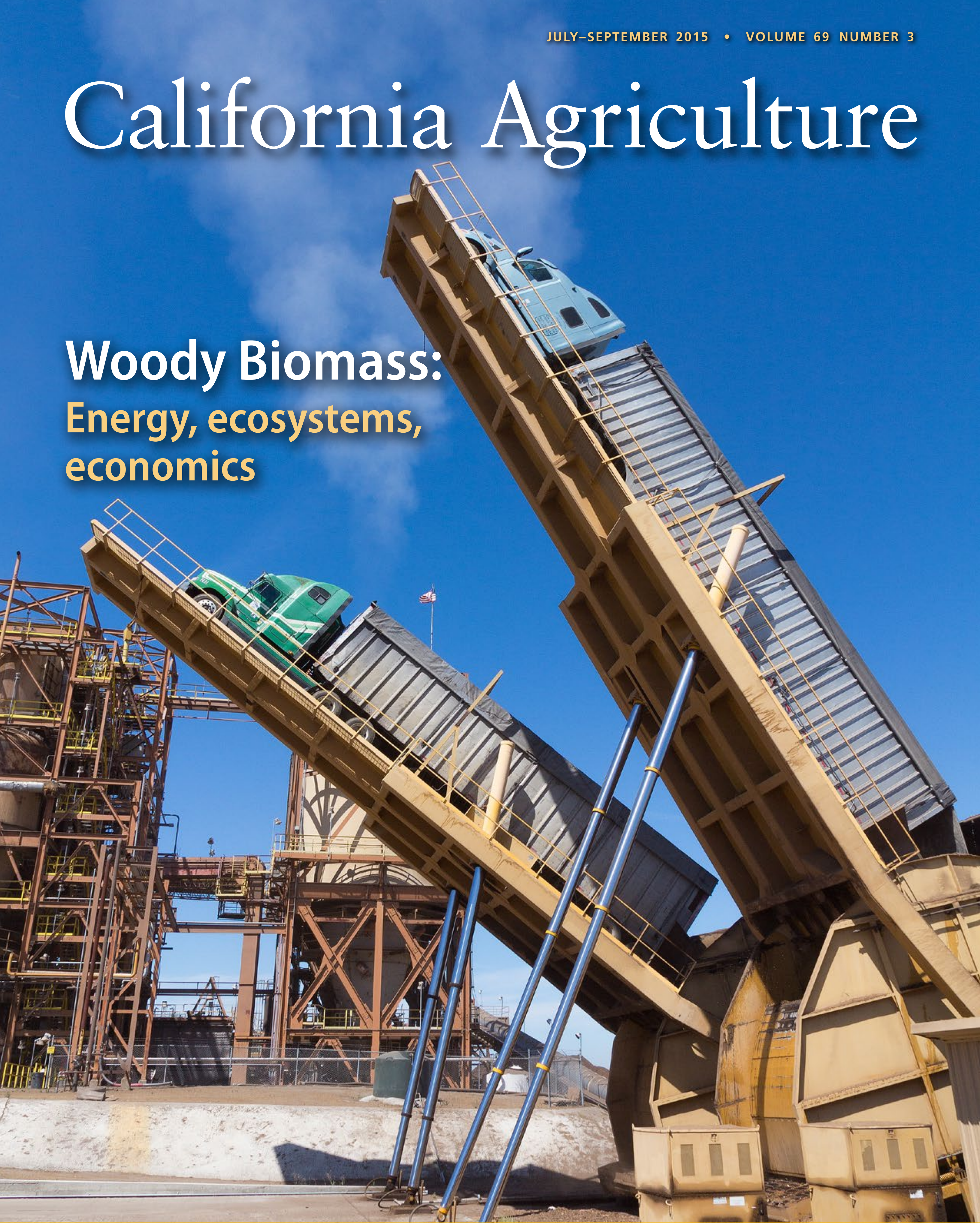
JULY–SEPTEMBER 2015 • VOLUME 69 NUMBER 3

# California Agriculture



## Woody Biomass:
### Energy, ecosystems, economics

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

# About *California Agriculture*

University *of* California
Agriculture and Natural Resources

*California Agriculture* is a quarterly, peer-reviewed journal reporting research and reviews, published by the University of California Agriculture and Natural Resources (ANR). The first issue appeared in 1946, making *California Agriculture* one of the oldest, continuously published, land-grant university research journals in the country. There are about 11,000 print subscribers.

**Mission and audience.** *California Agriculture* publishes refereed original research in a form accessible to a well-educated audience. In the last readership survey, 33% worked in agriculture, 31% were university faculty or research scientists, and 19% worked in government agencies or were elected office holders.

**Electronic version of record.** In July 2011, the electronic journal became the version of record; it includes printed and electronic-only articles. When citing or indexing articles, use the electronic publication date.

**Indexing.** The journal is indexed by AGRICOLA, Current Contents (Thomson ISI's Agriculture, Biology and Environmental Sciences and the SCIE databases), Commonwealth Agricultural Bureau (CAB), EBSCO (Academic Search Complete), Gale (Academic OneFile), Proquest and others, including open-access databases. It has high visibility on Google and Google Scholar searches. All peer-reviewed articles are posted to the ANR and California Digital Library eScholarship repositories. In the 2015 Thomson JCR, the journal's 5-year impact factor was 1.02.

**Authors and reviewers.** Authors are primarily but not exclusively from ANR; in the past 2 years, 25% were based at other UC or CSU campuses, in government agencies or at other universities and research institutions. In the same period, 39% of reviewers came from outside ANR.

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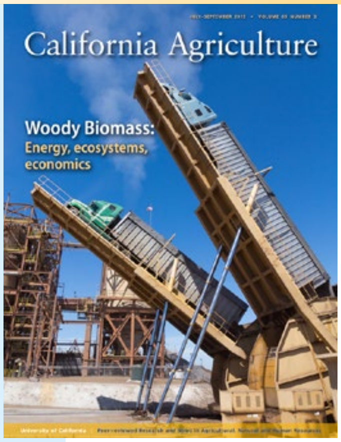



**COVER:** Truck tippers empty chip vans filled with woody biomass to fuel the Buena Vista Biomass Power facility near Ione (Amador County). *Photo by Will Suckow*.

## Woody Biomass: Energy, ecosystems, economics

### News departments



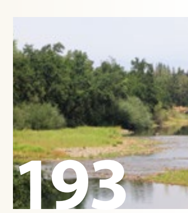
### Research and review articles



### E-edition review article

This article can be found in full on the *California Agriculture* website; for a summary and link, see page 191.






### Editors' note:

*California Agriculture* gratefully acknowledges the faculty chairs for this special issue: John Shelly, UC ANR Cooperative Extension Advisor, and Peter Tittmann, Academic Coordinator, Woody Biomass Utilization Group, UC Berkeley.

### Correction

On page 78 of the April-June 2015 issue, fig. 1 contained incorrect information in the bottom box at the far left. The corrected text reads as follows:

$K_{sat} > 42$ mmhr$^{-1}$

# Healthy landscapes will help California to mitigate and adapt to climate change

Climate change poses a real and pronounced threat to California's landscapes, people and economy. Frequent and wide-ranging wildfires, eroding coastlines, decreasing snowpack and increasing temperatures all affect our lifestyles, health and happiness. Tourists will come to know California as a state on fire with no winter and no water.

**Ashley Conrad-Saydah**

Deputy Secretary for Climate Change and Energy Policy, California Environmental Protection Agency

Recognizing both the incontrovertible scientific evidence that human-caused greenhouse gas emissions affect California and the understanding that human action can make a difference to slow the trend, Gov. Jerry Brown stated in a 2011 speech that "it's time for courage, it's time for creativity and it's time for boldness to tackle climate change." Through executive orders, he set the nation's most ambitious mid-term target for climate mitigation — a 40% reduction in greenhouse gas emission reductions by 2030 — and issued goals to reduce greenhouse gas emissions in our energy, transportation, building and natural resource sectors.

These directives and principles inspire transformation in the way we live, do business, play and move around the state. The goals will prepare us for the future by driving technological innovation, spurring job growth in emerging economic sectors and supporting scientific discovery to rapidly decrease climate-disrupting emissions.

California's landscapes — among them our forests, rangelands, agricultural lands, wetlands, deserts and grasslands — represent one of the best areas for investment to address climate change.

In working to reduce greenhouse gas emissions in all landscapes, we simultaneously receive the benefits of keeping more carbon in those landscapes and safeguarding habitats to survive climate change. These landscapes also provide countless other ecosystem services — erosion control, water quality, water supply, recreation, habitat for fish and wildlife and many more.

To reap the variety of benefits healthy landscapes confer, we must invest in California's lands now. We must set ambitious targets for improving the management of the state's landscapes, and to achieve those targets we must allocate financing that is commensurate with the services these landscapes provide.

Much of California's 30 million-plus acres of forestland is stressed by drought, attacked by pests and recovering from or currently besieged by fire. For decades, our forests have been managed to avoid or suppress fire, rather than to allow a natural fire regime to occur.

Policymakers and scientists are working together to understand the existing and future condition of forests and to develop management actions that will help protect and transition those forests for the future, allowing them to sequester carbon and fight climate change. We are considering a range of activities: pest control and removal of infested trees; thinning to produce sparser forests with a mix of species and ages of trees; prescribed fire; and partnering with communities to develop small-scale wood products and biomass-energy facilities that will engender greater economic security and energy independence in rural California. We know that the policies employed must match the needs of those living in the wildland-urban interface and the specific forest types. We also know that the patchwork of private, tribal and public land management or ownership necessitates dedicated capacity building and engagement.

Designing the management vision is only one part of the solution. Funding the implementation of the vision is a big part of the challenge. Partnerships between public agencies, philanthropic organizations and landowners themselves will allow us all to invest in our critical forests. The state is working to secure funding from the federal Housing and Urban Development agency to implement an innovative community and watershed resilience plan in Tuolumne County. The Sierra Nevada Conservancy and the United States Forest Service are working on a pilot of the Watershed Improvement Program in Tahoe National Forest. And state and federal agencies are developing a Forest Carbon Plan, set for publication in 2016, to detail the implementation process to sequester measurable carbon in our state's forests and help meet Gov. Brown's ambitious climate goals.

Reaching these goals will require a shift in our behavior and in our understanding of forests. Through support of a sustainable and appropriately sized wood products industry, coupled closely with smaller-scale community energy and smart infrastructure growth, we can work towards a healthier, vibrant future for forests and people. By prioritizing the existence and vitality of these lands, we can ensure their health and services for generations of Californians and visitors to come.

# The wood in the forest:
## Why California needs to reexamine the role of biomass in climate policy

Peter Tittmann, Academic Coordinator, Woody Biomass Utilization Group, Center for Forestry, UC Berkeley

**In California, the forestry sector and biomass energy producers have the potential to work together to reduce the state's net greenhouse gas emissions, reliably generate renewable electricity, provide low-carbon building materials, support healthy forests and improve air quality.**

**But wood energy producers are in a precarious position. Without quick policy changes, much of the state's remaining biomass power plant capacity will soon be shut down. Roughly half of the power plants in the state that run on woody biomass are operating under power supply contracts set to expire by the end of 2016. Under current policies, it is likely that utilities will not offer new contracts at rates sufficient to cover the costs of operating these biomass plants.**

The biomass energy sector's predicament stems in part from an otherwise positive development — the rapid expansion of low-cost solar photovoltaic power in California (fig. 1). Under California's Renewables Portfolio Standard (RPS), one-third of the electricity provided by the state's utilities must come from renewable sources by 2020. To meet these goals, utilities must contract with renewable power producers such as solar power installations, wind farms or biomass power plants.

The price of electricity is a major factor in utilities' power procurement decisions. As the price of power from new solar installations has dropped — it's now in the range of 3 to 5 cents per kilowatt-hour less than what biomass plants can offer — utilities have little incentive to renew contracts with existing biomass power plants on terms that will allow the plants to stay open.

But this simple price comparison misses two important factors. First, by incentivizing better forest management and improved forest health, biomass energy leverages considerable climate and other environmental benefits beyond the direct reductions in carbon emissions from generating electricity from a renewable resource. Second, biomass power plants provide consistent "base load" power output. Solar, by contrast, delivers intermittent power that declines in the afternoon as the demand for power peaks, complicating the management of the grid and requiring the operation of natural gas-fired "peaker" plants. This intermittency adds significant costs to the operation of the state's power system that are not reflected in solar power's low market price, but are passed on to ratepayers.

### Forestry and climate change

The role of forests in climate change mitigation might seem simple: as trees grow, they remove

The Buena Vista Biomass Power facility near Ione (Amador County) generates up to 18 megawatts of electricity from a mix of forest slash, urban green waste and woody biomass generated by farms.

Will Suckow

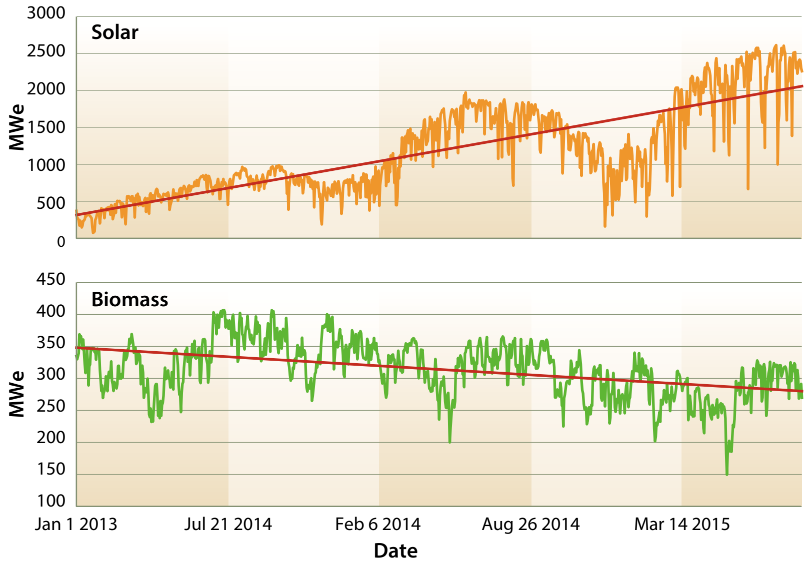



**Fig. 1. Daily average power records from the California Independent System Operator show the recent increase in solar power and decrease in biomass power on the state's electricity grid. Data may include out-of-state generation.**

carbon from the atmosphere and store it into their trunks, branches, roots and leaves. Simply protecting forests from agents that kill trees (insects, say, or wildfire) would appear to be a reasonable strategy to ensure that forests deliver their carbon benefit.

In reality, the role of forests in capture and storage of carbon is more complicated. According to state and federal estimates, the living trees in California's forests hold the equivalent of between 3 and 4 billion tons of carbon dioxide — around eight times the state's total annual emissions of all greenhouse gases. Maintaining or expanding this vast stock, however, depends on forests remaining healthy.

Nearly a century of wildfire suppression, in combination with the warming climate, has dramatically elevated the risk of high intensity wildfire across much of the state's forestlands. The role of fire in California's forests is similar to that of a dentist: just as frequent cleanings prevent major dental problems, so do frequent low-intensity fires prophylactically protect forest health. By consuming dead or dying trees and dead material on the forest floor, small fires reduce fuel load and thus the risk of extreme fire. Unfortunately, across much of California and the rest of the western United States, the now century-old policy of wildfire suppression has resulted in infrequent and catastrophic fire.

Some of the strongest opposition to thinning forests to reduce the fuel load comes from a few of the state's most prominent environmental groups. These groups oppose bioenergy uses of forest biomass on the grounds that catastrophic, stand-replacing fires are desirable because they leave the forest in a condition that may benefit certain species. Their opposition takes two main forms: lobbying state and federal legislators to further limit the ability of land management agencies and private landowners to actively prevent catastrophic wildfire through forest thinning and stand improvement; and pursuing legal action against community organizations' efforts to build small-scale, distributed power plants that would create markets for the limbs, brush and small trees that are thinned in the process of fire hazard reduction. Advocacy for increased levels of stand-replacing fire represents an implicit willingness to accept the impact of increased greenhouse gas emissions and lost sequestration in forests from catastrophic wildfire — the consequences of which will fall disproportionately on poor people in faraway places and residents of rural forested communities in California — as the necessary collateral to expanding the range of a particular species of interest.

Biomass power plants create a market for small trees, limbs and treetops — or what people in forestry call "slash" — generated by forest management operations such as fire hazard reduction treatments. However, the cost

U.S. Forest Service

**The Gasquet Complex Fire, which was caused by lightning in the Six River National Forest in California on Jul. 31, had consumed over 30,000 acres as of Sep. 14.**


Forest slash is piled following a thinning treatment at the UC Blodgett Forest Research Station in El Dorado County.

of conducting such treatments generally far exceeds what power plants are willing to pay for biomass fuel. Thus, while revenue from selling slash to power plants helps land managers by offsetting a portion of forest treatment costs, it does not provide a profit motive for increasing extraction of biomass from forests simply to supply power plants.

Fire hazard reduction treatments with chainsaws and forestry machines can mimic the effect of low-intensity wildfires, the kind that would have moved frequently through much of the state's forestland pre-settlement, burning smaller trees and brush but leaving larger trees alive. Such treatments can reduce fuel loads to a level that can then be maintained through low-intensity, prescribed natural fires overseen by firefighters and fire professionals. Without a biomass energy market for slash, fewer acres can be treated with the limited funds for fire hazard treatments available to land managers. In the absence of a biomass market, there is little to do with slash but to pile and burn it, erasing the climate benefit of using the biomass to generate electricity and resulting in substantial emissions of particulate matter and other air pollutants. Leaving slash on the ground, or avoiding thinning operations altogether, allows the buildup of fuels to continue and leaves the forest increasingly prone to severe fire.

In addition to natural sequestration from tree growth, a healthy forest sector contributes to meeting the state's climate goals by providing wood to California consumers. Wood's strength-to-weight ratio makes it widely appealing for use in construction. Wood is the product of photosynthesis — the metabolic sequestration of atmospheric carbon dioxide over the lifespan of a tree — and as a result, has dramatically less net greenhouse gas emissions associated with its use than other building materials used in similar applications such as concrete, steel and plastics. For example, using engineered-wood I-beams for floor joists rather than steel I-beams reduces lifecycle greenhouse gas emissions by more than 9 kilograms of carbon dioxide per kilogram of wood fiber used. Thus, increasing the use of wood and wood-derived products where economically feasible will have significant long-term climate impacts at relatively low cost. Right now, most of the wood used for construction in California is not grown in California. And yet, California has some of the most rigorous standards governing timber harvests in the world. Californians should be building their homes and businesses with wood grown and harvested responsibly in their own state rather than importing wood grown in other parts of the world where California's rigorous forestry rules do not apply.

The ability for California's forest landowners to generate revenue by producing wood and forestry

A forwarder collects forest slash for chipping at the U.S. Forest Service's Yeti Fuels Reduction project near Lake Tahoe.

byproducts also provides an economic buffer against conversion of timberland to other, less carbon-dense land uses such as residential development or agriculture.

## Wood bioenergy: Low-hanging fruit for climate gains

The production of electricity from wood biomass is an opportunity for low-cost, high-return climate change mitigation investment and policy. Biomass used in the state's existing fleet of biomass power plants can displace base load electricity generated by natural gas, coal or petroleum coke. Using wood to produce energy also helps to reduce the risk that carbon stored in the state's forests will be lost to fire and disease, and reduces emissions of particulate matter and black carbon from open pile burning of agricultural and forestry residues.

Other uses of forest biomass, such as conversion to biofuels or powering small-scale bioenergy plants — 3 megawatts electric (MWe) capacity or less — are promising. However, compared with the existing fleet of biomass power plants, these pathways are substantially more costly and have yet to be financed and constructed.

There has been extensive debate over the net greenhouse gas benefits that can be expected by generating electricity from forest biomass, and the consensus is clear: bioenergy production using residuals from forests managed for sustained yield reduces long-term climate impact through displacement of fossil energy sources, reduced emissions from the alternative (non-energy-producing) fates of forestry residuals, and continued sequestration from forest growth.


**A heel boom log loader feeds a chipper, which fills a chip van at the Yeti Fuels Reduction project near Lake Tahoe. Kirk Furlong-Wentworth of CTL Forest Management, Inc. monitors the job.**


**A mound of woody biomass at Buena Vista Biomass Power near Ione (Amador County).**

California's biomass-fueled power generation industry grew rapidly from the 1980s through the mid-1990s. At the peak, close to 1,000 MWe were installed and operational. These plants, ranging in size from 7 to 50 MWe, were typically built either alongside lumber mills — so as to utilize sawdust and off-cuts from the mill and logging slash produced from harvesting — or as stand-alone plants, utilizing the wood fraction of urban waste streams (construction debris, tree prunings, etc.) and wood from orchard removals or other agricultural activities. In most cases, these plants serve the dual purposes of producing electricity and providing an alternative to incineration or landfilling of forestry, agriculture and municipal biogenic waste. In this way, the biomass energy industry has facilitated air quality improvements, landfill diversion and forest health.

Today, there is roughly 962 MWe of installed capacity for biomass power production in California. But much of that capacity is not being used to generate energy (see map on facing page). The California Independent System Operator reports a substantial reduction in electricity produced from biomass in recent years. In the current period beginning 2013, close to 100 MWe of capacity has been idled in California and annual average generation has fallen by 57 MWe (table 1). Based upon interviews with plant operators and fuel buyers, approximately 30 MWe of additional capacity is very likely to be taken offline by the end of 2016. Plant idling is most often a result of a change in the price a utility is willing to pay to a generator.

