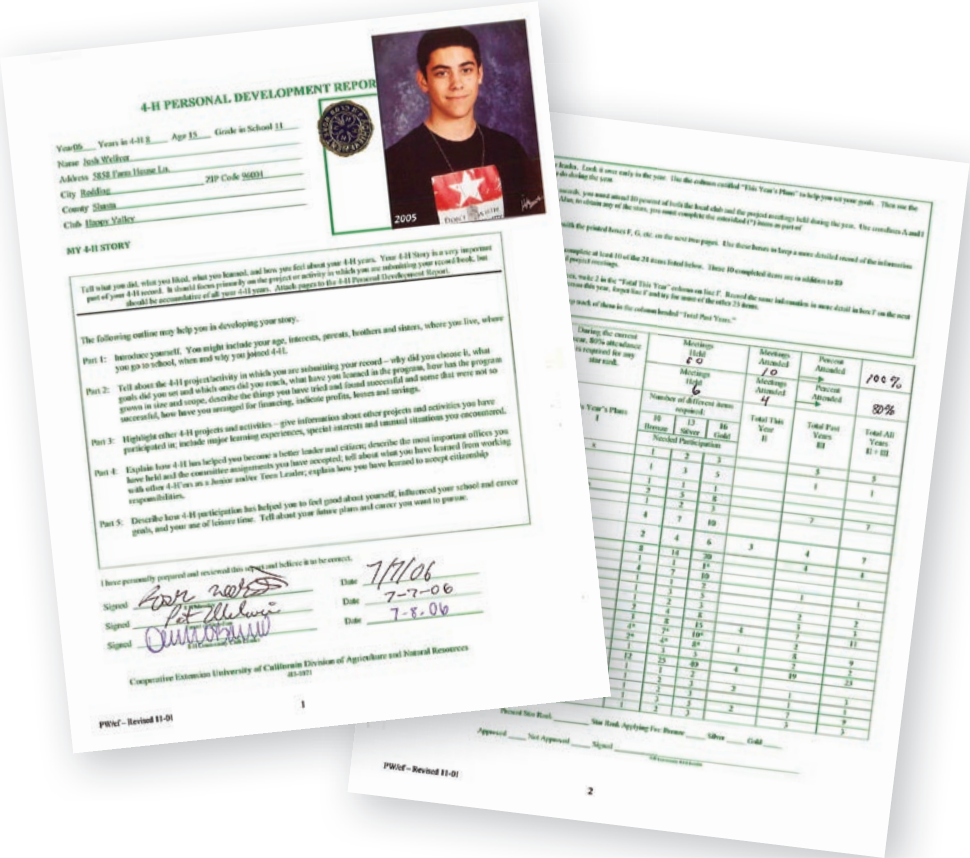
Characteristic	Responents
	number (%)
Age	
9–10	68 (20.1)
11–12	78 (23.0)
13–14	97 (28.6)
15–16	65 (19.2)
17 or older	31 (9.1)
Years in program	
1	86 (25.9)
2–3	112 (33.7)
4–5	54 (16.3)
6 or more	80 (24.1)
Gender	
Male	146 (42.9)
Female	194 (57.1)
County	
Shasta	273 (80.1)
Trinity	68 (19.9)

TABLE 3. Youth who developed various citizenship, leadership and life skills, according to personal development report (PDR) data (n = 341)

Principle	Members
	number (%)
Information from PDRs	
Developing life skills	312 (91.5)
Developing citizenship	285 (83.6)
Developing leadership	214 (62.8)
Life skills developed*	
HEAD	
Keeping records†	341 (100.0)
Planning/organizing	310 (90.9)
Goal-setting	308 (90.3)
Decision making	281 (82.4)
Problem solving	260 (76.3)
Critical thinking	255 (74.8)
Learning to learn	31 (9.1)
HEART	
Sharing	312 (91.5)
Communication	310 (90.9)
Nurturing relationships	295 (86.5)
Cooperation	294 (86.2)
Social skills	287 (84.2)
Concern for others	271 (79.5)
Empathy	240 (70.4)
HANDS	
Self-motivation	308 (90.3)
Marketable skills	305 (89.4)
Contributions to group effort	303 (88.9)
Teamwork	295 (86.5)
Responsible citizenship	285 (83.6)
Community-service volunteering	240 (70.4)
Leadership	214 (62.8)
HEALTH	
Self-responsibility	308 (90.3)
Self-discipline	304 (89.2)
Self-esteem	292 (85.6)
Character	240 (70.4)

* Ten life skills from the Targeting Life Skills model were not coded because PDR items did not relate to them.

† Since this data was drawn from record books completed by members, all members in the analysis were considered to have developed the life skill of record keeping. Using only PDR codes from table 1, 90.3% of youth developed this skill.



4-H PERSONAL DEVELOPMENT REPOR

Year06 Years in 4-H 8 Age 15 Grade in School 11
Name Josh Welker
Address 5858 Farm House Ln. ZIP Code 96001
City Redding
County Shasta
Club Happy Valley

MY 4-H STORY

Tell what you did, what you liked, what you learned, and how you feel about your 4-H years. Your 4-H Story is a very important part of your 4-H record. It should focus primarily on the project or activity in which you are submitting your record book, but should be accumulative of all your 4-H years. Attach pages to the 4-H Personal Development Report.

The following outline may help you in developing your story.

Part 1: Introduce yourself. You might include your age, interests, parents, brothers and sisters, where you live, where you go to school, when and why you joined 4-H.

Part 2: Tell about the 4-H project/activity in which you are submitting your record – why did you choose it, what goals did you set and which ones did you reach, what have you learned in the program, how has the program grown in size and scope, describe the things you have tried and found successful and some that were not so successful, how have you arranged for financing, indicate profits, losses and savings.

Part 3: Highlight other 4-H projects and activities – give information about other projects and activities you have participated in; include major learning experiences, special interests and unusual situations you encountered.

Part 4: Explain how 4-H has helped you become a better leader and citizen; describe the most important offices you have held and the committee assignments you have accepted; tell about what you have learned from working with other 4-H'ers as a Junior and/or Teen Leader; explain how you have learned to accept citizenship responsibilities.

Part 5: Describe how 4-H participation has helped you to feel good about yourself, influenced your school and career goals, and your use of leisure time. Tell about your future plans and career you want to pursue.

I have personally prepared and reviewed this report and believe it to be correct.

Signed Date 7/1/06
Signed Date 7-7-06
Signed Date 7-8-06

Cooperative Extension University of California Division of Agriculture and Natural Resources

1

PW/ef – Revised 11-01

PW/ef – Revised 11-01

2

The personal development record (PDR) is filled out by 4-H members to quantify their participation in activities and honors. This data and the accompanying personal narratives were used to evaluate whether the 4-H programs in Shasta and Trinity counties were meeting their goals.

Can books be used for evaluation?

The study's first component examined whether record book data was adequate to evaluate the 4-H program. Examination of the categories reported in the PDR and information reported in the narratives led us to conclude that the record books have data that can evaluate how well the program is meeting its primary missions of engaging youth in citizenship, leadership and life-skills activities, including many of the life skills identified in the Targeting Life Skills model. The PDR data provides a structured look at participation in specific activities, while the narratives filled in additional qualitative information about personal perceptions of program experiences.

These findings are not without limitations, however. The PDR categories described specific activities rather than the skills gained from those activities. Since the categories did not match items in the Targeting Life Skills model, the coding provides incomplete coverage of possible life skills gained. It is possible that specific projects may develop skills, for example stress management or managing feelings, but it is not possible to ascertain from the PDR.

The qualitative data drawn from narratives is also subject to limitations. These narratives were open-ended and did not necessarily represent the totality of the young person's experiences in the program. Since youth were not asked specific questions about their development, or about any of the individual item codes, the narrative can provide only a baseline for members who mention particular characteristics, rather than an accurate quantification of rates for variables examined in the narratives.

Evaluating 4-H program goals

PDR analysis. Youth in the 4-H club programs in Shasta and Trinity counties typically report a variety of activities, most commonly related to community service, individual projects and local fair participation (table 1). Completing at least one project was the most common activity noted on the PDR (87%). Additional commonly reported PDR items included "community pride service" (community-service projects) and "project showing contest" and "project exhibit" (showing projects at fairs, judging contests and demonstrations).

Analysis of the PDRs indicated that a majority of young people in the club program participated in leadership (63%), citizenship (84%) and life-skills activities (92%) (table 3). Most members (59%) reported PDR items indicating that they were engaged in all three types — citizenship, leadership and life-skills activities — while 28% reported two of the three and 4% reported just one.

Younger participants (below grade 6) are not expected to participate in leadership positions in their clubs such as holding an office, so it is not surprising that such engagement was reported less frequently than citizenship or life skills. The proportion of members who reported leadership activities was higher when the analyses were restricted to older members: among members in grades 7 to 12, 70% reported at least one such activity.

More than 90% of members developed the life skills of sharing, communication, planning and organizing, goal-setting, self-motivation, record keeping and self-responsibility.

Based on matching PDR data to life skills delineated in the Targeting Life Skills model, more than 90% of members developed the life skills of sharing, communication, planning and organizing, goal-setting, self-motivation, record keeping and self-responsibility (table 3).

Narratives. In the 330 qualitative narratives evaluated, most youth reported having fun (65%) and learning new life skills (68%). About 44% reported setting or achieving goals, and 39% said they learned responsibility. About one in five reported meeting new people and 16% reported that they gained self-confidence through participating in the program. These qualitative results represent only the characteristics or experiences that the members chose to describe, and as such represent a minimal baseline. For example, it is possible that more than 16% gained self-confidence, but only 16% mentioned it in their open-ended narratives.

Pros and cons of coding methods

Record books are completed by most youth in many county 4-H clubs, and they provide substantial detail about the 4-H participant's experiences, but until now the record books have remained an untapped data source. We found that this currently existing data source can be used for program evaluation at the county level. Other counties could use this project as a model for their own evaluations. Coding the record books was time-consuming, particularly for the longer record books typically completed by older members, but once entered into the spreadsheet and proofed, the PDR data was easily accessible and quantified.

Results showed that the 4-H programs in Shasta and Trinity counties were meeting the goals of cultivating citizenship, leadership and life skills among most youth. One significant limitation of this study is that the data available in this version of the PDR does not specifically describe the skills young people gain, so the results are limited by the accuracy of the assumptions in coding the PDR to the Targeting Life Skills model. Also, no data was available in the PDR on the amount of time youth spent on particular activities, so duration and intensity could not be quantified.

While this analysis attempted to identify the likely skills that youth were gaining from their participation, the life skills enumerated may not precisely match the skills youth gained. Our coding scheme may have overreported or underreported the resulting life skills, and the imprecise coding of life skills is a limitation of our study. The PDR items included some specifics allowing for the coding of 25 of the 35 life skills identified in the Targeting Life Skills model. The record book format has changed since this data was collected, improving the ability to evaluate members' life-skills development in the future. Rather than quantifying a particular array of activities, the new record book format allows youth to identify their development of leadership, citizenship, community-service and communication skills, as well as individual project skills gained.

The response rate of approximately 37% — in this case the proportion of record books that were collected at the county level — is an additional limitation. It is possible that the record books gathered did not constitute a representative sample of all youth in the program, which could skew the results. However, the record books collected represented members from 22 different clubs, in the full range of ages represented in the program as well as members who participated in a wide variety of activities, so it appears to be a broad sample. The 4-H club programs in Shasta and Trinity counties are not representative of all youth participating in 4-H around the state, so these results cannot be extended statewide. However, other counties may use this method to evaluate their own programs.

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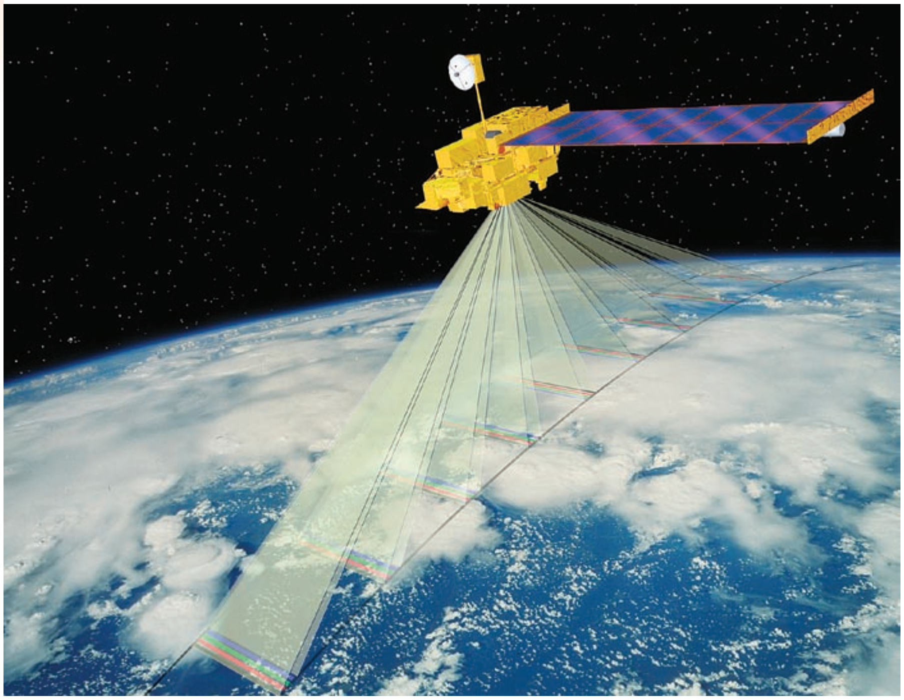
Satellite imagery can support water planning in the Central Valley

by Liheng Zhong, Tom Hawkins, Kyle Holland, Peng Gong *and* Gregory Biging

Most agricultural systems in California's Central Valley are purposely flexible and intentionally designed to meet the demands of dynamic markets such as corn, tomatoes and cotton. As a result, crops change annually and semiannually, which makes estimating agricultural water use difficult, especially given the existing method by which agricultural land use is identified and mapped. A minor portion of agricultural land is surveyed annually for land-use type, and every 5 to 8 years the entire valley is completely evaluated. We explore the potential of satellite imagery to map agricultural land cover and estimate water usage in Merced County. We evaluated several data types and determined that images from the Moderate Resolution Imaging Spectrometer (MODIS) onboard NASA satellites were feasible for classifying land cover. A technique called "supervised maximum likelihood classification" was used to identify land-cover classes, with an overall accuracy of 75% achievable early in the growing season.



NASA/courtesy of nasaimages.org

Imagery from NASA's Terra satellite was used to map agricultural land cover.

At approximately $35.4 billion in estimated economic value (AIC 2006), agriculture is extremely important to the economy and well-being of California. The state's high level of agricultural productivity is driven by favorable climate and water availability; the latter is a direct result of water planning and crop management. Water balances — the annual equation of water availability and usage — are used to develop plans and management strategies for ensuring agricultural productivity and optimizing water use.

In the Central Valley, which accounts for about 43% of California's agricultural production, water is scarce and the water balance is primarily determined by irrigation requirements for different types of crops such as corn, tomatoes and cotton. Accurate maps of agricultural land cover are critical if we are to develop annual water balances and maintain agricultural productivity.

Currently, agricultural land cover is mapped using an observational survey, which does not efficiently capture actual annual changes in crop type. This survey is generally conducted by representatives of state and federal agencies, who collect some information about crop types, land-use changes and agricultural land management for a subset of all agricultural land in the Central Valley, for example, land-use maps by the Department of Water Resources, State of California (www.water.ca.gov/landwateruse/lusrvymain.cfm). This information is compiled annually into a land-cover map, which is then analyzed to estimate agricultural water use.

Critics of this approach argue its intrinsic shortcomings. First, the annual compilation of data by human observation is expensive, incomplete and sometimes erroneous. Second, too much time is required to observe and compile land-use information and develop a water balance. Lastly, agricultural land-management objectives change from year to year as reflected by visible changes in crop cover; an observational survey does not completely assess these changes, since only a percentage of land is sampled in any one given year due to financial constraints.