## Valuing the benefits of biomass electricity generation

The price differential between solar and biomass and the resulting decline in the biomass power industry highlights a key gap in California's climate policies. The many public benefits provided by

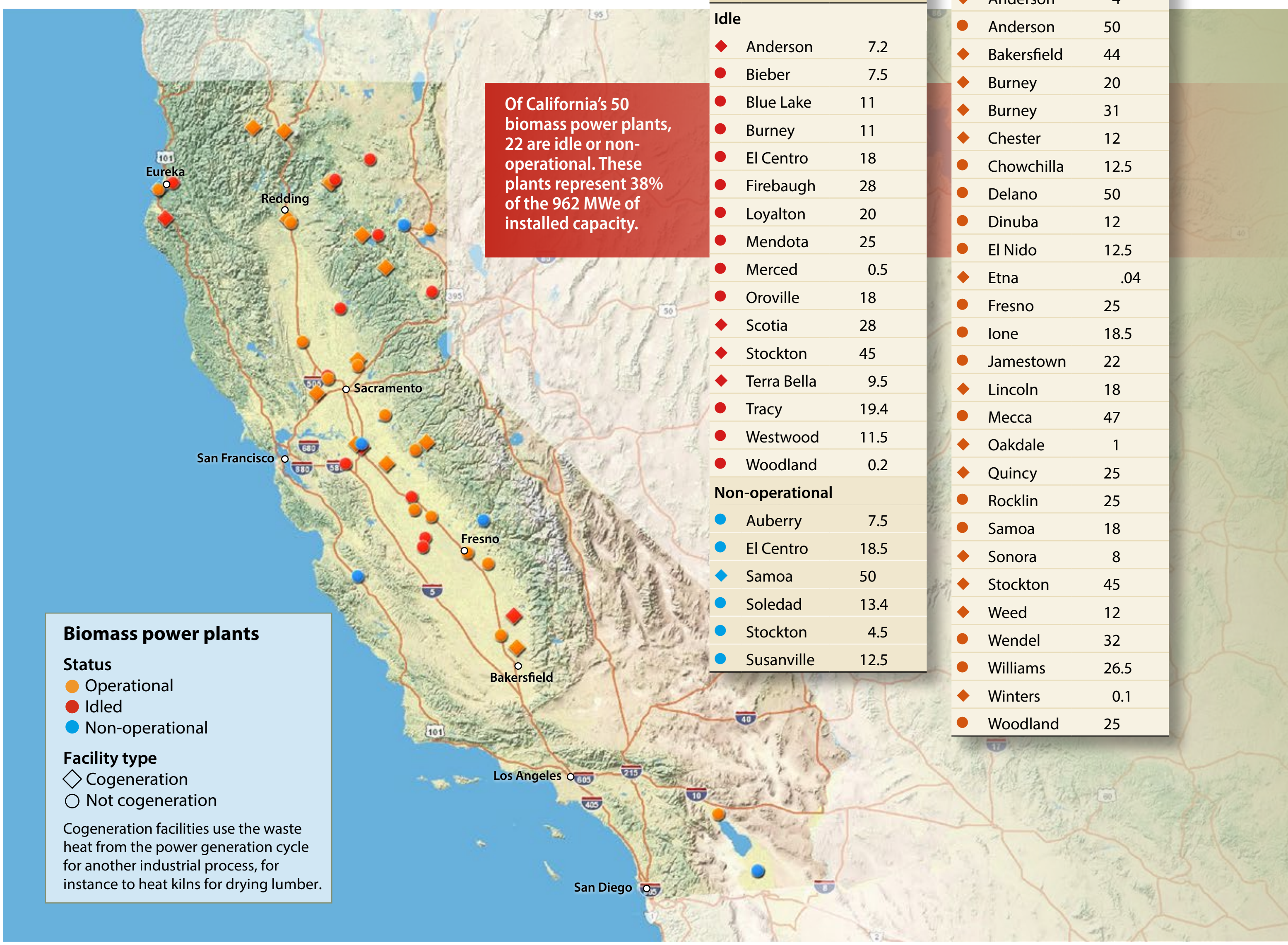
**TABLE 1. Annual average electricity on the California Independent System Operator grid from biomass, 2012–2016**

| Year | Annual average MWe* |
|---|---|
| 2012 | 326.6 |
| 2013 | 336.6 |
| 2014 | 315.3 |
| 2015 | 279.6 |

* May include out-of-state generation.

biomass power plants are not monetized through the existing RPS procurement strategy. Competition among renewable power sources based solely on the price of electricity risks missing a key opportunity for the state to use biomass energy generation to leverage major carbon benefits through better forest health, reduced fire risk and a sustainable forest products sector.

Forests will play a central role in meeting the state's goals for reducing greenhouse gas emissions both through sequestration and through the responsible use of wood in place of materials and energy sources with much greater climate impact. Forests can be used to help produce alternative energy without losing their intrinsic value to us as humans as beautiful, wild places. We can turn wood waste into electricity without compromising the ability of our forests to provide essential habitat to the wide range of animal, bird and insect species that depend on them. Bioenergy is a critical component of ensuring forest health now and in California's future. CA




**Of California's 50 biomass power plants, 22 are idle or non-operational. These plants represent 38% of the 962 MWe of installed capacity.**

**Idle and non-operational biomass power plants in California**

| | City | Capacity (MWe) |
|---|---|---|
| **Idle** | | |
| ◆ | Anderson | 7.2 |
| ● | Bieber | 7.5 |
| ● | Blue Lake | 11 |
| ● | Burney | 11 |
| ● | El Centro | 18 |
| ● | Firebaugh | 28 |
| ● | Loyalton | 20 |
| ● | Mendota | 25 |
| ● | Merced | 0.5 |
| ● | Oroville | 18 |
| ◆ | Scotia | 28 |
| ◆ | Stockton | 45 |
| ◆ | Terra Bella | 9.5 |
| ● | Tracy | 19.4 |
| ● | Westwood | 11.5 |
| ● | Woodland | 0.2 |
| **Non-operational** | | |
| ● | Auberry | 7.5 |
| ● | El Centro | 18.5 |
| ◆ | Samoa | 50 |
| ● | Soledad | 13.4 |
| ● | Stockton | 4.5 |
| ● | Susanville | 12.5 |

**Operational biomass power plants in California**

| | City | Capacity (MWe) |
|---|---|---|
| ◆ | Anderson | 4 |
| ● | Anderson | 50 |
| ◆ | Bakersfield | 44 |
| ◆ | Burney | 20 |
| ◆ | Burney | 31 |
| ◆ | Chester | 12 |
| ● | Chowchilla | 12.5 |
| ● | Delano | 50 |
| ● | Dinuba | 12 |
| ● | El Nido | 12.5 |
| ◆ | Etna | .04 |
| ● | Fresno | 25 |
| ● | Ione | 18.5 |
| ● | Jamestown | 22 |
| ◆ | Lincoln | 18 |
| ● | Mecca | 47 |
| ◆ | Oakdale | 1 |
| ◆ | Quincy | 25 |
| ● | Rocklin | 25 |
| ● | Samoa | 18 |
| ◆ | Sonora | 8 |
| ◆ | Stockton | 45 |
| ◆ | Weed | 12 |
| ● | Wendel | 32 |
| ● | Williams | 26.5 |
| ◆ | Winters | 0.1 |
| ● | Woodland | 25 |

## Research news

# New UC ANR working group to address residual material from anaerobic digesters

**Anaerobic digestion is an increasingly popular waste management strategy in California, with over 200 facilities operating and more under construction.**

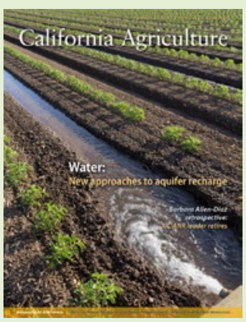
**Anaerobic digesters use microbes to break down organic wastes, including biosolids in treated wastewater, lawn trimmings, food wastes and manure. The digestion process produces methane-rich biogas, which can then be captured and used to generate electricity or power vehicles.**

The residual solids and liquids left over after digestion is complete are known as digestates. As the anaerobic digestion sector has grown, so has the need for a coordinated strategy to manage these digestates.

Since they are rich in nutrients and organic matter, digestates are potentially valuable as soil amendments. But their composition can vary considerably and their performance has not been well documented. Better information about digestates and their potential uses could promote the development of markets for the materials, which would in turn help make digester facilities more financially sustainable by replacing digestate disposal costs with revenue opportunities.

To facilitate the beneficial use of digester residuals, Stephen Kaffka, a UC ANR Cooperative Extension

## Letters



April–June 2015

**Re: O'Geen et al., "Soil suitability index identifies potential areas for groundwater banking on agricultural lands," *California Agriculture* 69:75-84:**

I believe we should also consider old approaches that at the time weren't considered aquifer recharge, but water wasted to the ground. Being raised in the Central Valley, I remember many a hot day spent swimming in cool canals carved into the soil. Then I observed the conversion of nearly all dirt-lined canals to concrete-lined canals, mostly in the name of water conservation. While probably reducing maintenance needs, this also eliminated miles (and acres) of recharge surfaces. If we could return lined canals back to earthen canals, this "old" approach could expand recharge across many portions of the state crisscrossed with canal systems. Furthermore, if the purpose of canal management could be expanded from water delivery conveyances to include water storage (i.e., kept watered year-round except during periods of maintenance), there might be enough water stored in them to obviate the need for new a reservoir or two.

Brad Valentine
Santa Rosa

I found the concept behind the article — artificial infiltration and accelerated recharge — fascinating.

Resource management looks at stormwater as an economic resource. In the climate upheavals to come, the predictions are for sudden, massive storms that shorten the infiltration intervals. The kind of flood infiltration talked about in the article tends to this direction.

I think we do need to design farms for recharge rather than drainage. Sustainable design aims at preserving the structure and function of the natural water cycle, including groundwater recharge, despite an unstable climate. Ecology tends to look at the structure and function of the natural world, and how best to preserve natural cycles is a high priority of sustainability. But this is a difficult, if not impossible, task that challenges the best of us. We need to know the natural recharge capacity of the land, and derive a realistic threshold value for recharge — what nature would do had the land remained wild and unconverted to farmland. "Ecological farming" strains my imagination, because I am not an ecologist — but I wonder if we couldn't model natural thresholds in the the same manner as this article models artificial recharge.

Bud Hoekstra
Glencoe

## RSVP

**WHAT DO YOU THINK?**

The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at: 2801 Second Street, Room 184, Davis, CA 95618, or calag@ucanr.edu. Include your full name and address. Letters may be edited for length and clarity.

(UCCE) agronomist at UC Davis, and David Crohn, a UCCE specialist at UC Riverside, are organizing a new working group of more than a dozen UC ANR researchers and private-sector collaborators.

The group seeks to characterize different organic amendments and fertilizer products created from digested materials as well as to analyze and compare their performance for a wide range of agronomic and horticultural uses. Results will be made public and the information used to support the development of in-state markets for fertilizer and soil amendment products for diverse uses, as well as to develop recommendations for their safe and effective use.

The newly forming group involves academic, industry and regulatory agency participants, and is currently applying for funding through the state Department of Food and Agriculture and other sources. Kaffka and Crohn said participation by any interested ANR researchers, campus-based scientists or anaerobic digestion industry participants would be welcome.

Ruihong Zhang

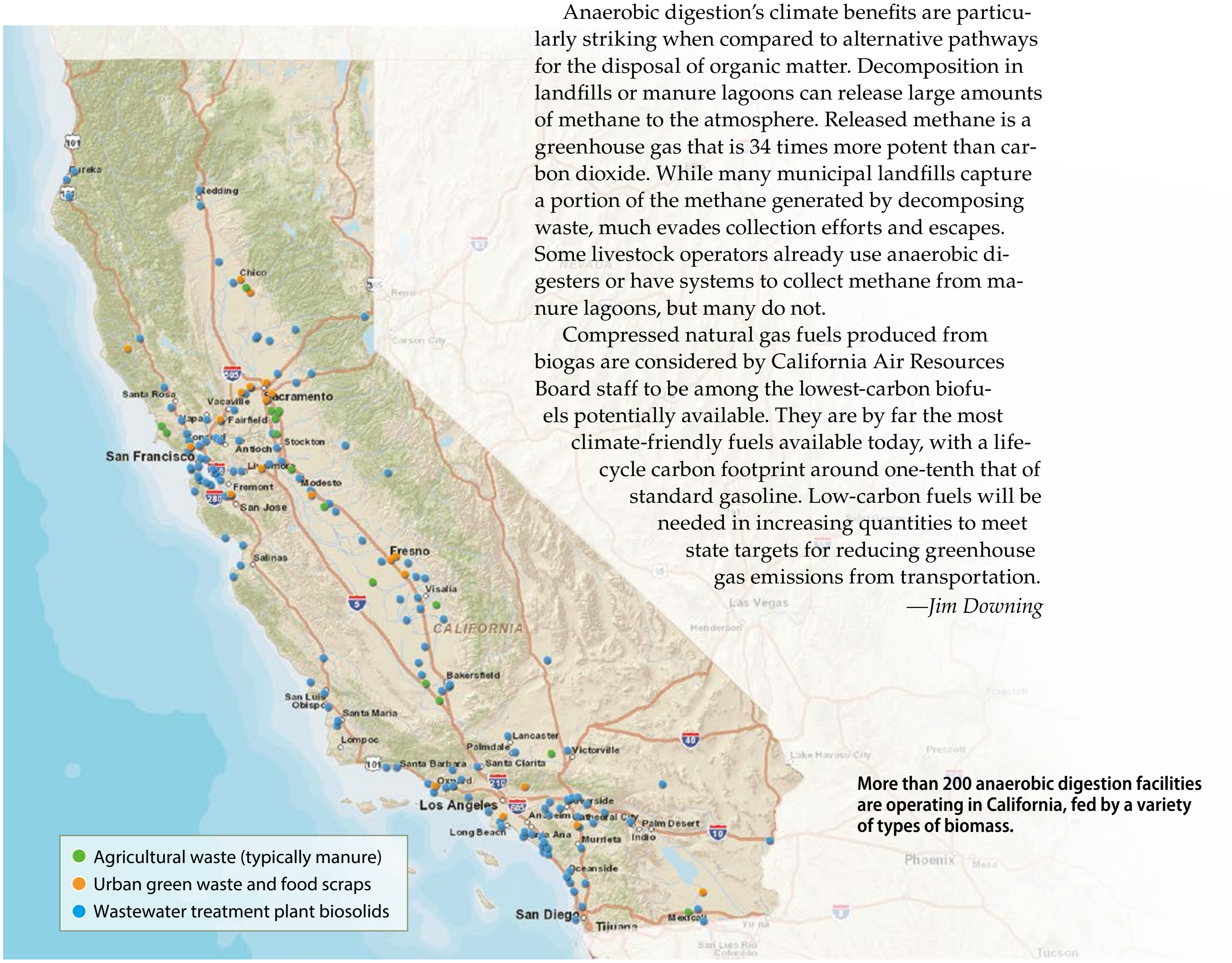
On the UC Davis campus, anaerobic digesters break down food waste and manure and generate biogas.

The nature of the anaerobic digestion process positions the technology well to contribute to reaching state goals for diverting organic wastes from landfills and reducing greenhouse gas emissions.

Anaerobic digestion's climate benefits are particularly striking when compared to alternative pathways for the disposal of organic matter. Decomposition in landfills or manure lagoons can release large amounts of methane to the atmosphere. Released methane is a greenhouse gas that is 34 times more potent than carbon dioxide. While many municipal landfills capture a portion of the methane generated by decomposing waste, much evades collection efforts and escapes. Some livestock operators already use anaerobic digesters or have systems to collect methane from manure lagoons, but many do not.

Compressed natural gas fuels produced from biogas are considered by California Air Resources Board staff to be among the lowest-carbon biofuels potentially available. They are by far the most climate-friendly fuels available today, with a lifecycle carbon footprint around one-tenth that of standard gasoline. Low-carbon fuels will be needed in increasing quantities to meet state targets for reducing greenhouse gas emissions from transportation.

*—Jim Downing*




More than 200 anaerobic digestion facilities are operating in California, fed by a variety of types of biomass.

# UC Global Food Initiative:

## UC ANR student fellows work on food insecurity, food communication and developing the next generation of Cooperative Extension experts

**The UC Global Food Initiative (GFI), launched by UC President Janet Napolitano in July 2014, is a systemwide effort to address food security, health and sustainability through coordinated work across the 10 campuses, UC Agriculture and Natural Resources (UC ANR) and Lawrence Berkeley National Laboratory. The GFI targets food systems at all scales, from the local to the global, and aims to drive changes that will help to sustainably and nutritiously feed a world population of 8 billion by 2025.**

Among the first programs funded through the GFI was a fellowship program for UC students. In December 2014, Napolitano announced the 54 winners, each of whom received a $2,500 stipend. UC ANR's three GFI student fellows have worked on projects this year with researchers or staff in the division.

**Jacqueline Chang**, who graduated in May from UC Berkeley with a degree in nutritional sciences, helped to carry out a two-pronged study of food insecurity and food environments on the 10 UC campuses.

The project was motivated, Chang said, by the growing evidence that many college students, for a variety of reasons, experience food insecurity, which the U.S. Department of Agriculture defines as "limited or uncertain availability of nutritionally adequate and safe foods or limited or uncertain ability to acquire acceptable foods in socially acceptable ways." She worked with Director Lorrene Ritchie and other UC ANR researchers at the Nutrition Policy Institute.

Global Food Initiative

The project included two major parts: A 10-campus survey of students designed to gather data on the prevalence and correlates of food insecurity; and a study of the retail food environment in the vicinity of each UC campus that assessed the quality of the available foods.

Chang presented results from the food environment study at a conference of GFI fellows in July. Nutrition Policy Institute researchers are continuing to analyze data from the 10-campus survey. During her undergraduate years, Chang was involved in several food security initiatives on the UC Berkeley campus and in the city of Berkeley. She is currently working at a health clinic in Los Angeles through Community HealthCorps, an AmeriCorps-funded program.

**Samantha Smith**, a graduate student in public health sciences at UC Davis, used her GFI fellowship to interview UC scientists about their research and extension efforts in agriculture, food and nutrition. The objective, she said, was to tell the stories of "people who have been notorious for not tooting their own horns."

Working with Constance Schneider, UC ANR's Youth, Families and Communities Director, as well as UC ANR Public Information Representative Jeannette Warnert, Smith wrote six profiles that are now featured in the "Stories from the field" section on the UC ANR Global Food Initiative website.

"There will never be a time when having writing skills is not going to be useful," said Smith, who learned of the GFI fellowship opportunity in a communications course during the Fall 2014 quarter. Smith completed her MPH degree in September and is currently working with a group developing a smartphone app related to personal sexual health and safety.

**Kevi Mace**, a doctoral candidate in the Department of Environmental Science, Policy and Management at UC Berkeley, used her GFI fellowship to expand her ongoing work to raise awareness about career opportunities in Cooperative Extension (CE) and help graduate students develop skills for CE work.

Many graduate students are interested in doing applied science but don't know much about CE, Mace said. "If you don't know what it is, it's hard to go about preparing to do extension," she said.

Mace grew up in rural Colorado and is a 4-H alum. In 2014, she was a member of the first cohort of graduate students funded through a 3-year UC ANR pilot, the Graduate Training in Cooperative Extension program. CE-specific training through the program includes workshops on outreach to non-scientists, communicating with people outside one's field and writing effective policy briefs.

Mace's fellowship, with UC ANR Program Policy Analyst Vanessa Murua, supported her work in helping to host this year's CE showcase, an annual outreach event for students on the Berkeley campus in February. CA

*— Jim Downing*

# Following the fuel:

## How portable biomass energy generation may help rural communities

**The forests that surround many of California's mountain communities tend to have an abundance of woody biomass and a pressing need for thinning to reduce fire danger. Revenue from selling forest residues to biomass power plants could help to support fuel reduction activities, but in many cases the nearest plant is so far away that hauling costs are prohibitive.**

The remoteness of such communities can also complicate electricity provision, due to constraints on the power grid.

A Berkeley-based company has a new device that may address both problems — and it is partnering with UC researchers to test it.

Under a $2 million grant awarded in April by the California Energy Commission (CEC), All Power Labs will work with two UC research groups — the UC ANR Center for Forestry at UC Berkeley, and the Renewable and Appropriate Energy Laboratory (RAEL) in the UC Berkeley College of Natural Resources — to evaluate the feasibility of small-scale, portable biomass power.

The "Powertainer" — the unit is built in a 20-foot shipping container, hence the name — uses a gasification process to generate up to 150 kilowatts from biomass such as wood chips.

The Powertainer's energy-conversion technology is not new, but its scale and mobility are.

"Our idea was, 'Let's do something small that we can take to where the fuel is,'" said Tom Price, director of strategic initiatives for All Power Labs. Price said the Powertainer could be moved, connected to the grid and ready to operate in less than two days, making it easy to follow fuel sources as they become available.

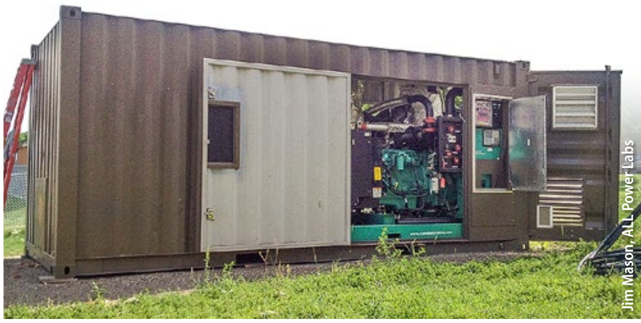
"We could theoretically have a contract with (Pacific Gas and Electric Co.) to deliver energy at a number of sites and migrate like beehives migrate with crops," he said.

Most biomass power plants in California are much bigger — by a factor of 50 or more — than the Powertainer. Other things being equal, large power plants can produce electricity at a lower cost than small ones. But a very small plant that can be moved as needed has two potential advantages that could reverse the usual economies of scale.

First, by moving close to the site of a biomass harvest, a portable plant can substantially reduce the cost of its biomass inputs. For large, stationary plants that must source feedstock from long distances, biomass trucking costs can easily account for more than half of fuel costs (see, e.g., Springsteen et al., this issue, page 142). In addition, because forestry operations tend to be seasonal and biomass can be stored only for a limited time before decomposition begins to create problems, it can be difficult to maintain a steady supply of fuel to a large plant throughout the year, which in turn can lead to shutdowns that increase the average cost of producing electricity.

Second, electricity generated and fed into the state's power grid in remote locations can sell for a price well above the statewide average. Because of transmission constraints, it's often difficult to keep the grid functioning properly in out-of-the-way spots — which makes additional generation capacity in those areas worth a premium. In such places, "you can provide a much larger value to the electric power system than you might by producing electricity in the Central Valley," said Daniel Sanchez, a doctoral candidate in the Energy and Resources Group at UC Berkeley and one of the RAEL researchers on the project.

Capitalizing on these potential advantages, though, requires a better understanding of the factors involved in providing woody biomass to a small generation unit like the Powertainer, and the best places for the device to connect to the grid. The CEC grant includes $370,000 in funding to UC to develop this information.




**The Powertainer is built into a 20-foot shipping container for portability. Fed by woody biomass, it can generate up to 150 kilowatts of electrical power.**

Researchers at the Center for Forestry will evaluate several aspects of the woody biomass supply chain as it would apply to the deployment of Powertainers, including the availability of forest residues, policy issues related to thinning, and the economics of the biomass supply chain. The group will also evaluate the market potential for biochar, which is produced as a byproduct of the Powertainer's gasification process. About 10% of the carbon in the feedstock consumed by the Powertainer ends up as biochar, which can sequester carbon for hundreds or even thousands of years and may be a beneficial soil amendment.

The RAEL researchers will work to identify regions in the state with a high need for the additional power that could be delivered by a Powertainer, and assess what the economic value of that power would be. RAEL will also assess the average cost of producing electricity with the Powertainer as well as the net greenhouse gas benefits of generating electricity from forest residues with the Powertainer.

All Power Labs will be field-testing the device in Placer County as part of the grant, with staff from the county air pollution control district monitoring emissions. CA

— *Jim Downing*

Research Article

# Forest biomass diversion in the Sierra Nevada: Energy, economics and emissions

*by* Bruce Springsteen, Thomas Christofk, Robert A. York, Tad Mason, Stephen Baker, Emily Lincoln, Bruce Hartsough *and* Takuyuki Yoshioka

***As an alternative to open pile burning, use of forest wastes from fuel hazard reduction projects at Blodgett Forest Research Station for electricity production was shown to produce energy and emission benefits: energy (diesel fuel) expended for processing and transport was 2.5% of the biomass fuel (energy equivalent); based on measurements from a large pile burn, air emissions reductions were 98%–99% for $PM_{2.5}$, CO (carbon monoxide), NMOC (nonmethane organic compounds), $CH_4$ (methane) and BC (black carbon), and 20% for NOx and $CO_2$-equivalent greenhouse gases. Due to transport challenges and delays, delivered cost was \$70 per bone dry ton (BDT) — comprised of collection and processing (\$34/BDT) and transport (\$36/BDT) for 79 miles one way — which exceeded the biomass plant gate price of \$45/BDT. Under typical conditions, the break-even haul distance would be approximately 30 miles one way, with a collection and processing cost of \$30/BDT and a transport cost of \$16/BDT. Revenue generated from monetization of the reductions in air emissions has the potential to make forest fuel reduction projects more economically viable.***

Large regions of Sierra Nevada mixed conifer forests are in need of hazardous fuels reduction treatments to reduce the risk of high severity wildfire and return forests to fire-resilient conditions. Whether as a complement or replacement to prescribed burning, it is highly desirable to increase the pace and scale of these treatments (North 2012; North et al. 2012). Significant quantities of woody biomass wastes are the unavoidable byproduct of these treatments.

Open pile burning in the forest is most commonly used to dispose of woody biomass waste, as fire hazard reduction objectives prevent leaving the material in-field to decompose, and because in many cases it is the most economically viable option. While woody biomass wastes represent a significant renewable energy resource, the cost to process and transport the material for use as fuel to produce electricity (or use for other value-added bioproducts such as biochar, biofuels, polymer precursors or thermal energy) often well-exceeds the combined value at the biomass electricity generation plant, the avoided cost to pile burn, and the potential value of nutrients returned to the soil (which is low due to the localized and limited pile burn location). A significant drawback of open pile burning is that it generates emissions of criteria air pollutants (particulate matter, carbon monoxide, volatile organic compounds and nitrogen oxides), greenhouse gases (GHGs) and air toxics such as polycyclic aromatic hydrocarbons and aldehydes.

The Placer County Air Pollution Control District sponsored — in cooperation with the UC Berkeley Center for Forestry, United States Forest Service (USFS) Rocky Mountain Research Station Missoula Fire Lab, and UC Davis Biological and Agricultural Engineering — a case study to quantify the energy, air quality and GHG benefits, as well as the economics, of utilizing woody biomass

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v069n03p142&fulltext=yes
doi: 10.3733/ca.v069n03p142


Contractor CTL Forest Management Inc. loads a chip van with woody biomass waste from the Yeti Fuels Reduction Project in the Lake Tahoe Basin Management Unit, Kings Beach, CA. A case study at Blodgett Forest Research Station quantified the air quality and energy benefits of converting biomass waste to electricity as an alternative to open pile burning in the forest.

Will Suckow


**Fig. 1. At Blodgett Forest Research Station, an excavator (left) loads forest slash into a horizontal grinder. Wood chips from the grinder are then conveyed into chip vans (center) for transport to Buena Vista Biomass Power plant (right).**

wastes generated at Blodgett Forest Research Station (BFRS) for renewable energy at the Buena Vista Biomass Power (BVBP) facility as an alternative to the status quo of open pile burning.

## Turning a waste into a resource

The UC Berkeley Center for Forestry manages BFRS, located east of Georgetown, California. Our research project targeted woody biomass waste piles (slash) from hazardous fuels reduction and timber operations at BFRS that included tree tops, limbs and small trees. The piles were generated from thinning treatments in mixed conifer plantations during the summer of 2012. The treatment objectives were to reduce fire hazard, increase average tree vigor and increase species diversity. Operations were typical of those in the Sierra Nevada, where young and dense forests have developed following wildfires or even-aged harvests. Plantations were thinned to an average of 110 trees per acre from pre-treatment stocking levels of 222 trees per acre. Four plantations were thinned, covering a total of approximately 80 acres. Because smaller trees were preferred for removal, average stem diameter (for residual trees) at breast height (DBH) increased from 11.9 to 13.1 inches. Sawlogs greater than 6 inches diameter on the small end and at least 10 feet long were transported to a sawmill for processing into lumber products. Unmerchantable trees (too small to process into sawlogs) plus the limbs and tops of merchantable trees were piled at roadside landings for disposal by open burning. The overall size of the piles generated were typical of thinning operations in young and mature forests, with bulk volume averaging 63,000 $ft^3$ per pile.

A forest biomass processing contractor, Brushbusters Inc., was retained to process and transport six woody biomass waste piles for use as fuel in the BVBP generation facility located near Ione, California. BVBP is the nearest biomass plant to BFRS. At each BFRS slash pile, an excavator was used to transfer the waste material into a horizontal grinder (fig. 1). Wood chips from the grinder were conveyed directly into chip vans, and transported to the BVBP facility, typically a 65-mile one-way trip. Due to road construction projects and detours, the actual one-way distance averaged about 79 miles. Equipment used for the chipping and transport operations (detailed in table 1) were sized for scale of operations that a medium or large landowner might consider — projects for which landing piles contain at least 100 green tons (GT) of biomass wastes (the equivalent of four chip vans each holding 25 GT). All biomass received at BVBP had been chipped prior to transport.

Brushbusters' operations (grinder, loader and chip vans) were carefully observed and tracked by our team, including total operating hours, productive operating hours (time when grinding and not including time when idling or waiting), diesel fuel use, biomass production and miles traveled. Engine and equipment air emission factors used to determine processing and transport emissions were taken from the manufacturer for each particular model. The following equipment cost factors were used, based on current contractor bid rates: grinder: $450/hour; excavator: $175/hour; chip van: $90/hour.

**TABLE 1. Equipment and engines for biomass processing and transport**

| Equipment | Vendor, model, year | Engine model, horsepower |
|---|---|---|
| Horizontal grinder | Bandit Beast, model 3680, 2008 | Caterpillar C18, Tier III, 522 kW |
| Excavator | Link-Belt, model 290, 2003 | Isuzu CC-6BG1TC, 132 kW |
| Chip van | Kenworth, 1997 | Cummins N14, 324 kW |
| Chip van | Kenworth, 2006 | Caterpillar C13, 298 kW |

The BVBP facility uses a wood-fired boiler that produces steam for a turbine and generator rated for 18 megawatts (MW) of electricity. The boiler is a Combustion Engineering/Lurgi circulating fluidized bed design fueled by biomass wastes including agricultural wastes (nut shells and orchard removals and prunings), forest slash and urban wood waste (tree trimmings and sorted construction debris). The boiler utilizes selective non-catalytic reduction for nitrogen oxides control, and multiclones and a baghouse for particulate matter control.


**Fig. 2. To sample air emissions from the pile burn, researchers used a 20-foot steel probe at the edge of the pile (top); nitrogen oxides, black carbon and carbon dioxide were measured on site using continuous emissions monitors. Canister samples were collected and sent for offsite analysis for total fine particulate matter, trace hydrocarbons and carbon monoxide.**

**TABLE 2. Forest slash composition**

| | Moisture | Carbon | Nitrogen | Ash | Higher heating value |
|---|---|---|---|---|---|
| | *wet wt %* | *dry wt %* | *dry wt %* | *dry wt %* | *Btu/dry lb* |
| Chips | 9.4 | 52.5 | 0.14 | 1.3 | 8,359 |
| Wood | 17.7 | 48.8 | 0.58 | | |
| Needles | 15.3 | 51.3 | 1.29 | | |
| Branches 1”–3” | 8.8 | 50.2 | 0.46 | | |
| Branches > 3” | 17 | 50 | 0.48 | | |

BVBP energy production and air emissions from the use of the BFRS forest slash were determined from direct measurements of biomass use and heat content, boiler continuous emissions monitors, air pollution source test (Avogadro 2013) and boiler heat rate. Emissions from electricity displaced by the biomass project were determined from overall California state generation factors (CARB 2010).

Staff from the USFS Rocky Mountain Research Station Missoula Fire Lab conducted field measurements characterizing air pollutant emissions from an open burn of one of the forest slash residue piles at BFRS (for details see Baker et al. 2014). Air emissions from pile combustion were sampled through a 20-foot steel probe angled over the edge of the pile (fig. 2). Real-time continuous nitrogen oxide (NOx) (Thermo Model 42i analyzer), black carbon (BC) (microAeth Model AE51 aethelometer) and carbon dioxide ($CO_2$) (LICOR LI-820) measurements were conducted on site. Particulate matter less than 2.5 microns ($PM_{2.5}$) was collected on 37-mm Teflon filters at 15-minute intervals. Emissions samples were collected in SUMMA canisters — three during the flaming phase, and 31 at 10-minute intervals during the burn down — and analyzed for carbon monoxide (CO), nonmethane organic compounds (NMOC), methane ($CH_4$) and $CO_2$ at the Missoula lab using gas chromatography and flame ionization detection. Pile material samples were analyzed at Missoula for moisture, carbon and nitrogen content; Hazen Research Laboratory (Golden, CO) performed ultimate analysis on a representative chip sample. Emission factors were determined using the carbon mass balance method (Hao 1996) for both a “fire average” integrated over the full duration of the flaming and smoldering phase, and a smoldering-only phase.

During the period of August 20, 2013, through September 4, 2013, on eight separate work days, Brushbusters collected, processed and transported 601 bone dry tons (BDT) (928 GT) of forest slash from BFRS to BVBP. This comprised a total of 37 separate chip van loads, with deliveries averaging 16.3 BDT (25.1 GT).

Table 2 shows forest slash biomass waste pile composition — material was relatively dry (9% to 18% moisture) with ash (1.3% dry weight) and heat content (high heating value of 8,359 Btu/dry lb) comparable to virgin conifer slash, indicating minimal contamination with rock and soil.

## Energy tradeoffs

Energy use input requirements and output production for the biomass project are shown in table 3. The energy of the diesel fuel used in collection, grinding and transport is only 2.5% of the available energy of the biomass wastes delivered to BVBP; and 4.6% of the energy of the natural gas (that would be required for producing an equivalent amount of electricity in a combined cycle natural gas–fired generation facility) that is displaced by the BFRS-BVBP bioenergy project. This is consistent with displaced generation found in other studies (e.g., Jones et al. 2010; Pan et al. 2008; Springsteen et al. 2011).

## Challenging economics

Biomass project economics are shown in table 4. The total delivered cost of $70/BDT was almost equally split between collection and processing at $34/BDT and transporting to BVBP at $36/BDT.

Production rates were less than expected due to lack of full-time availability of chip vans to the grinder landings. This was due to the following considerations: (1) BVBP was not in commercial operation and curtailed the hours they were accepting fuel deliveries. In many cases, trucks had to be parked loaded overnight rather than complete a one-day round trip; (2) public road contruction activities caused transport delays, resulting in average chip van transport speeds of only 31 mph; and (3) trees and brush from BFRS spur roads and landings needed to be cleared to allow van access.

Three to four chip vans were used each day for hauling. Each chip van averaged only 1.25 delivered loads per day rather than the potential two loads per day for the round-trip distance of 158 miles.

Time-motion evaluation found the grinder to be actively processing material for only 2.5 hours/day, while the grinder engine and excavator actually operated 3.8 and 4.8 hours/day, respectively (including idling and non-processing time). The biomass piles were originally created with pile burning as the planned disposal method, not grinding and removal for use as energy. The low density piles slowed feeding of the biomass wastes into the grinder. There were other delays due to moving equipment, preparing roads to access the piles and waiting for chip vans. All of these are common challenges that should be expected when first introducing biomass operations on forestlands. With improved pile stacking and a reduction in grinder idling, projected processing costs could be reduced to about $30/BDT (table 5).

Project expenditures for processing and transport were close to $70/BDT, while the competitive market value at the time of the project for biomass sourced from timber harvest residual in the central Sierra Nevada region was $45/BDT. The economic cost to dispose of the biomass wastes at the site of generation through open pile burning was less than $5/BDT. Thus, the demonstration project operated with a cost deficit of approximately $20/BDT.

Transport costs are a significant cost driver when collecting, processing and transporting forest biomass. To achieve a market price of $45/BDT for biomass fuel, the projected break-even transport distance would need to average approximately 30 miles one way. As shown in table 5, this estimate assumes

**TABLE 3. Energy accounting for BFRS-BVBP bioenergy project**

| Operation/energy type | Basis | Energy |
|---|---|---|
| | | *Btu/lb dry biomass* |
| **Expenditures** | | |
| Grinding | | |
| Grinder | 411.6 gal diesel* (0.44 gal/wet ton biomass) | 47 |
| Excavator | 204.2 gal diesel (0.22 gal/wet ton biomass) | 23 |
| Water truck | 42 gal diesel | 5 |
| Transport | 1,177 gal diesel (5 miles/gal) | 134 |
| Total | | 209 |
| **Production** | | |
| Biomass energy content | Hazen lab analysis, high heating value | 8,359 |
| BVBP biomass facility electricity | Boiler heat rate: 13,265 $Btu_{heatinput}/kWh_e$ | 2,134 |
| **Avoided/displaced** | | |
| Natural gas combined cycle (NGCC) | NGCC heat rate: 7,200 $Btu_{heatinput}/kWh_e$ | 4,503 |

* Diesel energy content (higher heating value): 137,000 Btu/gal.

**TABLE 4. Economics of biomass processing and transport for BFRS-BVBP project**

| Equipment | Unit operation cost | Average operating time | Production rate | Total cost |
|---|---|---|---|---|
| | *$/operating hour* | *hours/day* | *BDT/machine-day* | *$/BDT* |
| Grinder (Bandit Beast) | 450 | 3.8 | 75.1 | 22.8 |
| Excavator (Link-Belt 290) | 175 | 4.8 | 75.1 | 11.2 |
| Chip van | 90 | 8 | 20.3 | 35.5 |
| Total | | | | 69.4 |

**TABLE 5. Projected economics of biomass processing and transport for 30-mile one-way haul distance**

| Equipment | Unit operation cost | Average operating time | Production rate | Total cost |
|---|---|---|---|---|
| | *$/operating hour* | *hours/day* | *BDT/machine-day* | *$/BDT* |
| Grinder | 400 | 5 | 95.0 | 21.1 |
| Excavator | 160 | 5 | 95.0 | 8.4 |
| Chip van (30 miles one way) | 85 | 9 | 48.9 | 15.6 |
| Total | | | | 45.1 |

improvements in grinder processing efficiency and transport costs of $15.60/BDT (based on a chip van capacity of 16.3 BDT per load, chip van speed of 30 miles/hour, round trip of 60 miles, van loading and unloading time of 1 hour, and hourly van rate of $85/hour).

## Emissions from open pile burning

On the morning of January 20, 2014, one pile at BFRS, roughly 80 feet by 100 feet wide and 15 feet tall, containing approximately 300 BDT, was burned. The pile material composition, size and stacking arrangement was similar to those moved to BVBP. The pile was lit at the edge near the steel sampling probe. Within 5 minutes, a strong convective column with 100-foot-high flames formed. Due to the size and height of the burn it was not possible to sample the main section of the plume during the full flaming combustion mode of the burn. Figure 3 shows the pile as the ignition progressed through flaming and smoldering stages. Flaming phase transitioned to smoldering phase approximately 40 minutes after ignition.

CO is a strong surrogate indicator for other products of incomplete combustion (NMOC and $CH_4$), as shown in fig. 4 (canister measurements taken throughout the pile burn). Because monitoring CO is comparatively straightforward, it is important to establish its relationship to compounds that are more difficult to monitor (including NMOC and $CH_4$). The pile burn overall modified combustion efficiency (MCE) value of 94% (table 6) is consistent with the observation of good pile burning conditions — dry material, good air mixing and high burn temperature.


**Fig. 3. In 2014, researchers measured air emissions from an open pile burn at BFRS. Due to the size and height of the burn, they were unable to sample the main section of the plume during the full flaming combustion mode (see time interval at 13 minutes). Flaming phase transitioned to smoldering phase approximately 40 minutes after ignition.**

Emission factors from the open pile burn at BFRS are shown in table 6, including measurement variability (standard deviation) for both the smoldering phase and the total overall integrated (flaming and smoldering phases) burn. Due to the researchers' inability to sample the primary pile smoke plume, BC results are only presented for the smoldering phase; total overall burn results are reported for the other air pollutants but may not adequately represent the flaming conditions in the main pile burn exhaust plume.

Emissions factors for $PM_{2.5}$, CO and $CH_4$ were consistent with those reported in the literature (see Springsteen et al. (2011) for a recent compilation of forest residue open pile burn emission factors). Emission factors for NOx and NMOC were 50% to 75% and 0% to 75% lower, respectively, than other studies. The lower NOx may be the result of the large pile size and inability to sample the high temperature locations of the pile plume during the flaming phase. As expected, emission factors for products of incomplete combustion, including CO, NMOC and $CH_4$, were significantly higher for the smoldering phase.

**Emissions comparison.** Criteria air pollutant and GHG emissions (per BDT of woody biomass) from BFRS open pile burning and the BVBP biomass energy project alternative are compared in figs. 5 and 6, respectively. GHG emissions are shown as $CO_2$-equivalent based on Global Warming Potential factors from the Intergovernmental Panel on Climate Change (IPCC 2013). Details of the emission factors used and calculations are in tables 7 and 8.

Reductions of $PM_{2.5}$, CO, NMOC and BC were from 98% to 99%, which is consistent with other findings (Jones et al. 2010; Lee et al. 2010; Springsteen et al. 2011). These results are due to the efficient combustion and controls at the biomass energy facility and engines used for processing and transport. NOx emissions reductions of only 17% result from the lower-than-typical NOx measured from the open pile burn.

GHG $CO_2$-equivalent reductions of 0.5 tons/BDT of biomass from the BVBP bioenergy project result from reduction in BC, CO, NMOC and $CH_4$ compared to the pile burn; and renewable electricity that displaces fossil fuels required for equivalent power generation.