We believe that a better approach would be to include automation, objectivity and a feasibility study for complete annual land-use assessments. Automation reduces the cost of human labor, time and, potentially, error and enables the collection of timely information in a consistent manner. Objectivity, or the ability to collect unbiased information, gives credibility to water planning.

Remote sensing, or the analysis of satellite imagery, is a widely used method to obtain information for water planning, since it employs objectivity and can be used to automatically map agricultural land cover (Erol and Akdeniz 2005; Martinez-Casasnovas et al. 2005; Murakami et al. 2001; San Miguel-Ayanz and Biging 1997; Turker and Arikan 2005; Xie et al. 2007). One type of widely available satellite data is Moderate Resolution Imaging Spectrometer (MODIS) imagery collected and maintained by the National Aeronautics and Space Administration (NASA). This imagery is free, which makes it especially desirable from a cost-savings perspective. Additionally, MODIS images are recorded twice a day for the entire Central Valley, allowing for some unique temporal analyses. In this study, we explored how MODIS imagery can be used to map agricultural land cover for a portion of the Central Valley. Our long-term goal is to improve and extend the described methodology to the entire valley, to efficiently support water planning.

The objectives of this study were to (1) demonstrate the feasibility of MODIS imagery to monitor crop types for water planning, (2) assess the accuracy of derived crop-type maps and (3) determine when crop types can first be identified from MODIS imagery on an annual basis. The latter objective is critical to the timely development of water balances for planning purposes.

Accurate maps of agricultural land cover are critical to develop annual water balances and maintain agricultural productivity.

TABLE 1. Agricultural land-use changes over time for primary concern counties, including the study area, Merced County

County	Time period	Total area	Change	Change
		acres	acres	%
Fresno	1986–1994	1,347,669	1,004,809	74.6
	1994–2000	1,337,723	961,184	71.9
Kings	1991–1996	591,238	394,883	66.8
	1996–2003	577,953	375,681	65.0
Merced	1995–2002	558,819	315,997	56.5
Sutter	1998–2004	298,984	123,889	41.4

Analyzing MODIS data

Study area. Four counties are particularly important to the agricultural economy of the Central Valley: Fresno, Kings, Merced and Sutter (fig. 1). The total value of agricultural products sold from these counties is about 36% of all those sold from the valley, and these counties depend on flexible agricultural systems that are adaptable to annual or semiannual economic conditions, as indicated by historic map data (USDA 2004). This data shows that approximately 40% to 60% of land cover in the four counties has changed within the last 5 to 8 years, and that land-cover changes have gone unrecorded by current land-use sampling methods (table 1). Any of these counties were logical study areas for our research because of their economic importance and because planners need accurate land-use information; however, we chose Merced County arbitrarily.

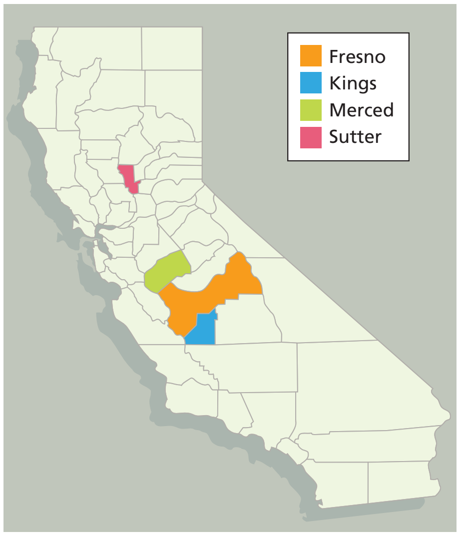


Fig. 1. Counties of primary concern, including the study area Merced County.

Satellite images. In this study, MODIS imagery was analyzed to identify agricultural land cover using reflectance and changes in reflectance over time. MODIS imagery was selected for its coverage, frequency, quality and cost. Unlike other types of satellite imagery, individual MODIS images cover large land areas that are repeatedly observed on an 8-day cycle. Additionally, MODIS imagery is high quality and available for free public download (https://wist.echo.nasa.gov/api).

Other types of satellite imagery were considered but found inadequate to our study objectives. We considered NASA's Landsat Thematic Mapper and Enhanced Thematic Mapper Plus (TM/ETM+), which also provides free images, but found it had poor coverage, relatively low frequency and quality issues. Although the spatial resolution of Landsat imagery is higher than MODIS imagery (30 meters versus 250 meters for optical bands), many more Landsat images are required to cover the same land area. Also, Landsat makes observations on a 16-day cycle rather than daily, which increases the risk that images may be obscured by cloud cover, especially during Central Valley winters. Landsat imagery is more likely to be unusable than MODIS imagery, which significantly affects the time-series analysis used in this methodology. Finally, due to the malfunctioning of the ETM+ sensor onboard Landsat 7 (the most recent satellite of the Landsat series), the quality of the imagery has largely deteriorated, which would negatively affect the accuracy of agricultural land-cover mapping.

Quantifying vegetative growth. A common measure called the normalized difference vegetation index (NDVI) was used to quantify vegetation growth. Like all color digital images, MODIS captures bands of spectral reflectance information during each exposure. Each pixel (picture element) in the image contains these bands, and for most hand-held digital cameras they correspond to the red, green and blue segments of the visible spectrum. Satellite imagery has additional bands that are taken from the invisible portions of the spectrum, such as the near infrared (NIR). NDVI is calculated from a combination of the red and near-infrared spectra for a single pixel as:

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$

This ratio is based on the photosynthetic attributes of vegetation, which tends to absorb red and blue radiation from the sun (hence reflecting the color green) but reflect more near-infrared

Improvements in high-resolution satellite imagery and modeling techniques will help to classify crops at higher degrees of accuracy.

NASA/courtesy of nasaimages.org

energy. More importantly, NDVI can be used to determine plant vigor. Using a series of images over time, the change in vigor as measured by NDVI can be used to identify specific crop types (Choudhury and Chakraborty 2006; de Wit and Clevers 2004; de Santa Olalla et al. 2003; Martinez-Casasnovas et al. 2005; Murakami et al. 2001; Tso and Mather 1999; Turker and Arikan 2005).

Supervised classification. We identified agricultural land cover for the entire study area using an approach called "supervised classification," which involves training a computer to associate pixels with types of land cover. First, we trained the computer in two different types of pixel data over time: (1) NDVI and (2) red (620 to 670 nanometers [nm]) and near-infrared (841 to 876 nm). The latter of these types is referred to as componential, since it spans two layers of spectral information (red and near infrared) as opposed to a single composite NDVI layer. Second, the computer classified the MODIS imagery into agricultural land-cover classes for two sets of images: (1) those taken during the growing season and (2) a subset taken early in the season.

High-quality images. MODIS imagery, which is adjusted for atmospheric and radiometric conditions, has a spatial resolution of approximately 250 meters by 250 meters and temporal sampling frequencies that depend on the type of pixel data. The NDVI pixel data is a time series with 16 days between sequential images, while the componential pixel data has an 8-day period. Within each period, all daily images, barring heavy cloud cover and equipment error, are extracted to produce an extremely high-quality composite image for the entire 16- or 8-day period. Therefore, both types of pixel data can be viewed as having multiple spectral bands, each related to a specific period in time. For example, pixel data having a series with six periods will have six layers under the NDVI type (one spectral band per period times six periods), while the componential type will have 12 layers (two spectral bands per period times six periods). Similar research on sugar cane shows that imagery such as MODIS, with temporal sampling frequencies, will give good results (Xavier et al. 2006).

TABLE 2. Major agricultural land covers in Merced County, 2002

Name	Acreage	Percentage
Almonds	96,439	17
Alfalfa and alfalfa mixtures*	91,143	17
Grain/corn rotation†	66,576	12
Cotton	59,781	11
Mixed pasture	44,235	8
Grain and hay crop‡	36,871	7
Tomato	29,998	5
Corn	16,311	3
Vineyard	14,260	3
Others	90,631	17
Total	546,246	100

* Alfalfa for short.

† A multiuse type with grain and corn grown alternatively.

‡ Grain for short.