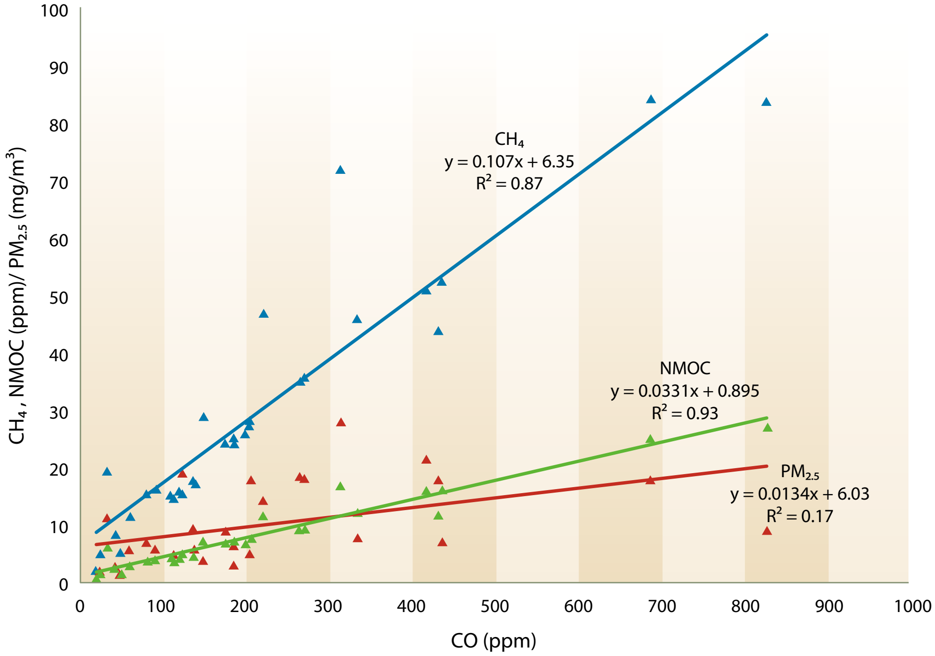



**Fig. 4. Relationship between CO and NMOC and $CH_4$ for open pile burn.**

**TABLE 6. Open pile burn emission factors (g/dry kg forest slash)**

| | Total (flaming and smoldering) | | Smoldering | |
|---|---|---|---|---|
| | Average | Standard deviation | Average | Standard deviation |
| $CO_2$ | 1,708.0 | 89.6 | 1,511.0 | 56.7 |
| CO | 66.3 | 45.8 | 157.6 | 33.2 |
| $CH_4$ | 5.00 | 4.60 | 13.50 | 3.50 |
| NMOC | 1.48 | 2.66 | 7.39 | 1.68 |
| NO | 0.94 | 0.41 | | |
| NOx | 1.03 | 0.41 | | |
| $PM_{2.5}$ | 5.27 | 5.31 | 5.31 | 5.92 |
| BC | | | 0.32 | |
| MCE (%) | 94 | 4 | 86 | 3 |

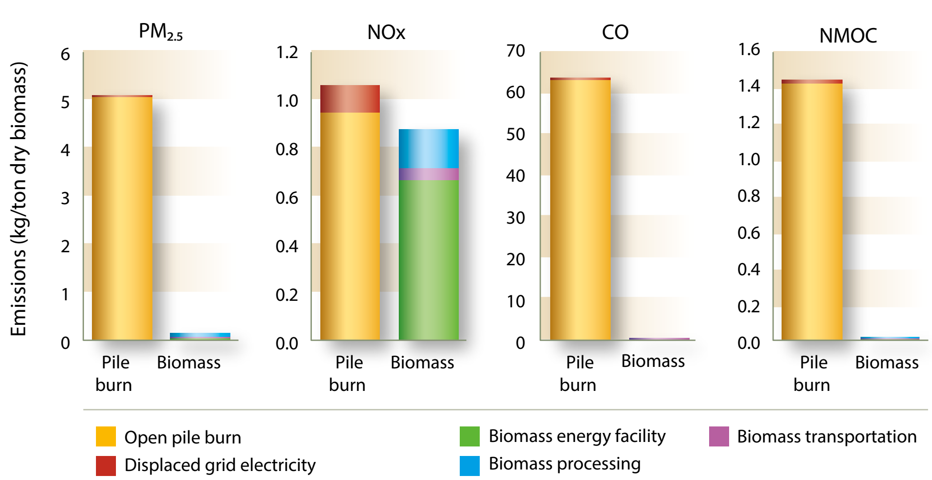



**Fig. 5. Criteria air pollutant emissions comparison: pile burn versus biomass energy project.**

***Sales of greenhouse gas and criteria air pollution reductions as mitigation offsets to meet environmental review requirements would help to make forest biomass projects economically viable.***

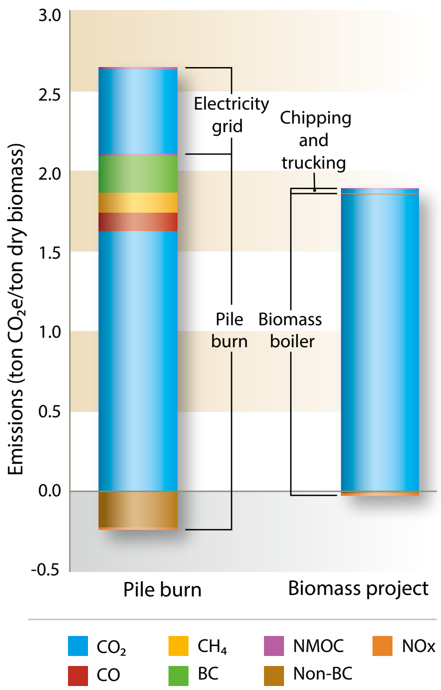



**Fig. 6. Greenhouse gas emissions comparison: pile burn versus biomass energy project. (For the biomass energy project, the contribution to the $CO_2$e total for all of non-$CO_2$ constituents (CO, $CH_4$, NMOC, NOx, BC and Non-BC) is included, but the bars are not visible because they are insignificant in comparison to that from $CO_2$.)**

## Conclusion

Energy production and reductions in criteria air pollutants and GHG emissions were quantified from utilization of forest woody biomass wastes to fuel electricity generation as an alternative to open pile burning. However, biomass energy project economics were not favorable due to inefficient processing operations and the long transport distance between biomass origin and energy facility. Expected improvements in processing and transport efficiency alone will not bridge the gap. Sales of greenhouse gas and criteria air pollution reductions as mitigation offsets to meet environmental review requirements (such as those under the California Environmental Quality Act) would help to make forest biomass projects economically viable. A potential greenhouse gas value of $20/ton $CO_2$-equivalent (the approximate rate of credits under South Coast Air Quality Management District Rule 2702, Greenhouse Gas Reduction Program) would add $10/BDT to the biomass value and reduce the BRFS-BVBP project deficit by half. Monetizing criteria air pollutant reduction benefits could fully close the deficit. Under California's Carl Moyer Program, mitigation of NOx, NMOC and $PM_{2.5}$ is valued at up to $16,000 per ton. There is a growing demand for such emissions reductions as air quality standards tighten and economic growth in rural air basins continues. For instance, new businesses and land development projects that generate emissions are often required to mitigate their impact under the California Environmental Quality Act review process or purchase emissions reduction credits to meet New Source Review requirements under the federal Clear Air Act.

A video documenting the BFRS biomass project was produced that includes interviews with a unique and diverse set of resource professionals, researchers, state and federal agency representatives, utility representatives and elected officials. The video can be viewed at http://vimeo.com/89771199. CA

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Will Suckow

Buena Vista Biomass Power plant and mound of woody biomass in storage area.

**TABLE 7. Emissions comparison between open pile burning and biomass energy project**

| | | NOx | $PM_{2.5}$ | BC | Non-BC | NMOC | $CH_4$ | CO | $CO_2$ | $CO_2e$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **Baseline no project** | | | | | | | | | | |
| Open pile burn | tons | 0.52 | 2.7449 | 0.1372 | 2.6077 | 0.7769 | 2.5896 | 34.338 | 884.6 | |
| Electricity grid | tons | 0.06 | 0.0188 | 0.0019 | 0.0169 | 0.0075 | 0.0038 | 0.098 | 288.7 | |
| **Biomass project** | | | | | | | | | | |
| Chip van | tons | 0.02 | 0.0139 | 0.0002 | 0.0137 | 0.0009 | 0.0005 | 0.003 | 12.0 | |
| Water truck | tons | 0.00 | 0.0001 | 0.0000 | 0.0000 | 0.0001 | 0.0000 | 0.000 | 0.4 | |
| Grinder | tons | 0.05 | 0.0482 | 0.0014 | 0.0469 | 0.0025 | 0.0011 | 0.055 | 4.2 | |
| Excavator | tons | 0.04 | 0.0015 | 0.0011 | 0.0004 | 0.0038 | 0.0000 | 0.010 | 2.1 | |
| Biomass boiler | tons | 0.36 | 0.0041 | 0.0004 | 0.0037 | 0.0006 | 0.0003 | 0.018 | 1000.3 | |
| **Reductions** | | | | | | | | | | |
| | tons | 0.10 | 2.70 | 0.14 | 2.56 | 0.78 | 2.59 | 34.3 | 154 | |
| | kg/dry ton biomass | 0.18 | 4.95 | 0.25 | 4.70 | 1.42 | 4.75 | 63.0 | 283.0 | |
| | % | 17.1% | 97.5% | 97.7% | 97.5% | 99.0% | 99.9% | 99.7% | 13.1% | |
| | Global Warming Potential* | −4 | | 900 | −46 | 5 | 28 | 1.8 | 1 | |
| | tons $CO_2e$† | −0.4 | 0.0 | 122.4 | −117.8 | 3.9 | 72.6 | 61.8 | 154.3 | 296.7 |
| | tons $CO_2e$/dry ton biomass | | | | | | | | | 0.54 |

* From IPCC (2013).
† $CO_2e$ = $CO_2$-equivalent.

**TABLE 8. Emission factors used for comparison between open pile burning and biomass energy project**

| | | NOx | $PM_{2.5}$ | BC* | Non-BC* | NMOC | $CH_4$ | CO | $CO_2$ | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Open pile burn† | g/kg dry biomass | 1 | 5.3 | 5% | 95% | 1.5 | 5 | 66.3 | 1708 | Baker et al. (2014) |
| Electricity grid | kg/$MWh_e$ | 0.08 | 0.025 | 10% | 90% | 0.01 | 0.005 | 0.13 | 384 | CARB (2010) |
| Chip van | g/mile | 4.17 | 0.05 | 75% | 25% | 0.15 | 0.08 | 0.59 | 10.2‡ | CARB (2011) |
| | lb/mile dirt | | 0.6 | 0% | 100% | | | | | CARB (1997) |
| Water truck | g/mile | 9 | 0.3 | 75% | 25% | 0.4 | 0.2 | 1.2 | 10.2‡ | CalEEMod (2013) |
| Grinder | g/bhp-hr | 2.3 | 0.088 | 75% | 25% | 0.12 | 0.05 | 2.6 | 10.2‡ | CalEEMod (2013) |
| | lb/ton wet biomass | | 0.1 | 0% | 100% | | | | | U.S. EPA (1985) |
| Excavator | g/bhp-hr | 7.5 | 0.28 | 75% | 25% | 0.71 | | 1.89 | 10.2‡ | CalEEMod (2013) |
| Biomass boiler | lb/$MMBtu_{biomass,HHV}$ | 0.08 | 0.0009 | 10% | 90% | 0.00014 | 0.00007 | 0.004 | 219 | Avogadro (2013) |

* % of total PM, from Reid et al. (2005), McMeeking et al. (2013), U.S. EPA (2012), Chen (2007).
† Used with a 95% pile burn-out efficiency.
‡ kg $CO_2$/gal diesel fuel.

# Effects of fuel treatments on California mixed-conifer forests

*by* Eric M. Winford, Jens T. Stevens *and* Hugh D. Safford

***Land managers implement forest fuel reduction treatments, including prescribed fire, mastication, and hand- and mechanical thinning, to modify wildfire behavior. Fuel treatments decrease tree density, increase mean canopy base height and remove surface fuels, and have been shown to reduce fire severity in yellow pine and mixed-conifer forests, even under relatively severe weather conditions. However, less is known about the impacts of fuel treatments on other facets of forest ecology. Synthesizing evidence from the scientific literature regarding their effects on forest structure, carbon, vegetation, soils, wildlife and forest pests, we found a developing consensus that fuel treatments, particularly those that include a prescribed fire component, may have neutral to positive effects on a number of ecological processes in frequent-fire coniferous forests and may increase forest resilience to future disturbance and stress.***

Forest fuel treatments modify forest structure and composition to affect fire behavior and reduce fire severity in the event of fire. Properly implemented, they can also improve forest habitat for species of plants and animals, and restore ecological processes and services (e.g., hydrologic function, soil nutrient cycling, subcanopy light availability, biodiversity, aesthetics) (McIver et al. 2012). Various fuel treatments have been developed, including prescribed fire, mechanical thinning, hand-thinning, mastication and combinations of these (Evans et al. 2011; Stephens et al. 2012).

Yellow pine and mixed-conifer (YPMC) forests cover millions of hectares of California forestland (Safford and Stevens, in press). These forests experience wet winters and dry summers and are generally composed of a variable mix of pine species (*Pinus ponderosa, P. jeffreyi, P. lambertiana*), white fir (*Abies concolor*), various oak species (*Quercus* spp.) and incense cedar (*Calocedrus decurrens*) (Barbour et al. 1993; Barbour et al. 2007). While there was substantial local variation, before Euro-American settlement in California this type of vegetation generally supported short fire return intervals (10 to 20 years), with a summer-fall fire season and fires dominated by low- and moderate-severity effects (Safford and Stevens, in press; Van de Water and Safford 2011; Van Wagtendonk and Fites-Kaufman 2006).

Until the early 20th century, those frequent low- to moderate-intensity fires with smaller patches of high-severity effects reduced the quantity and continuity of fuels in YPMC forests and created a complex patchwork of mixed-age tree clumps and gaps (Agee and Skinner 2005; North et al. 2009). Since then, however, fire exclusion practices, logging of large trees and livestock grazing have allowed fuel and young trees to accumulate in

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v069n03p150&fulltext=yes
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**A prescribed burn moves slowly through a forest in Sequoia National Park in June 2015. The burn is intended to help restore the area to more natural conditions by promoting sustainable tree growth and habitat for plants and animals while reducing tree density and ladder fuels.**

National Wildfire Coordinating Group, NWCG.gov some stands for a century or more, leading to high loads of spatially continuous fuels (Barbour et al. 1993; Stephens and Ruth 2005) and increased risk of tree mortality from moisture stress and tree pests (Fettig et al. 2007; van Mantgem and Stephenson 2007). Increasing fuel loads, higher summer temperatures, prolonged late summer droughts and decreasing fuel moistures are combining to create circumstances in which wildfires that escape containment in YPMC forests can burn at much higher severity over larger areas in extreme weather conditions than was common under the presettlement fire regime (Mallek et al. 2013; Miller et al. 2009; Miller and Safford 2012; Steel et al. 2015).

In YPMC forests, fuel treatments have proven effective at reducing fire severity and tree mortality, restoring forest structure and protecting human infrastructure and lives across the western United States (Martinson and Omi 2013; Safford et al. 2009; Safford et al. 2012). They also hold promise as sources of forest biomass, which can be used to produce a variety of timber and nontimber forest products as well as energy through biomass burning (Evans and Finkral 2009). As a result, there is interest in greatly expanding the pace and scale of fuel treatments (North et al. 2012), making it important that both managers and the public understand the effects that fuel treatments have on forest ecology. Our goal was to synthesize current scientific literature on forest fuel treatments and their ecological effects in YPMC forests in the Sierra Nevada and southern Cascades and similar locations in the western United States.

## Fuel treatments, forest structure

The primary objectives for fuel treatments are to create conditions in the forest in which fire can be more easily controlled, and where fire can occur without devastating ecological or socioeconomic consequences (Reinhardt et al. 2008). Forest fuel treatments target surface fuel (dead and down woody biomass, and dead and live shrubs and herbaceous material), which provides fuel for surface fires; ladder fuels (lower branches and smaller trees), which allow a fire to move vertically into the canopy and contribute to torching; and canopy continuity (tree spacing), which creates conditions for active crown fire (Agee and Skinner 2005). Fuel treatments primarily remove dead fuels, shrubs and mostly small- and medium-sized live trees, although some larger trees may also be removed. This can be accomplished in a variety of ways (see Agee and Skinner 2005, Evans et al. 2011 and Schwilk et al. 2009 for overviews), but there are four major categories of treatment, which may be employed



**These 2011 photographs illustrate the effect of a fuels treatment implemented prior to the 2008 American River Complex fire in Placer County. Nearly all the trees in the treated stand, *bottom*, survived the fire, while many trees in the denser, untreated stand, *top*, did not.**

**TABLE 1. Treatment types and impacts on forest structure**

| | Prescribed fire | Mastication | Hand-thinning | Mechanical thinning |
|---|---|---|---|---|
| Surface fuels | Reduction | Increase | Variable | Increase |
| Ladder fuels | Reduction | Reduction | Reduction | Reduction |
| Canopy continuity | Slight reduction or no change | Slight reduction or no change | Reduction | Reduction |



**A mixed-conifer stand in the El Dorado National Forest before, *top*, and after, *bottom*, a mechanized fuels treatment.**

singly or in combination: (1) prescribed fire, (2) mastication, (3) hand-thinning and (4) mechanical thinning (table 1).

Prescribed fire is usually implemented when the purpose of a fuel treatment is to restore stand structure, reduce surface fuels, and/or reintroduce fire for ecological benefits. At low to moderate fire intensities, which are common objectives of prescribed fires, surface fuels are consumed and understory trees may be killed. While prescribed fire can be implemented as a stand-alone treatment, it is often carried out as part of a treatment package, where some other method — such as mastication, hand-thinning or mechanical thinning — is used to first remove larger trees and woody debris (Agee and Skinner 2005; Schwilk et al. 2009; Stephens et al. 2012). Mastication is carried out by a machine that shreds woody materials on the surface, reducing the height and vertical continuity of fuels but leaving the masticated material on-site as a compact layer of surface fuel. Hand-thinning involves a crew cutting small-diameter trees (typically up to 20 to 25 centimeters diameter at breast height, DBH) and larger surface fuels. Hand thinning reduces the vertical continuity of fuels and increases the spacing between residual trees, often by leaving larger, more fire-resilient tree species. Fuel is subsequently piled or scattered for additional treatment with fire or mastication. Mechanical thinning, which can involve a number of different types of wheeled or tracked vehicles, generally removes small- and medium-diameter (usually shade-tolerant) trees (e.g., white fir, incense cedar) while retaining larger-diameter trees (often fire-resilient pines).

Fuel treatments that generate additional surface fuel as a result of treatment activities can greatly increase future wildfire severity if these additional fuels are not safely moved off-site or burned using prescribed fire (Safford et al. 2009). The most effective treatments at reducing future wildfire severity depend upon the starting stand conditions. In some cases, prescribed fire alone can achieve the fuel reduction objective but in other situations, such as when pre-treatment fuels are higher, may require mechanical and/or hand-thinning followed by prescribed fire or pile burning to dispose of surface fuel generated by the first treatment (Safford et al. 2012; Schwilk et al. 2009; Stephens et al. 2012).

## Effects on vegetation

Fuel treatment effects on live forest vegetation can be distinguished as direct effects on target vegetation (trees and woody shrubs), indirect effects on nontarget vegetation, or indirect effects on vegetation by affecting subsequent wildfire severity. Most studies of treatment effects on vegetation compare differences between treatment regimes, and/or the effects of a specific regime versus vegetation in an untreated forest.

**Direct effects.** The primary direct effect of fuel treatments on target vegetation is a decrease in live tree basal area and density (Collins et al. 2007; Stevens et al. 2014; van Mantgem et al. 2011). During thinning operations, fire-intolerant species (e.g., fir) are often targeted and the composition of residual surviving trees can be shifted toward fire-tolerant species, like pines (Chiono et al. 2012); however, prescribed fire on its own does not necessarily shift tree species composition, because it rarely kills the large trees which contribute most of the seeds (van Mantgem et al. 2011). Abundance of tree seedlings generally decreases in the years immediately following treatments (Schwilk et al. 2009; Stevens et al. 2014) but recovers over time (Chiono et al. 2012).

Fuel treatments may also target shrubs for removal, but shrub responses to fuel treatments are complex. There is evidence that mechanical thinning, prescribed fire, or a combination of the two can reduce shrub cover (Collins et al. 2007; Wayman and North 2007) or have no effect (Chiono et al. 2012; Collins et al. 2007; Stevens et al. 2014) over a span of 1 to 5 years post-treatment. Shrubs may respond positively to treatments over longer time periods by resprouting and regenerating from seed (Kane et al. 2010; Stevens et al. 2014), particularly when prescribed fire is used, as fire scarifies the seeds of many common montane chaparral species (Stephens et al. 2012). One way to reduce shrub recruitment is to repeatedly burn the site at time intervals short enough to exhaust the energy reserves of resprouting shrubs and to inhibit recovery of the shrub seedbank (Busse et al. 2009).

**Indirect effects.** The most commonly studied responses of nontarget vegetation to fuel treatments are herbaceous productivity and understory species diversity. Herbaceous productivity (generally measured by plant cover) often shows little or no response to fuel treatments in the Sierra Nevada and southern Cascades, over either the short term (1 to 2 years, Collins et al. 2007) or long term (2 to 15 years, Busse et al. 2009). However, at a national level, treatments often do increase herbaceous productivity (Stephens et al. 2012), suggesting that at more mesic sites, where the understory vegetation is less limited by moisture stress, treatments may stimulate increased plant cover and richness (Stevens et al. 2015). Mastication alone does not necessarily reduce understory species cover or richness, but when masticated material is tilled into the soil or, especially, prescribe-burned, there can be significant increases in bare ground and reductions in litter, which lead to much higher understory cover (with a major component of fire-scarified shrubs) and diversity (Kane et al. 2010).

Responses of native plant diversity to treatments appear to depend on the treatment regime and time since treatment. Collins et al. (2007) found a slight decrease in native diversity following mechanical thinning, but no change following prescribed fire only, during the first 2 years post-treatment. Studies measuring native plant diversity from 2 to 20 years following treatments involving the use of prescribed fire generally show a moderate to strong increase in diversity relative to controls (Kane et al. 2010; Stevens et al. 2015; Wayman and North 2007; Webster and Halpern 2010).

In YPMC forests, non-native species richness and cover tend to increase following treatments, particularly when they involve mastication or mechanical thinning followed by prescribed fire (Collins et al. 2007; Kane et al. 2010; Stevens et al. 2014). This is consistent with findings from other regions (Freeman et al. 2007; Schwilk et al. 2009; Stephens et al. 2012). However, non-native species richness in untreated forests that burn at high severity has been shown to exceed non-native species richness in treated forests, both in California (Stevens et al. 2015) and nationally (Freeman et al. 2007). These findings indicate that low- and moderate-severity fires may reduce the risk of non-native plant invasion compared with high-severity fires in some cases.

Finally, treatments can indirectly affect all vegetation through their moderation of subsequent wildfire severity. When untreated forest burns under severe fire weather conditions, fire severity is generally high (Martinson and Omi 2013; Safford et al. 2012; Stevens et al. 2014). When treated forest burns in a wildfire, there is generally less effect on the forest overstory than in untreated forest, suggesting that treatments can increase forest resilience to future disturbance. This overstory resilience translates to understory resilience: compared with untreated stands, treated stands after wildfire have more tree regeneration, less shrub regeneration and higher native species diversity at the stand scale (Stevens et al. 2014; Stevens et al. 2015). Native species diversity at the plot scale increases following both low- and high-severity fires, but diversity at the stand scale is greater following low-severity fires (Stevens et al. 2015), possibly because some species that are not adapted to fire may be able to persist during low fire intensity, and even among fire-adapted species, some may prefer low-intensity fire to high-intensity fire (Rocca 2009). Thus, stand-scale diversity can likely be maintained at high levels under a heterogeneous regime of predominantly low- and moderate-severity fires with smaller patches of high severity.

## Effects on carbon

While fuel treatments reduce the carbon stocks of forests by removing biomass, they also benefit the long-term ecosystem carbon equation by reducing the carbon emissions from subsequent wildfires. There is great interest in increasing the carbon in forests to reduce the impacts of global warming but there is also much uncertainty and debate about the total extent of the carbon benefits of fuels treatments (Campbell et al. 2012; McKinley et al. 2011). Because of their high fire risk and moderate productivity, YPMC forests may not be optimal places to try to sustainably sequester large amounts of carbon, but properly implemented fuel treatments can at least theoretically reduce fire severity sufficiently to maintain ecosystem carbon over the long term (Hurteau et al. 2008; Mitchell et al. 2009), provided the reduced fuel structure is maintained over time by future treatments, prescribed fire, or managed wildfire.

In YPMC forests, fuel treatments that target surface and ladder fuels by removing small-diameter trees and shrubs can more quickly recover the carbon lost in the vegetation removal than treatments that target larger trees, because large trees store more carbon than small trees and add it at a faster pace, so it takes longer to recover the carbon losses (Hurteau and North 2010; Stephenson et al. 2014). In the event of wildfires, treated forests lose less carbon (from the burning of live and dead vegetation) than untreated forests and recover the lost carbon faster due to the higher numbers of live trees. However, fuel treatments may remove more carbon in total (in live and dead material) than the carbon lost in a wildfire (Carlson et al. 2012; North and Hurteau 2011; Winford and Gaither 2012). Site-specific measurements that include the vegetation type, the fire regime, the type of treatment, the decay of dead trees, and the fate of the biomass removed can help answer the question of whether the carbon removed in fuel treatments is greater than the carbon released by wildfire.

## Effects on soils

In the national Fire and Fire Surrogates (FFS) study, which was designed to assess fuel treatment impacts in different forest types (Schwilk et al. 2009), fuel reduction treatments and prescribed fire had few long-term impacts on soil, while short-term impacts varied from region to region (Stephens et al. 2012). In the short term, prescribed fire decreases the organic layer on the forest floor, which leads to temporary exposure of mineral soil and also volatilizes carbon and nitrogen (e.g., Caldwell et al. 2002; Murphy et al. 2006). However, within a decade or less, total nitrogen and carbon generally rebound to pre-treatment levels (Boerner et al. 2009; Stephens et al. 2012). In the FFS study, there was no long-term impact on mineral soil carbon or nitrogen, soil bulk density, soil pH or available cations from any of the studied treatment types (Stephens et al. 2012), and a long-term study on slash retention and prescribed fire found no changes in site productivity after 20 years (Busse 2010).

Note also that relatively high short-term losses of nitrogen and carbon from litter combustion in fire can be due to the long-term accumulation of litter resulting from fire suppression (Johnson et al. 2009). A common finding is an ephemeral increase in inorganic nitrogen ($NO3^{-}$ and $NH4^{+}$) following fire and combined fire and thinning, but the response is not entirely consistent across studies (Moghaddas and Stephens 2007; Minocha et al. 2013).

## Effects on wildlife

Fuel treatments have a range of impacts on wildlife species, depending on the species and the scale studied (Stephens et al. 2012). A meta-analysis of avian and small-mammal responses to wildfire, thinning, and thinning plus prescribed fire showed that most short-term responses at fine spatial scales mimicked species responses to low- and moderate-severity wildfire (Fontaine and Kennedy 2012). The majority of the responses to the fuel treatments were neutral; thinning combined with prescribed fire had the most positive species responses; and species responded to high-severity wildfire with the strongest reaction (both positive and negative) (Fontaine and Kennedy 2012).

Several wildlife species in the Sierra Nevada utilize the forest structure and early-successional conditions that occur following a high-severity fire, which are not well approximated by prescribed fire or thinning treatments (Fontaine and Kennedy 2012; Hutto 2008; Stephens et al. 2012). The black-backed woodpecker, a post-fire specialist that searches for insects in dead trees, may benefit from fire-scorched dead trees following prescribed fires with high intensities, or from leaving clumps of dense trees during thinning operations that can subsequently burn at higher severities (Hutto 2008). Treatments that seek to create heterogeneous landscapes with all successional stages present and the full range of disturbance conditions are most suitable to multiple species, though managers may still need to work

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**Several species in the Sierra Nevada, such as the black-backed woodpecker, may benefit from the conditions that occur after a high-severity fire.**

to include canopy gaps or patches of high-severity fire, either through mechanical treatments, prescribed fire or managed wildfire (Fontaine and Kennedy 2012 ).

A handful of studies have looked at impacts of fuels treatment on species of conservation concern, such as the California spotted owl (*Strix occidentalis*), the fisher (*Martes pennanti*) and the marten (*Martes americana*), though the studies are limited in the number of individuals, locations and scales they encompassed. At a stand scale, fuel treatments that avoid removing large live trees, large dead standing trees and large dead downed trees will best preserve important nesting, roosting and foraging habitat for multiple species (Keane 2014; Zielinski 2014).

The preferred late-seral habitat for fisher and spotted owl may experience short-term reductions in quality from the removal of woody biomass, including snags and downed woody debris, but the long-term benefit to the species is reducing the risk of stand-replacing fire, which could reduce nesting habitat quality for these species for a longer period of time (Lee and Irwin 2005; Scheller et al. 2011). Reductions in canopy cover from late-season prescribed fires and mechanical thinning plus fire can reduce the quality of fisher roosting habitat, but foraging habitat remains unaffected (Truex and Zielinski 2013).

Roberts et al.'s (2011) finding that spotted owls can persist in a landscape that has a low- to mixed-severity fire regime also suggests that fuel treatment effects may be relatively minor and transitory. Stephens et al. (2014) found that fuel treatments with an even tree spacing focused on fire hazard reduction caused a decline in spotted owl nesting activity, while most other wildlife species were unaffected. They argue that increased heterogeneity in treatments may improve the persistence of spotted owls in actively managed forest (Stephens et al. 2014).

### Effects on pests and pathogens

Reducing stand density can lead to notable reductions in bark beetle attacks, mostly by increasing tree vigor (Fettig et al. 2007). However, managers should be aware that fuel treatments may also cause indirect mortality from pests. Relatively low levels of delayed mortality (5% to 10%) can occur from beetles following treatment, particularly in treatments that include prescribed fire (Maloney et al. 2008; Stark et al. 2013). Where prescribed fire is used, post-treatment beetle-caused mortality can increase with fire severity (Breece et al. 2008; McHugh et al. 2003; Parker et al. 2006). Insect pests may also be attracted to thin-only activities that leave fuels on the ground (Fettig et al. 2007), although mastication may help prevent this (Stark et al. 2013).

Studies vary in whether *Abies* or *Pinus* species show more susceptibility to bark beetle attack following prescribed fire, though most agree that sugar pine shows higher incidence of indirect mortality than would be expected by chance alone (Maloney et al. 2008; Stark et al. 2013). Thinning treatments may reduce mistletoe abundance on larger trees, though thinning may also exacerbate the spread of root diseases such as *Armillaria* and *Heterobasidion annosum* (Maloney et al. 2008).

**High native species diversity can be maintained by recurring low- and moderate-severity fires following initial fuel treatments.**

### Conclusion

Ten years ago, we had a limited scientific understanding about the effectiveness of forest fuel treatments in YPMC forests and the effects they may have on forest ecology. Today, we know that certain treatments — for example, mechanical and/or hand-thinning followed by some sort of prescribed fire, or prescribed fire alone — are very effective at reducing wildfire severity. We are also learning that the ecological impacts of such fuel treatment combinations are not necessarily negative, indeed they are more often neutral to positive. This speaks to the restorative ability of forest thinning and prescribed fire in formerly fire-prone forests that have experienced a century of fire exclusion and a century and a half of other human impacts, including the removal of most large fire-tolerant trees and their replacement by high densities of smaller, less fire-tolerant species. Most scientific studies of the ecological impacts of fuel treatments in YPMC forests have been short term and small scale. There is a great need to scale upward and outward in our investigations of forest management impacts on YPMC forests, especially with respect to their landscape-level impacts on forest resilience to ecosystem stressors such as climate change, fire, prolonged drought, insects and disease. CA

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# Thinning treatments had minimal effect on soil compaction in mixed-conifer plantations

*by* Robert A. York, Richard K. Keller *and* Ariel C. Thomson

***If biomass utilization results in soil compaction and reduced forest productivity, the potential benefits may be considered to be not worth the long-term impacts. We analyzed soil strength, an indicator of soil compaction, prior to and following commercial thins (sawlog and biomass harvest) and mastication treatments in 24- to 30-year-old mixed-conifer plantations in the central Sierra Nevada. Soil strength in mature, untreated second-growth stands was also measured as a reference. Neither the commercial thins nor the mastication treatments resulted in statistically detectable increases in compaction. Most of the existing compaction came from the original regeneration harvest that established the plantations several decades earlier. It will be important to monitor repeat treatments and long-term effects, but this study suggests that managers should not expect large impacts from thinning treatments on soil compaction in forests such as the one studied here as long as best practices are used.***

Worldwide, plantations make up 5% of forestlands but contribute 15% of the world's wood production (Carnus et al. 2006). They also play an increasingly important role at the global scale in contributing to a wide variety of social and ecosystem services such as jobs and wildlife habitat (Paquette and Messier 2010). In California, plantations are common on both private and public lands. Especially in locations that are highly productive, these plantations have potential to be valuable for timber production.

When managed for timber or fire hazard reduction, management operations in plantations often involve heavy equipment, which has the potential to reduce soil productivity if the soil compaction effects are great enough. Soil compaction is of special concern because of the repeated use of heavy equipment in young stands, where elevated levels of soil compaction may have occurred already from previous harvests and site preparation operations.

Plantations are ideally structured for mechanized operations. They may be established following even-aged regeneration harvests (e.g., clearcuts) on industrial private lands, or following high severity wildfires across all types of ownerships. Although they can be quite diverse if managed for that objective, plantations are typically associated with homogeneity. Compared to mature tree stands with canopy gaps and developed under- and mid-stories, most plantations have trees that are roughly the same size (if not the same species) and tree density is relatively high and uniform throughout. By one account, in California an even-sized structure (i.e., a bell-shaped diameter

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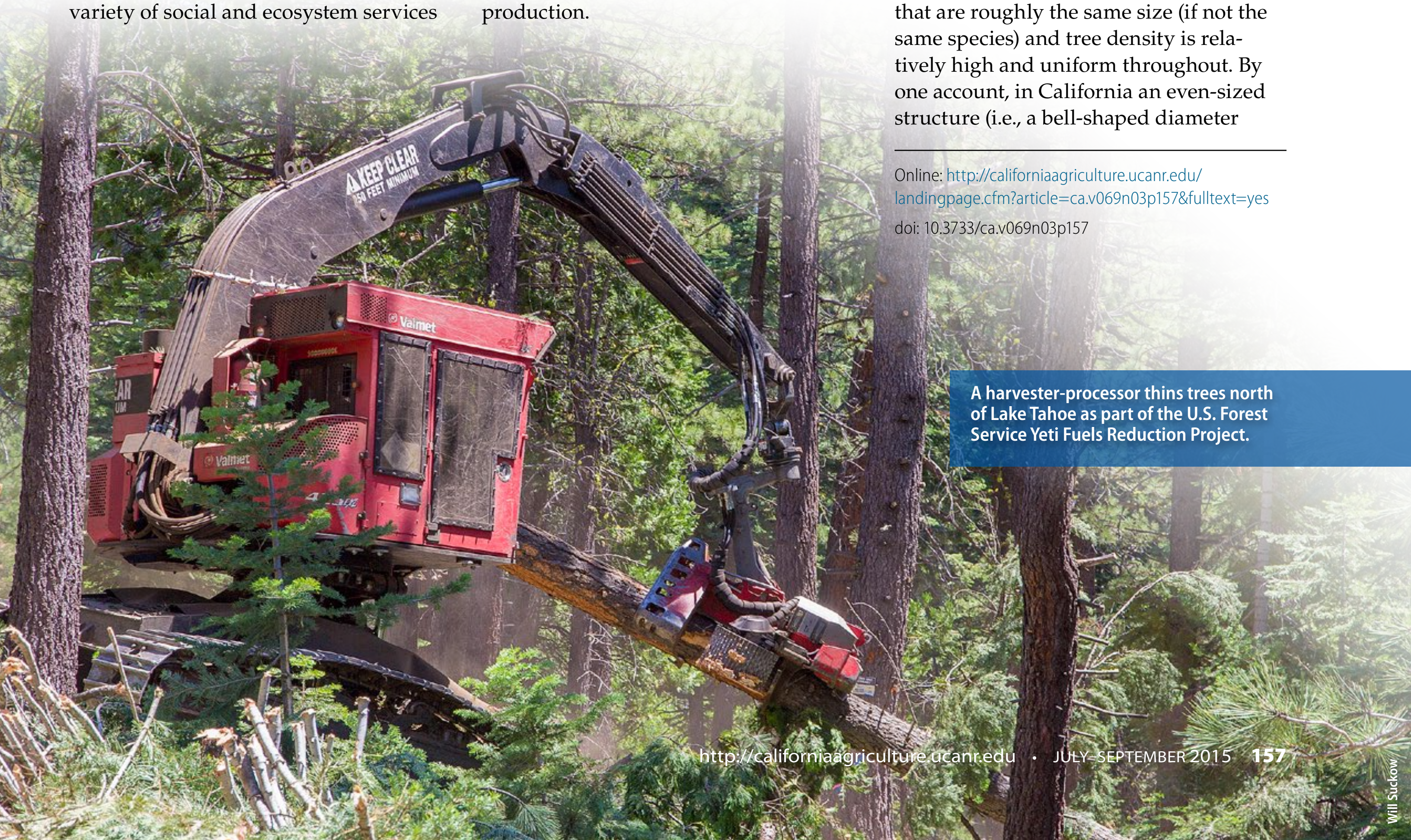


A harvester-processor thins trees north of Lake Tahoe as part of the U.S. Forest Service Yeti Fuels Reduction Project.

Will Suckow

distribution) is present on 23% of federal forestland and 31% of private forestland (William Stewart, UC Berkeley, personal communication). Young, even-aged stands in California forests are common, and they may become even more so as wildfire severity and extent increase and create additional large patches of young planted forests (Collins and Stephens 2010).

Plantations are often identified as high-priority areas for fire hazard reduction treatments because of their high potential value for timber and risk of complete loss during wildfires (Pollet and Omi 2002). In dry mixed-conifer forests, young plantations can burn at particularly high intensities during wildfires. Increased fire intensities in plantations have been both observed (Pollet and Omi 2002) and predicted using fire modeling (Stephens and Moghaddas 2005).

A common fire hazard reduction treatment is density management through mechanical thinning. Thinning that removes small or midrange trees while avoiding large increases in surface fuel can help meet objectives for reducing fire hazard, and it can also be used for increasing physiological resilience in the face of climatic change (Chmura et al. 2011). Thinning young stands may be especially effective from a fire hazard perspective, as trees will develop in size more quickly and therefore be more resistant to fire sooner (Agee and Skinner 2005).

When trees are of commercial size, mechanized thinning can be a cost-effective approach for reducing tree density because treatment costs can be covered with the sale of sawlogs (commercial thinning; fig. 1). Yarding whole trees into landings is of value from a fire hazard perspective because relatively little activity fuel (logging slash) is left behind. The tradeoff, however, is that a net movement of large amounts of biomass debris (treetops and limbs) from forested stands into landings is a necessary byproduct of such operations. The current standard practice is to dispose of large debris piles resulting from mechanized thinning via open burning. Where feasible, the biomass may be hauled away for utilization at a biomass energy facility, avoiding the negative air quality impacts of open burning (e.g., Hurteau et al. 2014).

Many of the plantations in the Sierra Nevada on both public and private lands were established 20 to 40 years ago and the trees are just now becoming large enough to accommodate a commercial thinning. Thinning projects are therefore likely to increase significantly over the next decade, and the increase will be even greater if the demand for biomass material increases. Increased restrictions on open burning because of health concerns will also increase thinning since prescribed burning for density management will be less feasible. Given these developing motives for conducting thinning treatments, there is an especially high demand for understanding the ecological trade-offs between the various thinning treatment methods that can be used.

Most studies of biomass removal impacts involve using treatments that either remove entire mature stands or, to a lesser extent, thin mature stands (Page-Dumroese et al. 2010). These studies have limited applicability for commercially thinning plantations. Treatment effects in a plantation could be quite different than in a mature stand, especially with respect to soil impacts. A mature second-growth stand in the Sierra Nevada has not had a regeneration harvest since railroad logging, often over a century ago (Beesley 1996). Within 10 to 30 years of the establishment of a plantation, however, heavy equipment is often used to conduct thinning and harvest treatments, potentially compounding soil impacts from the relatively recent harvest of the previous stand.

Nutrient depletion of soils following biomass removal is not considered to have long-term impacts unless the site already has relatively low productivity (Page-Dumroese et al. 2010). Operations that result in enough physical compaction to curtail root growth and reduce productivity, however, may be of long-term significance (Grigal 2000; Powers et al. 2005). To minimize compaction effects, thinned trees can be chipped in place with a masticating machine (mastication treatment; fig. 1). A mastication treatment is noncommercial, but it may be predicted to have less of an effect on soil strength than commercial thinning, because only one machine is used (commercial thins have two) and no weight-bearing logs are skidded to landings.

Both treatment types — commercial thinning and mastication — can achieve stand density management objectives but may have very different effects on soil strength. Alternatively, both treatments may have relatively little effect on soil strength if standard practices for avoiding negative impacts are used. Two of the more important practices are operating during dry soil conditions and minimizing skid trails.

In this study, we compared commercial thinning treatments (whole-tree yarding into landings for sawlog and biomass

## Soil compaction in forests

Changes in soil compaction in forests occur from natural processes such as tree fall, root growth and freeze/thaw cycles. Mechanical operations also cause changes in soil compaction: direct impacts from heavy equipment and dragging (skidding) logs to landings increase compaction; mechanical treatments can also be done to break up compacted soil.

Negative effects of compaction occur when root growth is inhibited by severely compacted soil. Whether compaction reduces productivity at a given site depends to a large degree on soil type. Soils with high clay content are more likely to experience negative effects, while loamy or sandy soils may experience neutral or even positive effects on productivity. Further monitoring of long-term effects and repeated operations is needed to assess trends on time scales that are relevant for forests.

Management practices to avoid soil compaction effects include

- using track-laying machines, which apply less force to soils than rubber-tired machines
- avoiding operations during conditions of high soil moisture, or, as an alternative, conducting operations when the ground is frozen
- re-using skid trails and landings when conducting repeated thinning operations
- utilizing wing-tipped subsoiling to decrease severely compacted soils, especially where clay content is high

harvest) with mastication treatments to measure the effects on soil compaction at the stand level.

We measured soil strength prior to and following treatments using a relatively intensive sampling scheme to increase measurement precision. For reference, we also measured soil strength in mature second-growth forests that had been undisturbed for ~ 100 years. In the context of root growth, soil strength is a relevant measure of compaction, because it shows the resistance that a given soil has to root penetration.