Supervised training

A computer-based software program was trained using a subset of data: images of Merced County captured in 2002 and historic information collected from the same year's land-use survey. We considered nine major crops comprising 83% of all agricultural acres in the county for training and classification (table 2). Groups of pixels, or samples in the MODIS imagery, were manually associated with each of the nine crops based on their spatial proximities to true land covers in the historic land-use survey data. Each group of pixels represented an observed class of agricultural land cover and more importantly, from a statistical perspective, each was a sample from a probability distribution. Although probability distributions are fairly complex mathematical objects, they are generally parameterized by means, variances and covariances.

Between 76 and 500 samples were used to estimate the means and variance-covariances for each of the nine classes. Based on the estimated statistics, the computer used a well-accepted technique called maximum likelihood classification (El-Magd and Tanton 2003) to assign a pixel with NDVI or componential data into one of the nine classes. Maximum likelihood is a mathematical approach to estimation that involves fitting model parameters using products of samples. The resultant models, one for each of the nine classes, were the fundamental bases for automatic classification.

Automatic classification

Prior to classifying all MODIS pixels, each of the nine parameterized models was examined for uniqueness, because models that are too similar will not give good results. Since training was conducted separately for each pixel data type — the NDVI pixel data separately from the componential (red and near-infrared) pixel data — the parameterized models corresponding to classes were analyzed for separability.

Based on the analysis, the classes derived from componential pixel data were more unique than those derived from NDVI pixel data. For example, the double-use land-cover class "grain/corn rotation" was similar to the land-cover class "grain" under the NDVI pixel data (fig. 2). This was also the case for corn and tomatoes. These similarities between classes under the NDVI pixel data might have been due to the limited number of

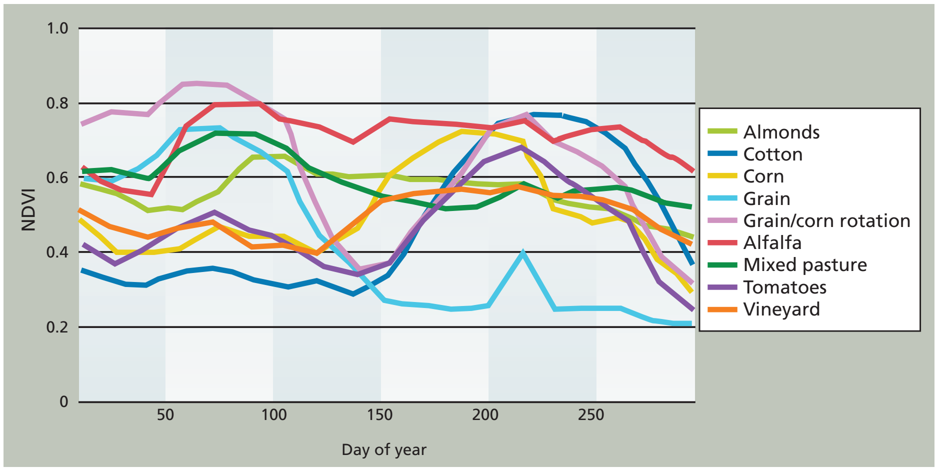


Fig. 2. Normalized difference vegetation index (NDVI) values by day of year for all time periods, for nine agricultural land-cover classes.

TABLE 3. Iterative accuracies as measured by percentage correct classification of NDVI pixel data, based on time periods for entire growing season

Iteration	Classification accuracy
	%
1	80.3
2	81.7
3	82.0
4	81.7
5	81.7
6	80.4
7	81.3
8	80.7
9	80.6
10	80.2
Average	81.1

samples used in the maximum-likelihood estimation of model parameters.

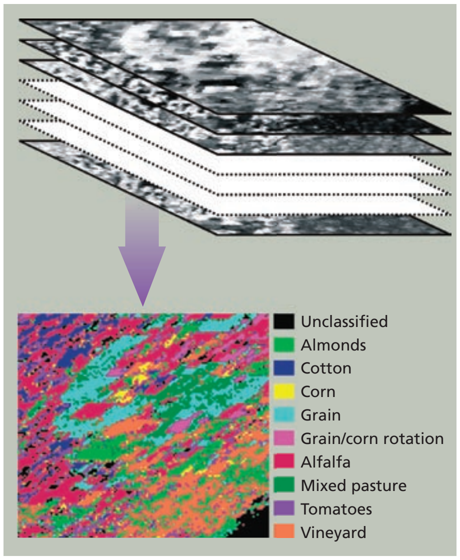
Despite the observed limitations in crop-class separability (fig. 2), we implemented the automatic classification of all MODIS pixels for both the NDVI and componential pixel-data types separately. Each pixel having bands and values corresponding to periods in time was evaluated under each of the nine models for each of the pixel-data types. Discriminate analysis was used to decide the best model for each pixel, and each pixel was classified to one of nine land covers.

Cross-validation of accuracy

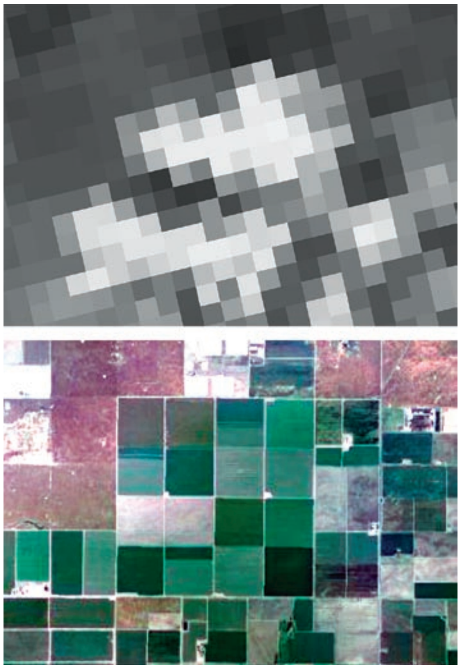
Classification accuracy was measured as a percentage of pixels correctly classified in a set of test pixels randomly chosen in the imagery. Just as groups of training pixels were used to parameterize probability models for each of the nine classes, groups of test pixels were used to evaluate the classification accuracy of the models. A special iterative technique called "cross-validation" was used to calculate a robust measure of classification accuracy. Given an entire set of pixels with known land-use classes (identified from the historic land-use survey data), half were randomly selected and used for training and their complement was used for accuracy testing. Upon a certain number of iterations — random training, classification and accuracy testing — the average of iterative classification accuracies converges to overall classification accuracy. We examined this measure based on 10 iterations for two sets of images in time, one captured during the entire growing season and another early in the growing season.

Entire growing season. Only the NDVI pixel data was used for classification over the entire growing season. It was fairly accurate in classifying crop types despite limitations in the separability of cover classes such as grain and grain/corn rotation or corn and tomatoes (fig. 2). Four time-periods (scenes) of the NDVI pixel data are shown in figure 3 along with the overall classification results, which are based on all periods in the time series. An overall classification accuracy of 80% was achieved using the NDVI pixel data (table 3), but the classification accuracy for corn, tomatoes and cotton was lower than overall (about 50%).

As indicated by the separability analysis, these misclassifications were probably due to the limited amount of training data, for corn in particular. Another possible cause might have been spectral mixing. Since the resolution of the MODIS imagery is about 250 meters per pixel, two or more types of land cover could exist in any one pixel, causing an inseparable mixing effect



▲ Fig. 3. Arbitrary NDVI pixel data displayed as stacked grayscale images for all time periods, and final classification of NDVI pixel data based on all time periods for entire growing season.



◀ *Top*, an image modified with normalized difference vegetation index (NDVI) technology; *bottom*, the same location and time at high resolution.

and confounding models for respective land-cover classes. Possible solutions to improve classification accuracy include using high-resolution imagery containing pixels that are less mixed or implementing a complex, multistage classification scheme.

Early growing season. The number of images used for early-growing-season classification was increased by period to determine when agricultural land cover can first be reliably identified. For the NDVI pixel data, this point occurs at approximately 12 periods or 192 days into the growing season with an overall classification accuracy of 75%. For the componential pixel data, the reliable identification time is approximately 17 periods or 136 days into the growing season to achieve accuracy as high as 75%.

For classification early in the growing season, the componential pixel data gave classifications that were equal in accuracy to the NDVI pixel data, but results were achievable almost 2 months earlier than with NDVI. This means that agricultural land cover can be identified by the month of May to support the current year's water planning. Similar to classification issues for the entire growing season, we expect that accuracy can be improved for early-growing-season classification with high-resolution imagery and a modified classification method.