## Experimental treatments

Our study took place at Blodgett Forest Research Station (Blodgett Forest) in El Dorado County. Mixed-conifer plantations at elevations between 1,220 and 1,370 meters and between 24 and 30 years

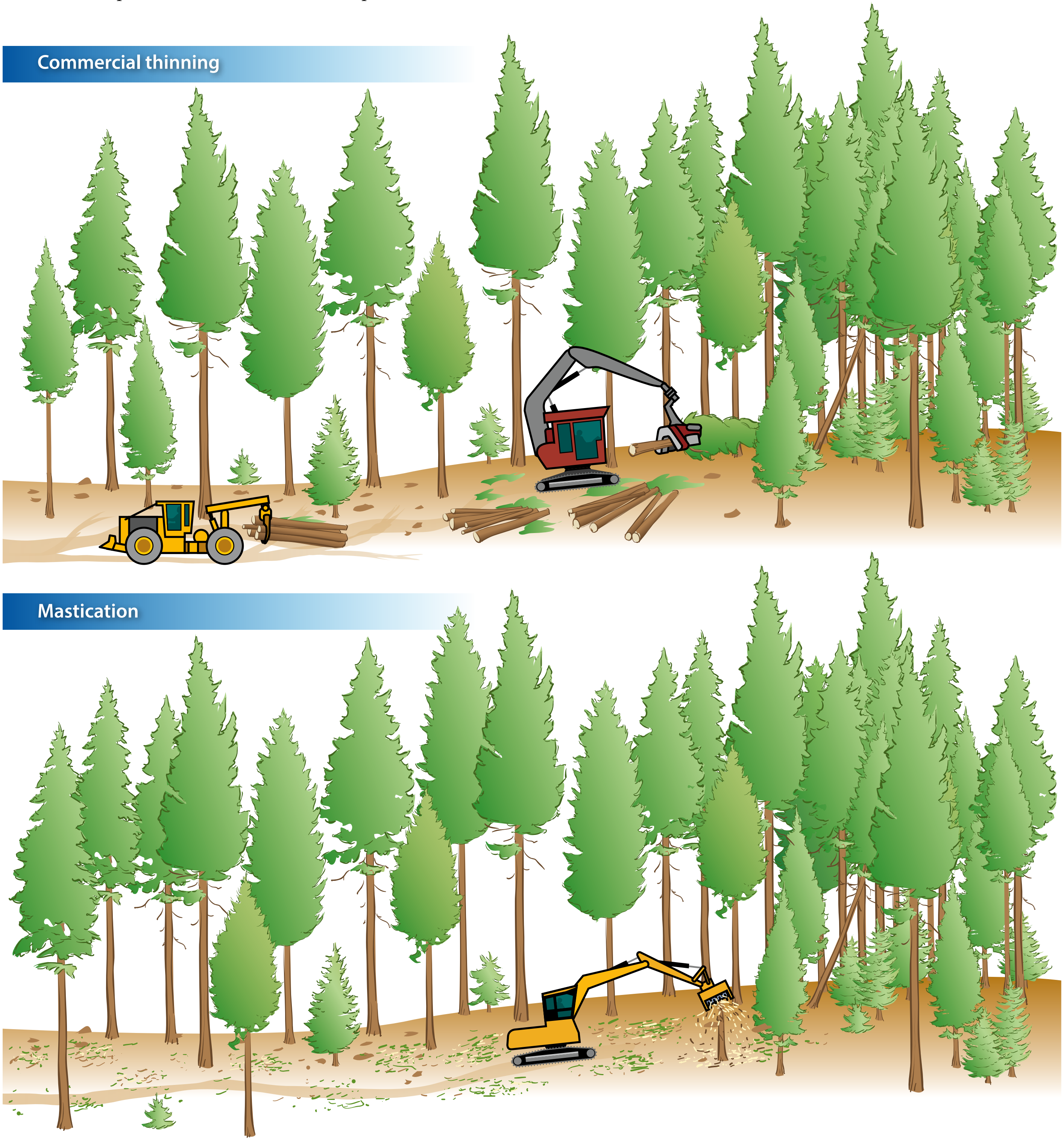


**Fig. 1. The study evaluated the soil compaction effects of commercial thinning (top) and mastication (bottom). A commercial thinning operation involves two machines — a feller-buncher to cut and bunch trees; and a skidder to grab the bunches and drag them to a loading area. Mastication involves a single machine that moves through the forest, chopping selected trees and other woody vegetation into small chunks.**

old were used. All plantations had been regenerated with either clear-cut or shelterwood harvests, followed by control of competing vegetation with herbicides and precommercial thinning with chainsaws during the first 10 years.

Soils originated from andesitic parent material and are classified as mesic Ultic Haploxeralfs. The general soil texture is loamy (particle proportions are approximately 50% sand, 35% silt and 15% clay). Precipitation averages 165 centimeters per year and productivity is high, with canopy trees reaching 30 meters tall in 50 years. The plantations are representative of those in the dry Sierra Nevada mixed-conifer forest that, because of their high productivity and operational feasibility, have relatively high potential for sustaining sawlog and biomass harvests.

Replicated commercial thinning and mastication treatments were applied to entire stands. Commercial thinning included whole-tree yarding of trees cut with a mechanized head and was representative of a typical sawlog and biomass thinning operation. Whole trees were cut and bundled with a tracked feller-buncher, followed by skidding of the bundles with a tractor and grapple. Old landings and skid trails (where logs are repeatedly dragged across soils) were reused when possible. Sawlogs were cut from merchantable-sized trees at landings, with the tops and limbs chipped for delivery to a power plant. The commercial thinning modified the forest structure from an average basal area of 43 square meters per hectare and average tree size of 20 centimeters DBH (diameter at breast height) to a postharvest average basal area of 25 square meters per hectare and average tree size of 33 centimeters DBH. Canopy was reduced from 60% to 40%.

The mastication treatment used a tracked excavator (model 490E, John Deere, Moline, Illinois) with a rotary disk–cutting head. The mastication focused on chipping woody shrubs and small trees, with the machine traversing most of the treated area. While under- and midstory densities were reduced to near zero, changes in canopy structure were minimal and within ranges of measurement error. DBH changed from 29 to 31 centimeters; basal area changed from 37 to 35 square meters per hectare; canopy changed from 57% to 59%.

Both treatments occurred in the early summer months (May to July), a period early enough to avoid extreme fire hazard conditions but late enough so that soils are not saturated with moisture — operating when soils are relatively dry is a best management practice for avoiding compaction. Duff and litter layers were relatively shallow prior to treatments, averaging less than 5 centimeters deep. Average stand size was 8 hectares, similar to the allowable upper size limit for even-aged stands on private lands in California. The experimental units were seven individual stands, three of which had replicated mastication treatments, and four had replicated commercial thinning treatments.


The rotating head of a masticator mulches timber and brush.

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Sampling was designed to accommodate the extremely high spatial variability, both vertically and horizontally, that occurs with physical soil properties at a small scale (e.g., Moghaddas and Stephens 2008). Grids of permanent plots were used as sampling locations, with clusters of subsample points precisely located before and after treatments. Plots were established on a 200-meter-by-200-meter grid, with witness trees for re-establishing plots following treatments.

Soil strength was measured with a recording cone penetrometer (model CP40II, Rimik, Toowoomba, Australia). The penetrometer consists of a probe that is pushed manually with consistent and low speed into the soil, while a load cell records the force (kPa) needed as the probe is pushed deeper into the soil. This measure of soil strength is an index of the resistance in soils to root penetration. Large increases in soil strength can negatively affect above-ground tree productivity depending on soil types. Soil strength was measured at eight subsample locations surrounding plot centers in a square pattern (a subsample point was located at each cardinal and intercardinal direction from plot center). At each of these eight subsample points, soil strength was measured three times (i.e., three replications per subsample, eight subsamples per plot, and five to nine plots per stand depending on stand size).

Each insertion measured soil strength in kPa between soil depths from 20 to 500 millimeters, with a measurement recorded every 20 millimeters. This resulted in a total of nearly 70,000 soil strength measurements. To increase precision at the plot level, the three insertions at the subsample location were averaged, followed by averaging of subsample values to get plot-level soil strength. For each soil strength measurement, soil moisture content (%) was measured at the same time with a soil moisture probe (ThetaProbe ML2, Delta-T Devices, Cambridge, United Kingdom). Soil strength is sensitive to soil moisture (Graecen and Sands 1980) because it influences soil cohesion. Soil moisture was therefore included as a covariate in the analysis of treatment effects on soil strength.

The intent of this study was to detect increases, if any, in soil strength at the stand level as a direct result of treatments and to assess the differences between the mastication and commercial thinning treatments. Plots that fell within skid trails or areas with little disturbance were not thrown out because these locations are part of the stand and their presence is a fundamental outcome of these operations. Skid trails comprise significant proportions of stands following harvesting, ranging from 20% to 26% in clear-cuts (Han et al. 2009). Skid trail proportions were not measured in this study, but visual observations suggested they comprised similar levels.

Analysis was done using multivariate ANOVA of repeated measures (MANOVAR). To find potentially different patterns in treatment effects at different depths, the analysis was repeated separately for each depth in 20-millimeter increments from 20 to 500 millimeters. The time series were the before and after measurements of soil strength. Predictor variables included treatment (mastication or commercial thinning) as well as the difference in soil moisture content between the before and after measurements. Including the difference in soil moisture content as a covariate accounted for any differences in soil moisture between the two sampling times.

The time × treatment interaction was the main effect of interest because it tested for differences in soil strength temporal trends between masticated and thinned stands (i.e., it tested if one type of treatment caused more or less compaction than the other). The within-subject effect of time was also of interest, because it indicated whether there was any overall trend in soil strength (i.e., it tested if, in general, the operations caused compaction). The time × soil moisture change interaction was an important variable to include in the model to account for any difference in soil moisture before and after treatments.

Statistical conclusions were based on $F$-test statistics with the determination at $P < 0.05$. A final comparison of mean pretreatment soil strength in these stands (all treatment plus control stands averaged) versus soil strength found in reserve stands where no operations have taken place for ~ 100 years was also done. This comparison provided a basic reference for soil strength conditions that occurred following an extended period of no operations. Two reserve stands where no operations have occurred were available for comparison. For a simple comparison of soil strength within these treatment stands versus the reserve stands, standard errors of mean soil strength in treatment stands were calculated for each depth and compared against a baseline, derived from the mean measured in the two reserve stands.

**TABLE 1. Soil strength measurements before and after mastication and commercial thinning treatments at Blodgett Forest, CA**

| Depth* | Strength before mastication | Strength after mastication | Strength before commercial thin | Strength after commercial thin | *P*-value of overall trend† | *P*-value of treatment effect† |
|---|---|---|---|---|---|---|
| *mm* | ..........*kPa*.......... | | | | | |
| 80 | 839 | 1,071 | 1,339 | 1,657 | 0.13 | 0.73 |
| 180 | 1,562 | 1,816 | 1,733 | 2,309 | 0.38 | 0.37 |
| 280 | 1,615 | 1,952 | 1,733 | 2,301 | 0.30 | 0.53 |
| 380 | 1,766 | 2,148 | 1,819 | 2,461 | 0.43 | 0.52 |
| 480 | 1,973 | 2,424 | 1,917 | 2,517 | 0.61 | 0.79 |

* To reduce table size, results are given for depths at 100-millimeter increments.

† *P*-values are from a multivariate analysis of variance with time as the between subject variable.

## No statistical differences

Although before and after measurements occurred at the same time of year, soil moisture content measurements taken at the time of soil strength sampling indicated that the soils were slightly drier during the post-treatment measurements than during the pre-treatment measurements. Mean soil moisture at the stand level was 45% prior to treatments and 33% following treatments. The decline in soil moisture was related to the seasonal dry-down of the soil, not the treatments themselves. A nearby weather station that recorded soil moisture at hourly increments throughout the study period recorded a similar rate of dry-down between measurement periods (from 28% to 17% at the weather station). The decline in soil moisture was identical between the masticated and commercially thinned stands (confirmed with a $t$-test; $P = 0.99$). This confirmed the importance of including soil moisture as a covariable in the analysis, and also confirmed that the treatment effects on soil strength were not caused by a difference in soil moisture related to the treatments themselves.

Despite the effort to maximize plot-level precision and careful relocating of before and after measurements, no overall increases in soil strength were detectable with statistical tests at any depth following the treatments, nor were there significant differences between the commercial thinning and mastication treatments. In general, soil strength did increase following treatments, from 1,605 kPa averaged across all depths to 2,091 kPa, but variability was high and $P$-values were far greater than 0.1 (table 1). Coefficients of variation at the stand level averaged 16% prior to treatments and increased to 29% following treatments.

The overall increase in soil strength was likely related at least to some degree to soil moisture, which as noted above was slightly drier following the treatments. The time × soil moisture variable was not significant, but it did consistently have more leverage in explaining soil strength than did the treatments. The results suggest that soil strength increases were not of great enough magnitude to detect operations-caused trends or differences between commercial thinning and mastication, given soil strength variability, which increased following treatments.

Prior to treatment, the soil strength pattern along the depth profile when all seven stands were grouped together followed what is typically observed: soil strength increases rapidly in shallow depths and increases at a much slower rate at greater depths (fig. 2). Despite the lack of a detectable increase in soil strength from either type of operation, it is clear that soil strength is, as expected, higher in actively managed stands than in reserve stands. This was especially the case at depths between 100 and 300 millimeters, but it was also true at the greatest depth (500 millimeters) measured for this study.

## Soil compaction in perspective

The effects of mechanical operations on the physical properties of forest soils are highly complex, depending upon site-specific soil conditions such as texture, soil moisture, root density, aeration and many other factors (Ballard 2000; Graecen and Sands 1980). The effects are also complex because the machinery operates sporadically, both in time and space. This is most evident where machine traffic is especially high. It has been documented consistently that compaction occurs in skid trails to a degree high enough to influence productivity (e.g., Froehlich et al. 1986; Moghaddas and Stephens 2008). Machines do not pass on all locations within a stand, however, and compaction effects can be relatively small or nonexistent only meters away from skid trails (Hatchett et al. 2006).

Because of the lack of skid trails in mastication treatments and because only one machine, instead of two, passed over the masticated areas, we expected to find that the mastication treatments had a noticeably lower effect on soil strength. No difference was detected, which could be interpreted as being the result of either a smaller-than-expected effect of commercial thinning or a larger-than-expected effect of mastication. Given the lack of any trend found in soil strength when all of the treatment areas were combined, we interpret the primary reason as being a smaller-than-expected effect by commercial thinning. In other words, the mastication treatment, as expected, did not compact soils significantly, but neither did the commercial thinning treatment.

It is important to note that variability in measured effects was high and contributed at least somewhat to the inability to detect differences. Replicating further at the stand level is difficult because of space and cost limitations. Greater replication, however, would be necessary to increase the experimental power enough to overcome within-stand variability.

In Sierra Nevada soils, texture has a profound influence on compaction effects, to the point where relatively severe compaction may cause negative, neutral or even positive effects on productivity depending on the soil texture (Gomez et al. 2002). The loamy soil textures of the stands in this study are expected to have a moderate capacity to withstand compaction, and compaction may even increase productivity due to increased water retention and hydraulic conductivity (Powers et al. 2005).

While it is well understood that compaction can reduce growth (Froehlich et al. 1986), there is no standard threshold at which negative effects on productivity may be expected, although 3,000 kPa is often cited as a critical point (Graecen and Sands 1980; Zyuz 1968). For our study, we set a soil strength threshold of 2,000 kPa (the vertical line in figure 2), which is a highly conservative threshold to use for these stands during soil moisture conditions typical of the growing season. Despite the clearly greater soil strength in the pre-treatment plantation stands compared with the undisturbed reserve stands, this conservative threshold was reached in the plantation stands only at the deepest levels of the soil profile.

The difference in pre-treatment soil strength in the treatment stands compared with the soil strength in the undisturbed reserve stands suggests that the majority of physical soil effects occurred in the past — several decades ago, when the sites were logged, with large trees felled and skidded in multiple machine passes, and the site prepared for regeneration. These stands are still under the lagging effect of initial compaction, when log loads were heavy enough to increase soil compaction relatively deep in the soil profile (Danfors 1974), as suggested in figure 2.

While this study suggests that no negative effects of soil compaction upon growth may be expected from operations in these soils, it is nonetheless important to continue to monitor the cumulative effects of repeated treatments over time. Whether managed over the long term for timber productivity, low fire hazard or resilience to climatic stress, these plantations and others in the Sierra Nevada will be considered for mechanical treatments as a wide variety of landowners consider diverse objectives. Long-term monitoring within the operational context and scales used in this study will be important.

As more mechanical treatments are repeated over time (a long-rotation plantation may have three or four commercial thins), possible outcomes include a compounding upward trend in compaction over time, no trend at all or a decreasing

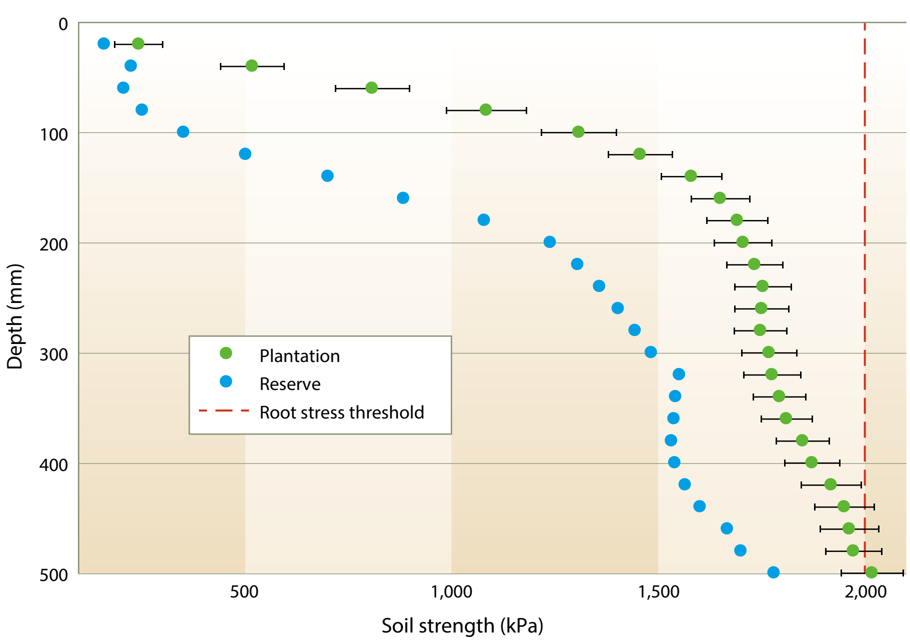


**Fig. 2. Soil strength profiles at Blodgett Forest, California. Means are provided with standard error whiskers for seven plantation stands between 24 and 30 years old prior to mastication or commercial thinning treatments. Two reserve stands that were railroad harvested roughly 100 years ago and not manipulated since then were measured for reference. The vertical line represents a conservative estimate of the point when soil compaction might begin to negatively influence root growth.**

trend as processes that cause physical soil movement (e.g., freeze/thaw cycles) cause a recovery from the initial and subsequent harvests. Monitoring that includes a high plot-level precision and untreated control stands, as in our study, should detect any correlation between soil compaction levels and growth over time.

***Meeting objectives of fire hazard reduction, timber productivity or forest health using mechanical treatments in plantations such as the ones studied here do not appear to negatively affect productivity.***

## Management implications

Implications from this study are most relevant for areas of the Sierra Nevada mixed-conifer forest with similar soil productivity and texture. Blodgett Forest has a midlevel productivity for forests classified in the upper tier of productivity (i.e., site class I). Productive mixed-conifer forests such as these are common between 900 and 1,800 meters on the western slopes of the Sierra Nevada. Results are most directly applicable to forests with a similar loamy soil texture. Care should be taken when extending the results to other textures, especially clayey soils.

Potential effects of soil compaction include changes in forest structure, soil moisture holding capacity, resistance to root growth and increased runoff. For good reason, effects of operations on soil compaction should be considered. While coarser soils appear to be more resilient to the effects of compaction, each compaction event from mechanical treatments may shift the soil, albeit slightly, toward a finer texture by incrementally reducing pore size. If thinnings are done too frequently to allow for recovery between them, the soil may become vulnerable to compaction, especially in terms of reduced water holding capacity on clayey soils (Hill and Sumner 1967). Further studies may help clarify the relationship between soil strength and silvicultural decisions such as commercial thinning frequency and rotation age in plantations.

The degree of compaction observed in this study is still far less than the degree experimentally created by Gomez et al. (2002), who compacted loamy soils close to our study site to > 3,000 kPa below 10 centimeters depth and still found no significant effect of compaction on above-ground tree productivity. Meeting objectives of fire hazard reduction, timber productivity or forest health using mechanical treatments in plantations such as the ones studied here do not appear to negatively affect productivity related to increased soil strength, although repeated treatments will be worth monitoring. Our study adds to the large body of literature suggesting that short-term objectives of fuel treatments can be met with little negative consequences on major ecosystem processes (Stephens et al. 2012).

This conclusion that negative impacts can be avoided, however, assumes that best practices are used to continue avoiding negative impacts. Best practices include, most importantly, avoiding operations with heavy equipment when soils are saturated with moisture. Additionally, equipment that uses less ground force, such as tracked rather than wheeled machines, are preferred. Over the long term, the input of organic matter into soil may be important as well, and can be ensured by maintaining a vegetative understory layer. Finally, skid trail length should be minimized and skid trails should be reused when possible. CA

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Review Article

# Modeling fuel treatment impacts on fire suppression cost savings: A review

*by* Matthew P. Thompson *and* Nathaniel M. Anderson

***High up-front costs and uncertain return on investment make it difficult for land managers to economically justify large-scale fuel treatments, which remove trees and other vegetation to improve conditions for fire control, reduce the likelihood of ignition, or reduce potential damage from wildland fire if it occurs. In the short-term, revenue from harvested forest products can offset treatment costs and broaden opportunities for treatment implementation. Increasingly, financial analysis of fuel treatments is also incorporating long-term savings through reduced fire suppression costs, which can be difficult to quantify. This paper reviews the findings and lessons from recent modeling work evaluating the potential relationship between fuel treatments and avoided fire suppression costs. Across studies, treatments are generally predicted to reduce future fire suppression costs, although the magnitude of savings is unlikely to fully offset fuel treatment costs. This funding gap highlights the importance of forest product revenues in facilitating landscape-scale treatment. Factors influencing the effects of fuel treatment investments on fire suppression costs include the causal pathway linking treatment inputs to suppression cost outcomes; the spatiotemporal uncertainty of wildfire–treatment interactions; and the scale of fuel treatment programs.***

Savings on fire suppression costs are thought to be a benefit of fuel treatments but have not been well quantified. Escalating suppression costs as well as policy initiatives such as the U.S. Forest Service's Collaborative Forest Landscape Restoration Program (CFLRP) — which funds collaborative, science-based ecosystem restoration of priority forest landscapes, and is intended in part to reduce wildfire management costs — are driving calls for systematic approaches that evaluate the return on fire management investments. Recent modeling work has yielded several alternative approaches to evaluate the relationship between investments in fuel treatments and future avoided fire suppression costs.

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## Fuel treatment costs

Figure 1 provides a conceptual economic model of fuel treatment–wildfire interactions. Net fuel treatment costs are a function of direct expenditures on treatments, including periodic maintenance like prescribed fire, and revenues generated from the sale of marketable products like biomass, pulpwood and sawlogs. In addition, fuel treatments may reduce future expenditures on fire suppression and some measure of these cost savings can be discounted and credited to the treatment.