A feasible solution

The accuracy and timeliness of land-cover classification can be improved over existing mapping methods using satellite imagery and remote sensing. We have shown that time-series MODIS imagery in the form of NDVI, or red and near-infrared spectra, provides a feasible solution for agricultural land-cover mapping. Our results indicate that the major agricultural crops can be identified by as early as May with an overall accuracy of about 75%. While our research was conducted in Merced County using MODIS imagery from 2002, we expect that our methodology is applicable to the entire Central Valley with similar results.

We have identified two possible improvements. First, MODIS imagery with a pixel resolution of approximately 250 meters contains some mixed pixels that cause inseparability between confounded, parameterized models, making them inherently difficult to classify. These problems can be addressed by higher-resolution imagery containing more pure pixels and using a larger number of samples for supervised training. Second, the maximum-likelihood technique used to parameterize the models for crop-cover types can be modified to improve the classification results, perhaps by making use of neural-network or support-vector machine-type classifiers (Gong et al. 1996; del Frate et al. 2003; Murthy et al. 2003; Pal and Mather 2006).

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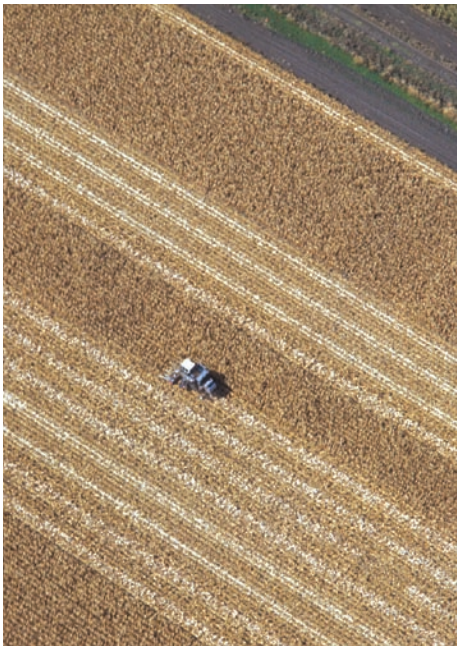

Jack Kelly Clark, UC Statewide IPM Program

Nine crops in Merced County were identified by satellite — including corn (shown) — with an overall accuracy of about 75%. The crops could be identified as early as May, allowing for better water planning throughout the growing season.

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Video market data for calves and yearlings confirms price discounts for Western cattle

by Steven C. Blank, Larry C. Forero
and Glenn A. Nader

We used 11 years of data from video auction sales across the western United States to address two long-standing questions posed by California cattle ranchers. First, as expected, ranchers receive lower prices for cattle sold here compared to prices received by ranchers in the Midwest. Second, some (but not all) "value-adding" production and marketing practices raise prices received by ranchers. We report the average amount of location discounts and quality premiums for several market regions.

Cattle markets are dynamic, responding to buyer preferences. *Above*, grass-fed cows at auction.

For years, California cattle ranchers suspected that buyers offer lower prices here than for similar cattle in the Midwest. They were correct. A study conducted in 2004 and 2005 by UC scientists showed that feeder cattle prices were discounted by increasing amounts in markets located farther west, relative to Midwestern prices (Blank et al. 2006). The primary reason is the Midwestern location of most feedlot, slaughter and packaging facilities; ranchers in California and other Western states are essentially paying to ship calves to these facilities. Transportation costs are the basis of these price discounts (Goodwin and Schroeder 1991; Clary et al. 1986). These results are alarming for California cattle ranchers because, with transportation costs increasing rapidly, their cattle price discounts can be expected to increase over time.

Western ranchers have long sought to counter location price discounts by applying management practices that add value to cattle. Cattle markets signal what they value by offering a price premium for the desired characteristics (Mintert et al. 1990; Schroeder et al. 1988; Faminow and Gum 1986). For example, Blank et al. (2006) found that preconditioning weaned calves adds to their sales value. (Preconditioning is a vaccination management program that makes calves more valuable to buyers.)

Cattle that are weaned and have recieved respiratory vaccines generally receive higher average prices than unvaccinated calves (King 2003; Bulut and Lawrence 2007; Chymis et al. 2007). However, an Oklahoma State University study found price premiums for preconditioned calves, but not enough to cover preconditioning costs (Avent et al. 2004). Blank et al. (2006) warned that this was increasingly likely as preconditioning changed from market niche to market norm. Their results also showed that many interactive factors influence cattle prices. In fact, when preconditioning and weaning effects were evaluated separately, weaning had a larger positive effect on feeder cattle prices. The price premiums for preconditioning, weaning and other value-adding factors changed over time, indicating the dynamic nature of Western cattle markets.

In 2008, we conducted research broadening Blank et al. (2006) to include yearling sales and found that Western cattle markets are indeed dynamic, as evidenced by several changes in management practices applied by ranchers and the pricing observed in calf and yearling cattle markets. Our study focused on price differences across locations and estimated average transport-based price discounts and individual value-added-program premiums received by ranchers. The new analysis shows that transportation-based discounts are increasing over time, and the pricing of value-adding factors such as preconditioning is changing as markets adapt to new supply-and-demand conditions. Our analysis included both calves and yearlings because previous studies have indicated that these two cattle-market segments have unique prices (Marsh 1985; Garoian et al. 1990).

New, expanded study

Western Video Market provided us with anonymous information on steers from 4,116 lots of calves and 5,147 lots of yearlings sold in all of their video auctions from 1997 through 2007. All calf lots had a flesh score of medium, a frame score of medium or medium-

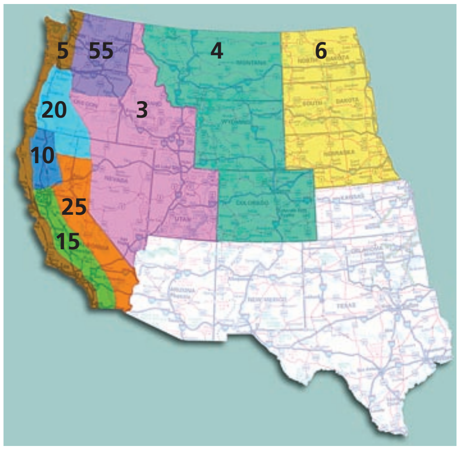

Fig. 1. Cattle market regions evaluated in study.

large and average weights from 500 to 625 pounds, to focus on the price effects of calf management at weaning. Yearling lots averaged from 750 to 925 pounds. No calves or yearlings between 625 and 750 pounds were considered, to limit and focus the study.

The number of calf lots sold per year increased from 154 in 1998 to 540 in 2007, and yearling lots from 234 in 1997 to 590 in 2007. In total, our data included approximately 571,000 calves and 874,000 yearlings. Cattle from split loads, the Holstein breed or of Mexican origin were not considered.

TABLE 1. Average effects of factors on cattle prices, 1997–2007

	Calves*		Yearlings	
Factor	**Price effect**	**Significance†**	**Price effect**	**Significance**
	$/cwt		*$/cwt*	
Region 5 (coasts of Calif., Ore., Wash.)	−10.54	***	−6.61	***
Region 55 (Wash., NE Ore.)	−11.63	***	−6.72	***
Region 10 (NW Calif.)	−8.77	***	−7.28	***
Region 15 (S Calif.)	−10.71	***	−8.29	***
Region 20 (W Ore., NW Nev., NE Calif.)	−10.12	***	−7.45	***
Region 25 (E Calif., W Nev.)	−10.86	***	−7.65	***
Region 3 (SE Ore., Idaho, Utah, E Nev.)	−9.89	***	−7.12	***
Region 4 (Mont., Wyo., Colo.)	−3.61	***	−1.89	***
Preconditioned	1.37	***	1.03	***
Age and source-verified	5.31	***	1.96	***
Bunk broke‡	−1.83	***	−0.90	***
Certified Angus Beef (candidates)	1.38	***	0.67	*
Domestic born	3.23	**	3.16	
Western Ranchers' Beef§	0.46		2.92	**
Implants	−0.50		−0.22	
Natural beef¶	2.25	***	3.78	***
Weaning 0 (calves not weaned)#	−3.59	***	na	
Weaning 1 (calves weaned < 30 days)	1.29	*	na	
Feed 1 (yearlings fed from hay lots only)††	na		−0.72	**
Feed 2 (fed on both pasture and hay lots)	na		−0.78	
Delivery month	−0.34	***	0.16	**
Sale month	0.25	*	0.71	***
Forward contracting period	1.04	***	1.06	***
Head (no. cattle in lot)	0.002		0.002	***
Variability of cattle in lot	−0.68	***	−0.39	**
Weight	−0.098	***	−0.03	***
Breed	a	Mixed	a	Mixed
Trend over time (year)	3.93	***	3.80	***

* Adjusted R^2 for calves is 0.6566 (4,116 observations) and yearlings is 0.7271 (5,147 observations).

† Factor is statistically significant (different than zero) when indicated by *, ** or *** (90%, 95% or 99% confidence level, respectively); no asterisk is essentially zero, with no price premium or discount.

‡ Cattle accustomed to eating out of feed bunk.

§ Rancher marketing cooperative with a standard for product sold by members.

¶ Certified in an affidavit from the seller.

\# For calf-weaning dummy variables, base is those weaned 30 days or more, "weaning 0" is not weaned and "weaning 1" is weaned less than 30 days.

†† For yearling feed dummy variables, base is yearlings fed on pasture only, "feed 1" is hay lots only and "feed 2" is both pasture and hay lots.

na = not appropriate in this model.

a = breeds received price discounts compared to Angus breed, half of which were significant.

We used sales information from video auctions because they operate much like a traditional auction, but with a much larger pool of potential buyers from across the country. Cattle sale prices observed in video auctions are often more indicative of national prices than local cash sales (Bailey et al. 1991). The data enabled us to analyze sales made at the same time at different locations across the West. Western Video Market is operated in a manner typical of video sales operations, with auctions broadcast via satellite almost every month of the year (www.wvmcattle.com).

Our analysis was simplified by grouping the sales data into market regions based on the pooling and flow of cattle over recent years (fig. 1) (Bailey et al. 1995). The out-of-state regions (3, 4, 55 and 6) are large, often covering entire states, whereas California was divided into three regions (10, 15 and 25) to enable detailed analysis. For example, region 20 covers western Oregon, the northwest corner of Nevada and the northeast corner of California. Also, a new region (5) was added, the coastal areas of California, Oregon and Washington. Blank et al. (2006) did not evaluate this "fog" region, but in recent years ranchers have indicated that the coastal area may be receiving price discounts even larger than neighboring areas.

Other information available for each of the lots included animal characteristics, such as breed, and details about each sales contract. Statistical regression models enabled us to estimate the effects on sales price of not only location, but also other variables that commonly influence cattle prices.

Regional price discounts

Blank et al. (2006) explained that according to economic theory, cattle prices are expected to be highest nearest to the feedlot and meat processing facilities, which are located mostly in the Midwest. The economics of transporting inputs (including calves and yearlings) make it most cost effective to ship the most valuable input (on a per-pound basis) to the least valuable (or most bulky) input, the feed grains.

Therefore, facilities that combine inputs, called feedlots, are mostly located near the source of feeds. Likewise, the output of feedlots, fed cattle, are the primary input for slaughterhouses and other meat processing operations, so those facilities are usually located near feedlots to reduce the costs of shipping live cattle.

The structure of the cattle and meat industries developed to minimize total transport costs (Clary et al. 1986). The bottom line for cattle ranchers is that the price received depends on their location relative to the buyer's location. Our study results are consistent with this theory (table 1), based on the average price discount or premium received by cattle producers in each market region after accounting for price effects due to other factors from 1997 through 2007. For example, calf prices in region 10 (northwestern California, except the coast), show an average discount of $8.77 per hundredweight (cwt) relative to region 6, which was used as the base because it includes the active cattle market in Nebraska.

Regional results for both calves and yearlings were generally consistent with the theory that average price discounts will be larger the farther away the seller is from the Midwest (fig. 1). The regional discounts were smaller for yearlings than calves, but with the same geographic pattern.

We evaluated the location price discounts by year to see if they changed over time (tables 2 and 3), and found differences in average discounts from one year to the next in 11 sets of regression results. Those changes imply that transportation costs are not the only source of price discounts between the Midwest and other regions; they also reflect changes in relative supply and demand. However, the fact that the discounts were usually higher for regions farther from the Midwest supports the conclusion that transportation costs are a major source of observed price differences.

To formally test whether the regional discounts increase over time, we performed separate regression analyses (tables 2 and 3). First, the amounts

TABLE 2. Regional price discounts (compared to region 6), weaned calves*

			Region†							
Year	n	R²	5	55	10	15	20	25	3	4
			nominal $ per hundredweight (cwt)							
1997	171	0.66	−5.49 ***‡	−3.55 ***	−4.86 **	−5.06 ***	−4.55 ***	−4.19 ***	−3.43 ***	0.14
1998	154	0.66	−6.93 ***	−1.35	−3.88 *	2.10	−2.44 **	4.01 *	−3.16 ***	−0.49
1999	234	0.81	−5.94 ***	−2.35 ***	−6.79 ***	−6.94 ***	−4.68 ***	−4.56 ***	−3.34 ***	−1.69 ***
2000	347	0.74	−9.56 ***	−5.48 ***	−5.45 ***	−4.92 ***	−6.43 ***	−7.79 ***	−6.04 ***	−0.53
2001	367	0.74	−8.30 ***	−7.76 ***	−3.84 *	−7.73 ***	−6.99 ***	−8.99 ***	−6.03 ***	−0.84
2002	331	0.67	−7.18 **	−3.67 ***	−2.31 *	−5.62 ***	−2.07 ***	−4.06 ***	−2.80 ***	−1.44 ***
2003	450	0.80	−10.65 ***	−8.50 ***	−7.38 ***	−7.45 ***	−8.38 ***	−10.13 ***	−7.80 ***	−2.88 ***
2004	529	0.65	−13.08 ***	−6.72 ***	−8.32 ***	−11.09 ***	−8.50 ***	−13.05 ***	−8.49 ***	−2.60 ***
2005	542	0.65	−15.13 ***	−10.37 ***	−6.08 ***	−1.71	−9.39 ***	−12.51 ***	−9.29 ***	−2.61 ***
2006	451	0.77	−19.03 ***	−13.65 ***	−12.97 ***	−16.76 ***	−13.84 ***	−14.60 ***	−13.73 ***	−4.99 ***
2007	540	0.76	−13.22 ***	−16.70 ***	−15.07 ***	−12.19 ***	−15.72 ***	−17.57 ***	−14.51 ***	−4.26 ***

* Regression results show average differences between region indicated and base region 6. Negative numbers are discounts, positive are premiums. (Region 6 had the highest average nominal prices.) Results not adjusted for inflation.

† Regions arranged left to right, approximately from west to east.

‡ Values statistically significant (different than zero) when indicated by *, ** or *** (90%, 95% or 99% confidence level, respectively).