In general, the costs of forest operations and logistics are well understood by contractors and forest engineers (e.g., Bolding et al. 2009; Pan et al. 2008; Vitorelo et al. 2011), though noncommercial fuel treatments are less well studied than commercial logging operations. As with other types of silvicultural work, fuel treatments are most costly when

**An interagency crew conducts a prescribed burn to help stop the Big Windy Complex Wildlands fire near Galice, Oregon, in 2013. In California, annual federal and state spending on wildfire suppression typically exceeds $1 billion.**

Lance Cheung / USDA

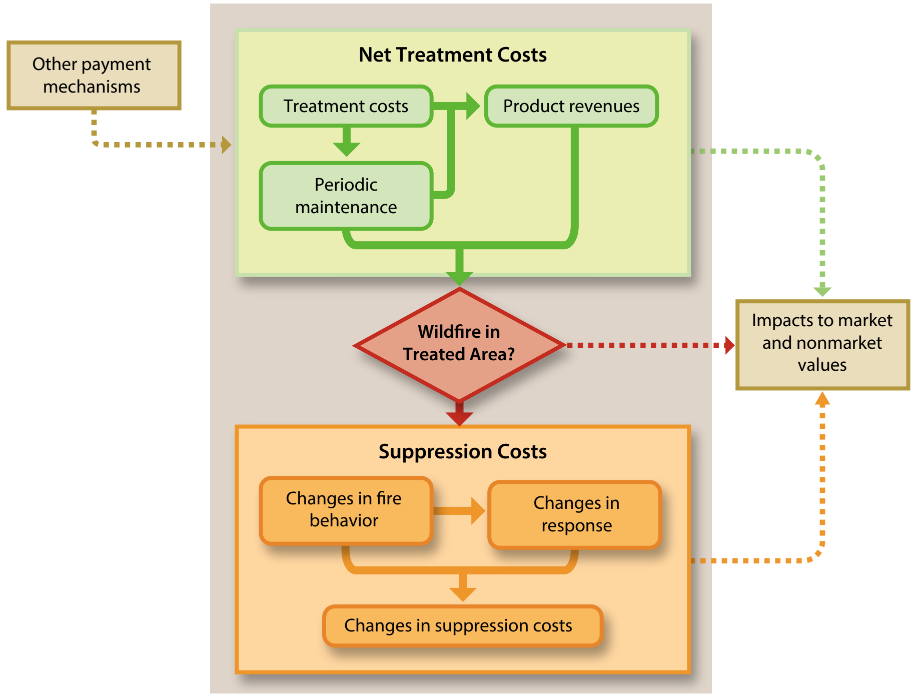


**Fig. 1. Model of the primary financial aspects of fuel treatment–wildfire interactions. Net treatment costs are a function of the direct costs of treatment and potential revenues from forest product removals. The type of treatment implemented may require subsequent maintenance treatments to maintain a low hazard state. If the treated area experiences a wildfire, then changes in suppression costs (relative to an untreated landscape) may occur.**

they involve difficult conditions such as steep terrain, limited access over low standard forest roads, long transportation distances, expensive labor and fuel, high transaction costs, dense residual stand conditions and costly site preparation and maintenance (Rummer 2008). Mechanical fuel treatments under these conditions can cost thousands of dollars per hectare (Prestemon et al. 2008; USDA Forest Service 2005). Less costly treatments are, as would be expected, characterized by more favorable conditions.

Research aimed at reducing fuel treatment costs has focused primarily on deploying new equipment and developing new systems for efficiently harvesting, processing and transporting biomass and small logs (Bolding et al. 2006; Demchik et al. 2009; Han et al. 2010; Johansson et al. 2006; Uslu et al. 2008). On federal land, the use of long-term stewardship contracts and the development of CFLRP also appear to have reduced transaction costs and increased the reliability of supply chains to some extent (Nielsen-Pincus 2013; Schultz et al. 2012).

The revenue component of the net cost equation for fuel treatments can vary widely as well; in noncommercial forests in particular, it may be much smaller than the cost of treatment. Often, fuel treatments generate primarily low grade, low value products, or no products at all. Furthermore, in areas that have lost much of their forest products infrastructure, even if the outputs from treatments meet commercial specifications, revenues cannot be generated if primary manufacturing facilities like pulp mills and saw mills are so distant from fuel treatment sites that transportation costs are uneconomical. In fact, long distance to market has been shown to result in less fuel treatment on the landscape (Nielsen-Pincus et al. 2013). Efforts to increase revenues have focused on stimulating demand for biomass and low-grade timber outputs, especially demand from solid wood products manufacturing, base-load power plants, industrial co-generation facilities, distributed-scale conversion systems and home heating (Baxter 2005; Best 2014; LeVan-Green 2001; Nicholls et al. 2008; Wood and Rowley 2011). Though farther from widespread commercialization, the industrial production of liquid fuels, chemicals and carbon products from biomass also holds promise (Anderson et al. 2013; Briens et al. 2008). Many of these uses for small logs and biomass have been supported directly and indirectly by a wide variety of public policies (Aguilar et al. 2011).

## Fire suppression costs

Expenditures on large wildfire management are driven by the amount and type of firefighting resources used over

**A trailer is loaded with wood chips at a U.S. Forest Service–funded fuels reduction project in the Lake Tahoe area. The chips will be hauled to a biomass energy facility to help defray disposal costs.**

Will Suckow

the duration of an incident. The deployment of these resources is in turn influenced by a multitude of factors including incident management strategies and tactics, proximity to human communities and private property, weather and landscape conditions driving fire behavior, and sociopolitical issues (Hand et al. 2014; Thompson 2014).

Although anecdotal evidence suggests treatments can enhance suppression effectiveness and firefighter safety, knowledge gaps and data limitations have precluded direct quantification of the influence of past fuel treatment investments on wildfire suppression expenditures. Further, it is not feasible to experimentally test how the suppression of otherwise identical wildfires would vary on untreated versus treated landscapes.

Model-based approaches to infer treatment impacts on suppression expenditures are therefore necessary. The main challenge is to identify a logical pathway connecting changes induced by fuel treatments to meaningful changes in factors influencing fire suppression expenditures. For example, inferences could be drawn regarding fuel treatments that limit fire spread and area burned, leading to smaller fire sizes, shorter incident durations or both. Alternatively, fuel treatments that reduce extreme fire behavior and burn severity could lead to less intensive firefighting resource demands because of reduced potential for damages or increased potential for resource benefits.

Note that a broad range of impacts — beyond the costs of fuel treatments and any corresponding reductions in fire suppression expenses — must be considered in a comprehensive economic analysis of potential fuel treatment strategies. As shown in the upper left box of figure 1, outside funding sources and other payment mechanisms could be tapped to increase the scale of fuel treatment investment, for instance through homeowner fees or public–private partnerships (Mueller et al. 2013; Warziniack and Thompson 2013). Perhaps more importantly, fuel treatments, wildfires and suppression activities can all impact market (e.g., timber, homes) and nonmarket (e.g., air quality, wildlife habitat) values (right side of fig. 1). Losses associated with destruction of homes and loss of life can overwhelm direct wildfire management expenditures. Nonmarket values such as ecosystem services can also be substantial, though assessments of such impacts are often specific to a particular wildfire and thus difficult to generalize. Stephenson et al. (2013) found that conservative estimates of the proportion of total loss attributed to loss of ecosystem services ranged from 9% to 71% across the wildfires studied.

When this broader range of benefits is accounted for, fuel treatment strategies may have a benefit:cost ratio exceeding 1:1 even in cases where the net costs of treatment far exceed any possible savings in fire suppression expenditures. Improved accounting of the full range of costs and benefits of fuel treatments could lead to improved policies for long-term fire management and forest health (Wu et al. 2011).

Unfortunately, characterizing the full range of potential benefits linked to fuel treatment investments is challenging. In some cases, the magnitude and even the sign (positive or negative) of impacts are not readily apparent. For instance, fuel treatments that enhance ecosystem resiliency to wildfire in the long-term may also degrade wildlife habitat in the near-term (Stephens et al. 2014). Further, assessments of the nonmarket impacts of wildfires may provide only limited utility for deciding when and where to invest in fuel treatments, since such assessments rarely consider uncertainty and risk, or how wildland fire management can reduce losses (Milne et al. 2014).

In this article we limit our focus to the financial considerations facing land management agencies that invest in and implement fuel treatments, and that incur wildfire suppression expenditures (highlighted in the grey box in fig. 1).

## Three modeling approaches

We compared three recent studies that vary by geographic region, spatiotemporal scope and assumptions about factors driving changes in suppression costs (fig. 2). Thompson et al. (2013) focus on reductions in fire size; Fitch et al. (2013) focus on reductions in crown fire behavior and associated reductions in burn severity; and Taylor et al. (2013) focus on state-transition dynamics in terms of ecological condition and potential site occupancy by an invasive species.

**Focus: Fire size.** The Thompson et al. (2013) study focused on the Deschutes Collaborative Forest Project in Oregon's Deschutes National Forest. This project was one of the first to be funded under CFLRP, and similar modeling approaches are currently being applied to analyze suppression cost impacts on other CFLRP-funded projects throughout the United States. The model couples a stochastic

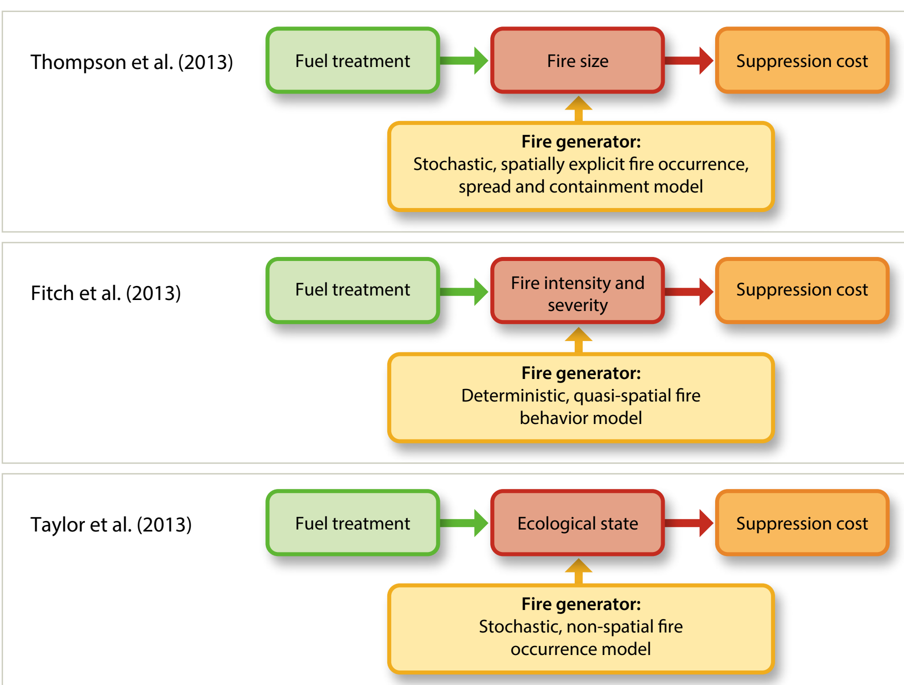


**Fig. 2. Primary assumed treatment impact pathways linking fuel treatments to suppression costs. The three approaches rely on different measures (fire size, fire intensity and severity, and ecological state) to model impacts to suppression costs.**

(probabilistic) fire occurrence, spread and containment model (Finney et al. 2011) with a large-fire (≥ 300 acres) statistical fire suppression cost model currently used by federal agencies for decision support and performance evaluation (Calkin et al. 2011; Gebert et al. 2007).

This approach simulates thousands of potential fire seasons based upon current landscape conditions and historical fire weather and fire occurrence patterns. Each simulated season has zero to multiple large fires, each of which is assigned a suppression cost. The model then generates distributions of per-season and per-fire costs.

Of the three studies, this approach arguably has the strongest spatial component, capturing (a) the heterogeneity of fire likelihood and behavior across the landscape; (b) the size and location of treatments with respect to fire spread direction; and (c) the location of ignitions with respect to factors influencing cost such as land designation and proximity to human development.

However, temporal issues are poorly addressed. The model assumes immediate implementation of all treatments across the landscape, and does not consider post-treatment regrowth or discounted cash flows from future savings. Thus, the model effectively focuses on the distribution of possible realizations of the next fire season alone.

The model projects that fuel treatments across 46% of the 145,000-acre study area would lead to smaller fires, leading to higher per-acre fire suppression costs in treated areas (mean 2.24% higher) but lower overall per-fire costs (mean 15.86% lower) consistent with historical wildfire size-cost relationships. Although the authors did not specifically provide modeling results for cost per acre on a per-fire basis, data on fire suppression costs in the Deschutes National Forest from 2000 to 2011 shows a range of $382 to $6,461 per acre with a mean of $2,117 per acre. Across the entire study area, modeling results indicate that mean per-fire size (9,541 acres) dropped by 4.7% after treatment, and mean per-fire cost ($9,003,597) dropped by 6.7% after treatment. Similarly, mean per-season area burned (5,398 acres) dropped by 11.1% after treatment, and mean per-season cost ($4,432,626) dropped by 13.0% after treatment (mean per-season cost estimates are lower because large wildfires do not occur every year).

**Focus: Intensity and severity.** Fitch et al. (2013) modeled another CFLRP project location, the Four Forest Restoration Initiative in Arizona, and like Thompson et al. did not consider issues related to the timing of treatment implementation, post-treatment regrowth or cash flow discounting.

Here, the analysis focused on the impact of fuel treatments on the severity of a single fire event that burns the entire 175,617-acre project area, reporting results in terms of per-acre and per-fire costs. Results are conditional, in the sense that the occurrence of a wildfire is assumed and the likelihood of the project area experiencing a large wildfire is not explicitly considered in the financial analysis. The FlamMap fire modeling system (Finney 2006) is used to project crown fire behavior under constant, non-extreme fire weather conditions for every pixel across the project area, and these fire behavior estimates are used to infer areas of high burn severity.

For cost modeling purposes, the authors developed a specific regression model incorporating burn severity, based on 39 large wildfires (≥ 1,000 acres) occurring within the study area between 2001 and 2009. The paper reports on two scenarios: (a) current conditions; and (b) a post-treatment scenario in which the entire project area has been treated. In the post-treatment scenario, the fraction of the landscape that burned with high severity is reduced from 28.6% to 2.6%, leading to substantial cost savings: per-acre cost

**A fire burns a Great Basin sagebrush landscape in Bridger-Teton National Forest, Wyoming, September 18, 2010.**

Mike Johnston / US Forest Service

($706) dropped by 59.3% and the total fire cost ($25,006,591) dropped by 10.0%.

**Focus: Ecological state.** Taylor et al. (2013) did not focus on a specific landscape, but instead abstracted their model to broadly consider Wyoming Sagebrush Steppe (WSS) and Mountain Big Sagebrush (MBS) ecosystems in the Great Basin. A key distinguishing feature of this study is the long-term perspective, focusing on vegetative succession, ecosystem state-transition dynamics and the role of treatments and wildfires through time. Additional dimensions of this study included uncertainty regarding thresholds differentiating ecological states, probabilistic treatment success rates and treatment cost estimation to determine return on investment.

The study considered three WSS states and four MBS states, ranging from most to least healthy. The healthy ecological states were characterized by vigorous native shrub or tree communities; wildfire in these ecological states is beneficial and helps to maintain health. The unhealthy states were characterized by less-healthy tree and shrub communities and increasing domination by invasive annual grasses; wildfires in these ecological states tend to promote unhealthy, fire-prone, annual-grass-dominated plant communities.

To accommodate the broader temporal perspective Taylor et al. reduced their spatial resolution to a single acre analysis unit. The authors did not model fire growth or size directly but accounted for variability in fire size by assigning per-acre fire suppression costs in their simulations in proportion to historical fire size distributions. Fire suppression cost data stemmed from 400 large wildfires (≥ 100 acres prior to 2003; ≥ 300 acres after 2003) occurring over the years 1995–2007 in the U.S. Forest Service's Intermountain Region.

The authors partitioned per-acre fire suppression cost estimates according to ecological state, using the National Fire Danger Rating System fuel model category as a proxy. This screening process reduced the set of fires analyzed to 125 by matching historical records to the set of ecological states analyzed in the model. Fire suppression costs ranged from $190 to $789 per acre.

Treatment costs were drawn from a Natural Resources Conservation Service database on the actual costs of conservation practices in Utah in 2011. They ranged from $20 per acre for healthy ecological states — which require only prescribed fire — to as much as $205 per acre for less-healthy states, which require rehabilitation including brush management, herbicide application and reseeding.

Across a 200-year planning horizon, treatment resulted in a decrease in mean per-acre fire suppression costs of 36% to 84% in six of the seven ecological states analyzed; in the seventh state, suppression costs increased 38%. However, when the high cost of treating the less-healthy ecological states is accounted for, treatment provides a clear economic benefit only when the WSS and MBS ecosystems are in their healthiest ecological states.

**TABLE 1. Planning context, fire and cost modeling approaches and summary results for the three models reviewed**

| Study attributes | Thompson et al. (2013) | Fitch et al. (2013) | Taylor et al. (2013) |
|---|---|---|---|
| **Planning context** | | | |
| Geographic area | Deschutes Collaborative Forest Project, Oregon | Four Forest Restoration Initiative, Arizona | Great Basin sagebrush ecosystems |
| Spatiotemporal scope | Single fire season; fires are distributed across landscape | Single fire event burns entire project area | 200 fire seasons; annual fire event burns single acre |
| **Fire model** | | | |
| Approach | Stochastic, spatial fire occurrence, spread and containment model | Fire behavior prediction under given fire weather and fuel moisture conditions | Annual fire occurrence probability |
| Fire likelihood characterization | Spatially heterogeneous burn probabilities | N/A | Constant, spatially uniform burn probability |
| Fire intensity characterization | N/A* | Crown fire activity | N/A |
| Fire size characterization | Output for each simulated fire event | Fire size is given as project area | Implicit; per-acre costs drawn from weighted distribution |
| **Cost model** | | | |
| Approach | Econometric regression model | Econometric regression model | Assigns historical costs on basis of fuel model |
| Cost characterization | Per-acre, per-fire and per-season cost | Per-acre and per-fire | Per-acre |
| **Summary results (generalized to positive/negative): a plus indicates an increase in fire suppression costs; a minus indicates a reduction in fire suppression costs** | | | |
| Per-acre cost | + | – | – |
| Per-fire cost | – | – | N/A |
| Per-season cost | – | N/A | N/A |

* While fire intensity metrics are output from the fire modeling system used, these values are not used for cost modeling purposes.

## Comparing the models

Table 1 compares and contrasts the studies by planning context, fire and cost modeling approaches and summary results. Fundamentally, all three studies rely on the same basic coupling of fire modeling with cost modeling techniques, based on geographically relevant historical suppression costs, albeit with different underlying fire and cost models. Further, all three studies rely on comparative simulations of existing conditions and post-treatment conditions, largely holding other parameters constant to isolate treatment impacts. All studies indicated that fuel treatments could result in suppression cost savings, with varying assumed treatment impact pathways and comparative strengths and weaknesses.

Fitch et al. (2013) and Thompson et al. (2013) have stronger connections to operational planning through CFLRP and employ econometric analyses for cost estimation, while Taylor et al. (2013) and Thompson et al. (2013) explicitly model the probability of treatments interacting with wildfire.

The Thompson et al. (2013) study is more appropriate for contexts with protection objectives, such as areas near human development or fire-susceptible

Revenue from the sale of forest products generated by thinning operations can help to offset the costs of fuel treatments. A forwarder collects marketable logs at the U.S. Forest Service Yeti Fuels Reduction Project near Lake Tahoe.

infrastructure, where treatments could reduce fire spread potential and/or facilitate containment. The focus on fire size, however, may preclude applicability to contexts with restoration objectives, and this stronger connection to fire-adapted ecosystems is a key strength of the Fitch et al. (2013) and Taylor et al. (2013) approaches.

Lastly, Fitch et al. (2013) has the strongest temporal component, capturing fire–treatment interactions and rangeland dynamics through time as well as a long-term financial perspective with a discounted cash flow of future expenditures through time.

No single analysis tells the entire story, but collectively the models provide insight and guidance for future investigation. Might fuel treatments result in suppression cost savings? Yes. Might these savings pay for the full cost of implementing fuel treatments? Not likely, except in rare circumstances. Leveraging the relative strengths of these studies could help to inform financial analysis of variable fuel treatment and suppression policies over space and time.

## Relevance to California

Opportunities for directly applying results from these studies to California are somewhat limited in scope but potentially significant; suppression costs for fires in California are among the highest in the nation, particularly for the U.S. Forest Service (Hand et al. 2014). As an illustration, from 2000 to 2012, seven of the top 10 most expensive national forest fires were in California; mean annual fire suppression costs for these forests ranged from $17 to $40 million (Thompson et al. 2015). The higher costs are in part due to a relatively high density of human communities in fire-prone areas, although even after accounting for the fire environment and homes, wildfires in California managed by the U.S. Forest Service still tend to cost more than anywhere elsewhere in the United States (Gebert et al. 2007). Fire management culture, sociopolitical pressures and other human factors may also account for the unusually high costs of fire suppression in the state (Thompson 2014).

A clear need is a similar analysis to those mentioned in this paper tailored to the geographic and socioeconomic conditions of California. Such work could build on existing research identifying potential areas of higher suppression expenditures in the state (Preisler et al. 2011), while additionally incorporating realistic treatment strategies, impacts and constraints (North et al. 2014). In some areas, such as Southern California, a high density of fire-susceptible assets and fire-prone vegetation may limit opportunities for treatments aimed at restoring natural fire regimes. In these areas, recognition of the limited effectiveness of fuel breaks under extreme conditions may lead instead to risk mitigation strategies focused on reducing susceptibility of the built environment (Calkin et al. 2014; Penman et al. 2014; Syphard et al. 2011). Elsewhere on publicly managed lands in the Sierra Nevada and Northern California, fuel treatment strategies could be designed to set the stage for increased rates of prescribed and managed wildfire (North et al. 2012).

## Lessons learned

An analysis of these studies and the broader literature on fuel treatment effectiveness points to several important themes.