TABLE 3. Regional price discounts (compared to region 6), yearlings*

			Region†							
Year	n	R²	5	55	10	15	20	25	3	4
			nominal $ per hundredweight (cwt)							
1997	234	0.58	−5.53 ***‡	−2.41 ***	−5.28 ***	−5.05 ***	−3.84 ***	−5.24 ***	−3.56 ***	−1.01 *
1998	345	0.72	−6.53 ***	−4.62 ***	−4.32 ***	−3.26 ***	−5.03 ***	−5.62 ***	−4.66 ***	−0.55
1999	373	0.77	−4.58 ***	−2.27 ***	−5.15 ***	−6.11 ***	−3.27 ***	−4.57 ***	−3.06 ***	−1.12 ***
2000	424	0.56	−3.95 ***	−2.31 ***	−4.16 ***	−4.85 ***	−3.40 ***	−3.61 ***	−2.75 ***	−1.48 ***
2001	455	0.72	−9.38 ***	−5.79 ***	−7.97 ***	−9.31 ***	−7.37 ***	−7.26 ***	−6.24 ***	−2.02 ***
2002	457	0.66	−5.73 ***	−3.11 ***	−4.03 ***	−6.41 ***	−4.63 ***	−4.72 ***	−3.89 ***	−0.51
2003	506	0.90	−7.43 ***	−5.39 ***	−6.84 ***	−8.29 ***	−6.85 ***	−7.69 ***	−5.83 ***	−1.11 *
2004	554	0.69	−9.57 ***	−9.78 ***	−10.20 ***	−13.51 ***	−10.24 ***	−9.96 ***	−10.31 ***	−3.14 ***
2005	641	0.70	−8.65 ***	−7.45 ***	−7.18 ***	−6.86 ***	−8.75 ***	−8.43 ***	−7.51 ***	−3.44 ***
2006	568	0.59	−14.09 ***	−11.43 ***	−12.06 ***	−15.84 ***	−11.10 ***	−11.71 ***	−12.03 ***	−1.47
2007	590	0.82	−14.18 ***	−11.81 ***	−11.86 ***	−11.46 ***	−12.27 ***	−11.52 ***	−9.90 ***	−2.71 ***

* Regression results show average differences between region indicated and base region 6. Negative numbers are discounts, positive are premiums. (Region 6 had the highest average nominal prices.) Results not adjusted for inflation.

† Regions arranged left to right, approximately from west to east.

‡ Values statistically significant (different than zero) when indicated by *, ** or *** (90%, 95% or 99% confidence level, respectively).

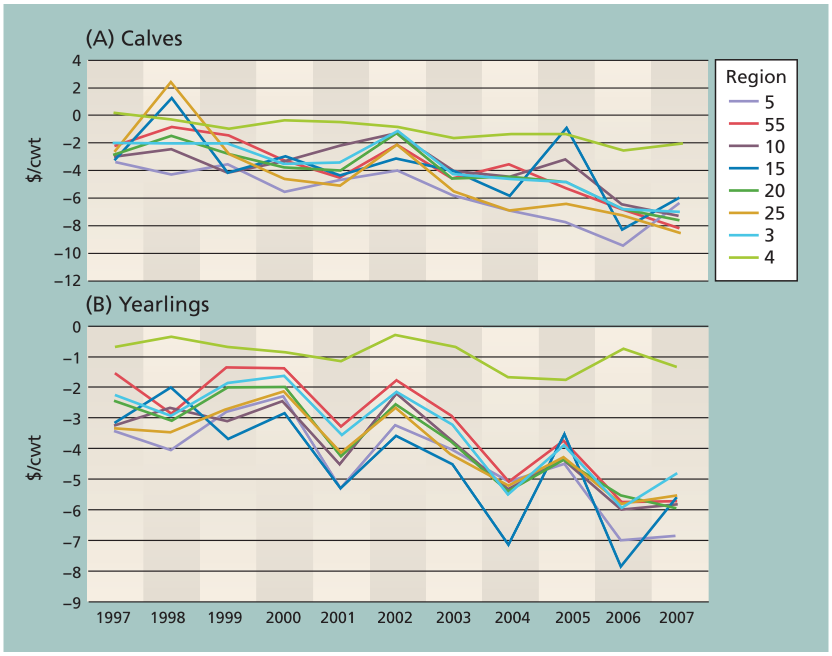

Fig. 2. Average regional price discounts (in deflated dollars), 1997–2007, relative to region 6, in each region each year. Prices were deflated using the Consumer Price Index with a base year of 1997 to eliminate inflation effects.

were adjusted for inflation by converting them into "real" terms using the Consumer Price Index, then the real discounts for each region were plotted over time (fig. 2). For both calves and yearlings, there was a clear downward trend, indicating that the discounts were indeed growing larger, on average, over time. Finally, the 11 annual observations for each region were regressed against a time trend, and for both calves and yearlings in nearly every region there was a statistically significant result. The average real increases per year in the discounts were about $0.35 to $0.77 per hundredweight for calves and about $0.29 to $0.39 per hundredweight for yearlings in the far western regions, but much less in region 4.

The bottom line for cattle ranchers is that the price received depends on the location relative to the buyer's location.

We found that mean price discounts increased over time, with transportation cost increases adding approximately $0.30 to $0.40 per hundredweight annually to the average discount to Western cattle producers, compared to their Midwestern competitors.

Value-added programs

In addition, we evaluated location and price effects of several value-adding programs (table 1). Reasons for not adopting these programs vary widely (Gillespie et al. 2007), and can include a rancher's unfamiliarity with a practice, nonapplicability of the program, cost and preference. Some programs became more popular from 1997 to 2007, whereas others grew and then faded. For example, preconditioning grew from a niche to the norm — in 1997, only 11% of calf lots and 17% of yearling lots sold were preconditioned, but by 2007 the market share had expanded steadily to 68% and 60%, respectively.

Natural beef. An interesting comparison is "natural beef," which means no implants, antibiotics or ionophores (another medication) are given to the animal, versus the use of implants (hormone delivery tools that stimulate growth). No calves were sold as "natural" until 1999, but lots of such calves increased slowly to 13% in 2003 before increasing rapidly to 38% in 2007; the pattern in yearling sales was similar, increasing from 1% in 1997 to 7% in 2003 and 28% by 2007. This uptrend in natural cattle approximately mirrors a downtrend in the use of implants. Forty percent calf lots and 65% of yearling lots were sold as implants in 1997, but those market shares declined steadily to 14% for calves and 47% for yearlings in 2007. Clearly, the two market segments view implants differently, with demand always higher for use with yearlings.

Market fads. Finally, a few value-adding programs were market fads that came and went quickly. One example is the industry's "Born and Raised in the USA" program (domestic born in table 1). It was created in response to the BSE (bovine spongiform encephalopathy or "mad cow" disease) events that adversely affected cattle prices early in this decade (Marsh et al. 2008), but disappeared as soon as the issue was resolved. The domestic-born program represented almost 9% of calf lots and just under 1% of yearling lots sold during 2003, but by 2004 only 1.5% of calves and no yearlings were sold. The program disappeared as the new USDA Country of Origin labeling program was being developed.

Program price premiums

Our study results indicate how much the average price received was affected by the presence of an attribute (table 1). Nearly all factors had a significant effect on calf and yearling prices. For example, calves that had not been weaned at the time of sale received an average price that was $3.59 per hundredweight less than calves weaned 30 days or longer. For yearlings, we found a $0.72 per hundredweight discount for cattle fed from hay lots only, compared to cattle fed on pasture only.

With regard to three value-adding factors — preconditioning, implants and natural beef — our results were similar to those of Blank et al. (2006) and consistent between the market segments for calves and yearlings. Preconditioning and natural beef each got a larger price premium during our study period than in Blank et al. (2006) for their shorter study period, while implanting programs again had no significant effect on prices over the entire 1997 to 2007 period (table 1).

The catalyst for these changes was the dynamics of a competitive market, with sellers responding to buyers product preferences. Buyers wanted preconditioned and natural cattle during the 1990s, but few sellers were aware at first, so few ranchers were supplying such animals to the market. Over time cattle ranchers learned of the new market demands and began supplying those products.

To see how cattle markets evolved with regard to value-adding programs, we estimated separate regression models for each of the 11 years for calves (table 4) and yearlings (table 5). The results show the volatility in cattle markets; no factor was statistically significant in every year. Due to the smaller number of observations (lots sold) each year, some factors had few significant annual results (tables 4 and 5) even though they had strongly significant results over the entire period (table 1).

ASV program. The age and source-verified program (ASV), in which the rancher submits written verification of the animal's age and genetic source, is an example of this problem. Calves received a statistically significant price premium averaging $5.31 per hundredweight overall (table 1), but had a significant result in only 1 of the 3 years the program had been available at the time of the study (table 4). For ASV yearlings the problem is similar, with only two of four annual results statistically significant (table 5). With hundreds of observations for calves and yearlings each year, ASV lots constituted 62.5% of calf sales and 36% of yearling sales in 2005, but the shares fell to less than 15% for both markets in 2007. The small number of ASV observations per year made it difficult to measure price effects in separate years, but it appears that producers did receive a premium, on average, from the program. Also, the current ASV program is much different than the one operating during our study.

Preconditioning. Annual results reflect the opposite trend compared to ASV, with preconditioning expanding during the study period to become the market norm (tables 4 and 5). With 68% of calves sold during 2007 being preconditioned, as well as 60% of yearlings, it appears that nonpreconditioned cattle are being discounted. For

TABLE 4. Price premiums for value-added calves

Year	n	R^2	Pre-conditioned	Implant	Not weaned*	Weaned < 30 days*	Age/ source-verified	CAB candidate	Natural
			· · · · · · · · · · nominal $ per hundredweight (cwt) · · · · · · · · · ·						
1997	171	0.66	0.77	0.58	−2.26	−2.93	na	3.88 ***†	na
1998	154	0.66	0.04	−0.06	−4.18	−0.92	na	2.24 *	na
1999	234	0.81	0.31	0.34	−1.72 ***	2.23	na	0.00	2.23 **
2000	347	0.74	1.42 ***	−0.20	−0.76 *	−0.38	na	1.52 *	0.68
2001	367	0.74	1.00 ***	0.56	−1.43 ***	1.57 *	na	1.53 ***	1.15
2002	331	0.67	0.56	−0.25	−3.53 ***	−2.49 *	na	1.77 ***	0.90
2003	450	0.80	0.96 ***	−0.63	−4.31 ***	−0.71	na	0.23	1.17 **
2004	529	0.65	0.40	0.19	−2.98 ***	−2.24 **	na	1.69 **	1.33 **
2005	542	0.65	0.62	0.47	−4.59 ***	−2.12 **	−0.10	1.33 **	0.69
2006	451	0.77	1.55 ***	−2.20 ***	−3.10 ***	−1.51	0.81	1.34 **	0.06
2007	540	0.76	0.92 **	−0.53	−1.32 ***	−0.22	1.58 ***	2.71 ***	0.25

* Discounts for weaning factors based on prices for cattle weaned 30 days or longer.

† Values statistically significant (different than zero) when indicated by *, ** or *** (90%, 95% or 99% confidence level, respectively).

na = not available; no observations in the year.

TABLE 5. Price premiums for value-added yearlings

Year	n	R^2	Pre-conditioned	Implant	Hay lot only*	Pasture and lot*	Age/ source-verified	CAB candidate	Natural
			· · · · · · · · · · nominal $ per hundredweight (cwt) · · · · · · · · · ·						
1997	234	0.58	0.28	−0.66 **†	0.07	−0.51	na	−0.88	1.94
1998	345	0.72	1.00 ***	−0.27	1.37 ***	−3.63 *	na	0.92 *	0.63
1999	373	0.77	0.33	−0.37 *	−0.05	0.68	na	0.44	1.16 **
2000	424	0.56	0.22	−0.25	−1.28 ***	−1.00 **	na	0.61	0.42
2001	455	0.72	0.67 ***	−0.02	−2.39 ***	−0.48	na	0.21	0.19
2002	457	0.66	0.36	−0.28	2.77 ***	0.58	na	0.47	−0.46
2003	506	0.90	0.33	−0.89 ***	1.87 ***	0.94	na	1.16 ***	1.46 ***
2004	554	0.69	−0.25	−1.06 **	−6.69 ***	−5.02 ***	6.28	1.04	6.32 ***
2005	641	0.70	−0.12	−0.34	−2.02 ***	0.03	0.86 ***	0.74 *	2.58 ***
2006	568	0.59	0.45	−0.04	−0.09	−0.47	−1.39 ***	2.78 ***	3.56 ***
2007	590	0.82	−0.08	−0.79 ***	−2.54 ***	0.87	−0.20	1.53 ***	1.58 ***

* Premiums/discounts for two feeding factors based on prices for cattle that have been in pasture only.

† Values statistically significant (different than zero) when indicated by *, ** or *** (90%, 95% or 99% confidence level, respectively).

na = not available; no observations in the year.

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Sales data confirm that the farther away cattle are from the Midwest, the less money ranchers receive per animal. Western ranchers are essentially paying to transport cattle for finishing and slaughter. *Above*, Alfonso Casillas loads yearlings at the end of winter grazing season on the Meyers Ranch in the hills above Union City.

example, there was a price premium for preconditioning calves, but it was statistically significant in only 5 of the 11 years (table 4). With the small number of nonpreconditioned lots sold in some years, it was not possible to clearly detect how much market price was affected. This problem was even stronger for yearlings, where only 2 of 11 years had a statistically significant premium for preconditioning (table 5), ranging from $0.92 to $1.55 per hundredweight for calves and $0.67 to $1.00 per hundredweight for yearlings. However, over the entire data period preconditioning clearly brought ranchers an average premium of $1.37 per hundredweight for calves and $1.03 per hundredweight for yearlings.

Certified Angus Beef. Good statistical results were found for Certified Angus Beef (CAB) candidates, for which the rancher must provide written certification that the animal is pure Angus. Blank et al. (2006) did not evaluate this factor, but we added it to account for what appears to be a strong market preference (Jones et al. 2008). There were CAB candidate premiums for both calves and yearlings (table 1), but calves had statistically significant premiums in 9 of the 11 years (table 4) while yearlings had statistically significant premiums in only 5 of the 11 years (table 5). The conclusion that cattle markets preferred the Angus breed over the study period is supported by the results for other breeds (table 1), which received price discounts relative to Angus cattle, on average.

Weaning and natural beef. Our study confirmed and expanded on the results of Blank et al. (2006) regarding two characteristics that received a price premium over the data period. First, our analysis gave similar results for calves, showing that unweaned cattle are discounted an average of $3.59 per hundredweight (table 1). However, increasing the length of time since weaning on the sale date did not always increase average prices further.

In our analysis, calf lots were divided into three categories: weaned the day of sale (“weaning 0”), weaned less than 30 days before sale (“weaning 1”) and weaned more than 30 days before sale (base group). In general, our results showed that the premium varied from one year to the next (table 4), but was statistically significant each year beginning in 1999.

We extended a similar analysis to yearlings and found that cattle fed from hay lots are discounted compared to those fed in pastures (table 1). Ranchers have hypothesized that yearlings purchased off grass pastures have more compensatory gains than yearlings in hay lots. To test this we divided yearling lots into three groups: those coming off pasture only (base group), hay lots only (“feed 1”) and both pasture and hay lots (“feed 2”). Yearlings fed in hay lots only were discounted in 8 of the 11 years (table 5).

Second, calves and yearlings that met the natural beef program requirements received a statistically significant premium, on average, but the premium’s size and price was larger for yearlings than for calves (tables 4 and 5). This is consistent with prior studies (Boland and Schroeder 2002). Also, industry participants note that it is more difficult for cattle to remain “natural” as they advance through production (Brad Peek, Western Video Market, personal communication, Oct. 3, 2008).

Photos: Western Video Market

Western Video Market of Cottonwood, Calif., supplied 11 years of data on their sales of calves and yearlings. To compensate for location discounts, Western ranchers have adopted value-adding practices such as preweaning, vaccination programs and natural production.

In the future, natural beef premiums and their amounts will depend on competitive responses within the cattle market. If buyers continue to expand their demand for natural beef, price premiums will continue. However, as ranchers provide increased supplies of natural beef to the market, this natural niche may become the norm, and premiums will be competed away. This may already be occurring for calves, as indicated by price premiums in recent years. On the other hand, natural beef is still very much a niche for yearlings, as indicated by the larger and statistically significant premiums in recent years.

Cattle market structure

In the future, the existence of location discounts and their amounts will continue to depend upon the cattle market structure. As long as most feedlots and meat processing facilities are located in the Midwest, calves and yearlings raised in California will be sold at a price discount and shipped out of state.

This leaves ranchers in California and other Western states with few ways to raise the average price recieved other than value-adding innovations, such as weaning calves before they are sold, or by using natural production methods for calves and yearlings. These factors can result in higher average market prices. However, ranchers will have to determine for themselves whether the associated costs are lower than the price benefits.

Beef producers are moving toward more standard use of preconditioning programs involving more value-adding use of vaccinations, and buyers are beginning to reflect consumers' preferences for cattle that are free of rancher interventions. The Western cattle industry's future may involve discovering new market trends and quickly changing practices to produce a profitable niche product.

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