First, to account for the inherent uncertainty of when and where wildfires will occur, evaluations of return on fuel treatment investments must use a spatial, risk-based framework (Thompson and Calkin 2011; Warziniack and Thompson 2013). Specifically, it is critical to quantify the likelihood that a given treated area will experience a wildfire during its effective lifespan (Kline 2004). Furthermore, models must account for the fact that the uncertainty surrounding treatment impacts grows as projections extend through time, owing to the joint influences of vegetative succession, disturbance dynamics, management activities and other drivers. Models that do not account for this spatiotemporal uncertainty may grossly overestimate the benefits of fuel treatments by assuming the occurrence of wildfire in treated areas at the point of their maximum effectiveness (Campbell and Ager 2013).

Second, the relative rarity of large wildfire on any given point on the landscape and the commensurate low likelihood of any given area burning in any given year suggest a need for large-scale fuel treatments. As the geographic extent of treated areas increases, so too does (a) the likelihood of treated areas interacting with wildfire; (b) the likelihood that, when tested by fire, treatments will have significant effects on landscape-scale fire behavior; and (c) the likelihood that information about the fuel treatments conducted in an area will be incorporated into wildfire response strategies and tactics. Thus, in order to save large amounts of money on fire suppression, land management agencies may need to spend large amounts of money on large-scale fuel treatment.

Third, the need for large-scale treatments coupled with the difficulty in financing such treatments with agency resources alone suggests a commensurate need for offsetting treatment costs with forest product revenues or other payment mechanisms in addition to fire suppression cost savings.

Clearly, in areas where suitable markets for biomass and low-grade logs exist, there are opportunities to generate immediate revenues to support broad treatment implementation.

These opportunities could be expanded by supporting existing capacity and stimulating new capacity for biomass and small log utilization as well as by coupling economically viable commercial treatments with noncommercial treatments to increase the total area treated.

Mechanisms do not currently exist to link fire suppression cost savings to fuel treatment costs, so local decisions to invest in treatments today are unlikely to include cost savings associated with future suppression efforts. Over time, if fuel treatment investments yield meaningful fire suppression cost savings at acceptable levels of reliability, agency budget processes could account for the anticipated savings when allocating funds for treatments. CA

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Research Article

# Economic sustainability modeling provides decision support for assessing hybrid poplar-based biofuel development in California

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***Biofuels are expected to play a major role in meeting California's long-term energy needs, but many factors influence the commercial viability of the various feedstock and production technology options. We developed a spatially explicit analytic framework that integrates models of plant growth, crop adoption, feedstock location, transportation logistics, economic impact, biorefinery costs and biorefinery energy use and emissions. We used this framework to assess the economic potential of hybrid poplar as a feedstock for jet fuel production in Northern California. Results suggest that the region has sufficient suitable croplands (2.3 million acres) and nonarable lands (1.5 million acres) for poplar cultivation to produce as much as 2.26 billion gallons of jet fuel annually. However, there are major obstacles to such large-scale production, including, on nonarable lands, low poplar yields and broad spatial distribution and, on croplands, competition with existing crops. We estimated the production cost of jet fuel to be $4.40 to $5.40 per gallon for poplar biomass grown on nonarable lands and $3.60 to $4.50 per gallon for biomass grown on irrigated cropland; the current market price is $2.12 per gallon. Improved poplar yields, use of supplementary feedstocks at the biorefinery and economic supports such as carbon credits could help to overcome these barriers.***

California policies designed to reduce greenhouse gas emissions are creating a new economic reality for in-state bioenergy production through the cap and trade program, the low carbon fuel standard (LCFS) program, Senate Bill 1122, which requires that utilities procure at least 250 megawatts of bioenergy, and increasingly stringent renewable portfolio standards. Assembly Bill 32 sets a goal of reducing greenhouse gas emissions in the state to 1990 levels by 2020, while the LCFS program aims to reduce transportation fuel carbon intensity by 10% to achieve those targets. In addition, an executive order issued by Gov. Jerry Brown in April 2015 calls for an 80% reduction in greenhouse gas emissions statewide by 2050. Locally produced renewable energy sources such as biomass-derived fuels have the potential to help achieve these goals and meet California's energy needs (Jenkins et al. 2009; Morrison et al. 2014; Youngs and Somerville 2013).

Numerous cellulosic biomass resources are potentially available for biofuel production in California, including crop residues (e.g., rice and wheat straw), perennial grasses (e.g., switchgrass [*Pennisetum purpureum*]), forest residues (e.g., logging slash and forest thinnings), and wood

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v069n03p171&fulltext=yes
doi: 10.3733/ca.v069n03p171

Partially irrigated hybrid poplar plantation at a demonstration field site in Clarksburg, California, about 1 1/2 years after planting.

GreenWood Resources

chips from dedicated energy crops (e.g., hybrid poplar [*Populus* spp.], willow [*Salix* spp.] and eucalyptus [*Eucalyptus* spp.]) (Youngs and Somerville 2013).

Hybrid poplar is a widely studied short rotation (harvested frequently) woody crop that not only can serve as a feedstock for biofuel production, but also can offer multiple ecological benefits including carbon sequestration — in amounts ranging from 0.2 to 0.7 tons carbon per acre per year in the topsoil (Baum et al. 2009; Garten 2002) — restoration of degraded lands such as former mining sites (Werner et al. 2012), stream protection from agricultural runoff, and habitat for wildlife (Ugarte et al. 2003). Due to its rapid growth and suitability for coppicing (harvesting trees near ground level and allowing the trees to resprout for the subsequent growth interval), poplar has the ability to provide a flexible and consistent supply of biomass for biofuel production (Yemshanov and McKenney 2008). Ease of propagation and interspecies hybridization will likely facilitate the development of hybrid genotypes that are highly productive and suitable for a wide variety of soil and climatic conditions (Wang et al. 2013).

In addition, earlier studies have suggested that hybrid poplar can be grown on various lands (e.g., marginal lands) and that its growth depends on soil productivity and management (Netzer et al. 2010; Pearson et al. 2010; Xue et al. 2014). The average water requirement for trees 3 years or older is approximately 45 acre-inches/acre in a semi-arid environment (Shock et al. 2002), which implies that in drier regions, irrigation may be required to ensure plant survival and reasonable yields.

Although poplar is already recognized as a potential feedstock source for low-carbon biofuel production, commercial deployment is not yet realized due in part to economic conditions (e.g., net revenue constraints) and uncertainties about resource availability (e.g., land and water resources for poplar

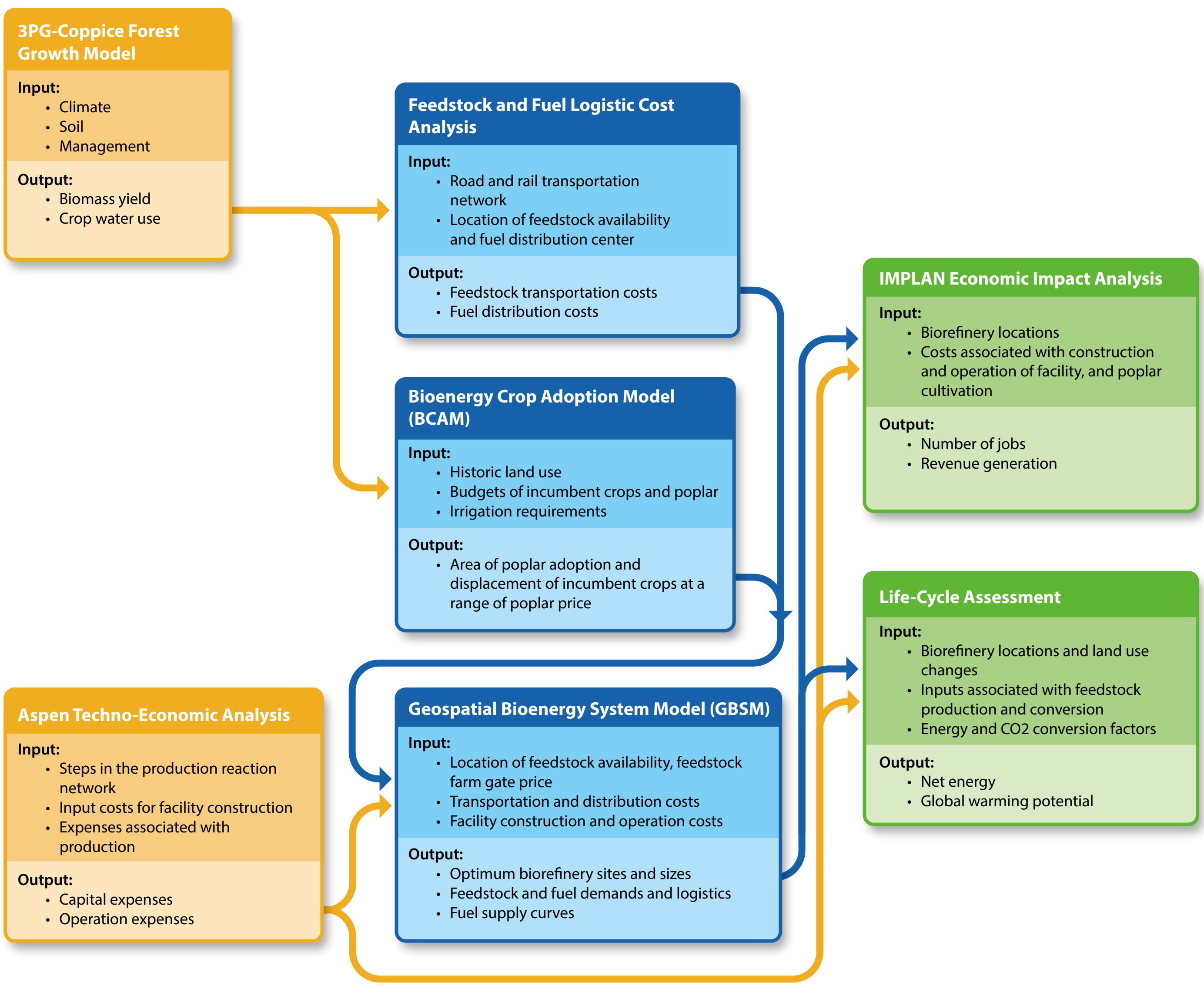


**Fig. 1. Integrated modeling framework used to assess the feasibility of poplar-based biofuel in Northern California. This framework consists of models and commercial software to assess various sustainability aspects related to poplar-based biofuel industry development. The arrows reflect the flows of data from model to model.**

cultivation). As part of a larger research and development initiative in the Pacific Northwest on sustainable production of biofuel from poplar (for details, visit hardwoodbiofuels.org), we used an integrated modeling framework comprised of multiple models (fig. 1) to assess the potential for poplar-based biofuel industries in a region comprised of 32 counties in Northern California (fig. 2). In this study, we evaluated poplar-based jet fuels, hydrocarbon fuels that meet current fuel quality specifications and are compatible with the existing infrastructure for handling and using petroleum-based fuels.

Aviation grade biofuels are particularly interesting because they are the only near-term option for low-carbon aircraft propulsion that does not require a complete redesign of aircraft. Over the longer term, other renewable energy carriers such as hydrogen and electricity may emerge if aircraft are developed to utilize those fuels. Liquid fuels generated from sunlight are another promising alternative that is currently in the laboratory development stage, e.g., methanol synthesis from carbon dioxide and water (Fairley 2011).

## Modeling approach

The framework integrates seven models that represent the elements of a poplar-based biofuel supply chain (fig. 1): feedstock production, optimization of biofuel production, facility-specific technical and economic performance, transportation network costs and life-cycle environmental and economic impacts. The framework includes (1) the 3PG-Coppice growth model, (2) the Bioenergy Crop Adoption Model (BCAM), (3) the Geospatial Bioenergy System Model (GBSM), (4) feedstock and fuel logistics cost analysis, (5) Aspen Plus techno-economic modeling software, (6) IMPLAN social and economic impact analysis software and (7) SimaPro life-cycle assessment software. BCAM and GBSM were developed at UC Davis. 3PG-Coppice was also developed at UC Davis as a modification of the original Physiological Principles in Predicting Growth (3PG) forest growth model created by Landsberg and Waring (1997) that did not allow for coppicing of the crop. The other models in the framework are commercially available products.


**Harvesting hybrid poplar at a demonstration site in Clarksburg, CA.**

**Poplar biomass yield.** We used the 3PG-Coppice model to predict potential yields of poplar biomass on available lands. When poplar is grown as a short rotation crop, coppicing facilitates multiple harvests during the production cycle. However, since the original 3PG model does not include algorithms for coppicing regrowth, we included a coppicing submodule to account for the root contribution to stem regrowth after harvesting (Prilepova et al. 2014).

**Transportation costs.** Where poplar biomass is produced influences the economic performance of refineries, as biomass collection and transportation costs depend on the location of feedstock production relative to the refinery site and the amount of feedstock demanded. To calculate the transportation costs for biomass, feedstock logistics data were applied within a GIS network analysis utilizing cost values from the literature for different transport modes (truck, rail and barge) (Parker et al. 2010).

**Crop adoption.** To be adopted by growers, poplar produced on croplands must economically outperform other crops. BCAM was used to examine the potential for poplar to compete with existing crops. BCAM is a whole-farm economic profit maximization model based on Positive Mathematical Programming optimization principles (Jenner and Kaffka 2012). It uses production budgets for hybrid poplar estimated from simulated biomass yields along with budgets for current crops with yields from U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (USDA 2010) historical data, and it computes crop shifting and area of poplar adoption at different market prices in a given region based on profit levels.

**Biofuel industry optimization.** GBSM is a spatially explicit optimization model developed using mixed-integer linear programming principles (Parker et al. 2010). The model considers the entire biofuel supply chain (i.e., distribution of biomass resources, costs associated with biomass production and harvesting, transportation costs of biomass supply to the refinery, and capital and operating costs of biorefineries as a function of size) and determine the optimal sites for the refineries based on maximizing overall profit. The capital and operating costs of biorefineries used in GBSM were estimated using a techno-economic model created in the process simulation software Aspen Plus (AspenTech 2011) and process-specific information regarding the conversion of biomass to fuel (Crawford 2013).

**Environmental and economic impacts.** The data from GBSM on optimum refinery sites and spatial land use change, and bioconversion data from Aspen Plus, were used in SimaPro v.7.3.3 (PRé Consultants 2012) to assess environmental impacts of poplar production. The socioeconomic impacts (e.g., job creation, revenue generation) at regional and state levels were analyzed using IMPLAN software. Results on the environmental and socioeconomic impacts are preliminary and are not discussed further here pending further analysis.

*Irrigated croplands and nonarable lands in Northern California have the potential to provide 18.9 and 7.1 million dry tons of poplar feedstock annually, which could result in 1,648 and 618 million gallons of jet fuel per year.*

## Potential poplar cultivation sites

We used land quality metrics and 2009 USDA land use and land cover data (Johnson and Mueller 2010) to identify potential nonarable lands (pasture and grasslands) and croplands for poplar cultivation in the study region, then used the 3PG-Coppice model to estimate the inherent biomass yield potentials on these locations under irrigated and nonirrigated conditions. Lands that were characterized by soil salinity (> 4.0 dS/m), steeper slope (> 15%), acidity (pH < 4.0), alkalinity (pH > 8) and shallow soil and water table depth (< 20 inches) were excluded and remaining soils were considered as suitable for poplar cultivation.

Our analysis showed that there are approximately 2.3 and 1.5 million acres of suitable croplands and nonarable lands available in Northern California, respectively. While suitable nonarable lands are scattered widely across the region, croplands are mostly concentrated in the Central Valley (fig. 2). Simulated biomass growth suggests that biomass potential varies substantially across the study region and ranges from 1.5 to 14.1 dry tons/acre per year depending on location, land type, climatic conditions and management (fig. 3). Irrigated croplands result in considerably higher yields (on average 44%) than nonarable lands (which are not irrigated) with spatial averages of 8.2 and 4.6 dry tons/acre per year, respectively (fig. 3).

Overall, irrigated croplands and nonarable lands in Northern California have the potential to provide 18.9 and 7.1 million dry tons of poplar feedstock annually, which could result in 1,648 and 618 million gallons of jet fuel per year based on projected fuel yields of 80 gallons per dry ton of biomass feedstock (Crawford 2013). However, it is important to recognize that the actual amount of biomass available for biofuel production and amount of jet fuel produced depend on many factors, such as the amount of available cropland that will be converted to poplar cultivation.

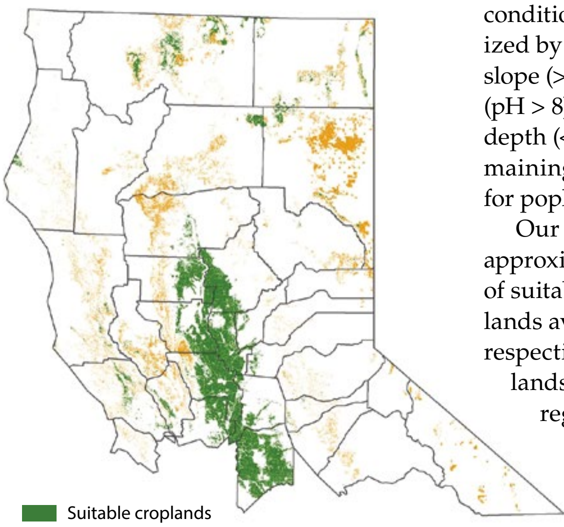


**Fig. 2. Available croplands and nonarable lands (nonirrigated pasture and grasslands) in the study region (32 counties in Northern California) suitable for poplar cultivation under model analysis. Black lines represent county boundaries.**

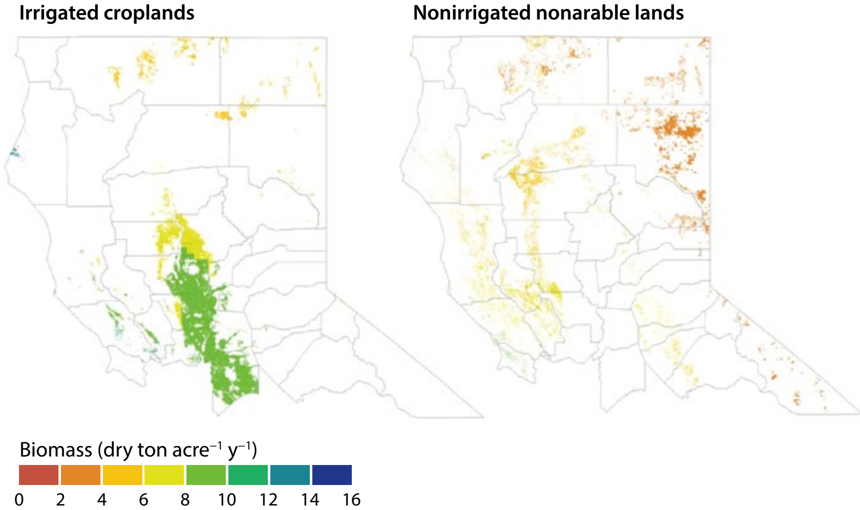


**Fig. 3. Spatial estimates of poplar biomass yields (dry tons per acre per year) from suitable irrigated croplands and nonarable lands (nonirrigated pasture and grasslands).**

## Economics of poplar production

Higher profits from poplar cultivation compared to other feasible crops are needed for landowners to adopt hybrid poplar for bioenergy purposes. We evaluated the economics of poplar production on both irrigated croplands and nonarable lands.

We estimated that the average poplar production cost (not including transport to the biorefinery) on nonarable lands in Northern California is $74/dry ton; for irrigated croplands, the average cost is $53/dry ton, due mostly to higher yields and lower establishment costs. Even though the production cost for irrigated croplands is lower than that for nonirrigated lands, the opportunity costs of displacing other crops are likely to be much higher, as poplar must compete with existing crops and typically incurs a 20-year production commitment.

**Nonarable lands.** In the case of nonarable lands, the opportunity cost of land is less than on irrigated cropland; however, due to lower biomass yield potentials and higher production costs associated with establishment and harvesting, poplar production is on the whole less economically viable. In addition, the intermittent cash flow from 2- to 3-year harvesting cycles may discourage some landowners from growing poplar. Therefore, to make poplar production economically attractive on nonarable lands, substantial incentives may be required, such as the Biomass Crop Assistance Program (BCAP) (Schnepf 2014). Research efforts targeting plant breeding to develop high yielding varieties could help further by increasing the profitability of hybrid poplar on nonarable lands (Berguson et al. 2010), although water is likely to remain a critical constraint for such lands in California.

**Irrigated croplands.** Croplands in California are characterized by highly diversified farming systems comprising numerous high-value specialty crops such as vegetables, fruits and nuts, and field crops (e.g., rice, wheat, corn). As such, poplar will encounter significant competition from these cropping systems. The total potential for poplar adoption in a given region depends on local farming patterns. A region with a high number of lower-value crops could witness a high fraction of poplar adoption. Economic analysis using BCAM indicates that hay followed by corn silage are the crops most likely to be displaced by poplar.

Another important observation is that the entry price (the market price at which poplar is likely to be adopted) will vary from region to region depending on the demand for existing crop commodities, poplar biomass potential and poplar production costs. For instance, BCAM results suggest that because of higher average yields, the north central region of California has a lower entry price ($48/dry ton) for poplar adoption when compared to northwestern ($54/dry ton) and northeastern California ($69/dry ton).

## Economics of potential biorefineries

The financial performance of the biofuel industry is influenced by many factors, including the distribution of biomass resources, collection and transportation costs, and economies of scale associated with facility construction and operation (Leduc et al. 2010). The interactions among these factors and how they influence each other is important in determining the overall economic feasibility of the biofuel industry. We used GBSM to assess the economic efficiency of potential poplar-based jet fuel facilities in Northern California each with a production capacity of 100 million gallons per year (MGY). A total of 212 representative potential facility sites were selected from a set of locations having existing industrial land or similar industrial facilities in the vicinity (figs. 4 and 5). Site-specific capital costs were based on the cost of adding infrastructure (such as building a rail spur to the site) and the value of industrial land at the location. Facility construction and operating costs were based on data from the ZeaChem demonstration biorefinery at Boardman, Oregon (Verser and Eggeman 2011), which was designed with a production yield of approximately 80 gallons of jet fuel from each dry ton of biomass feedstock.

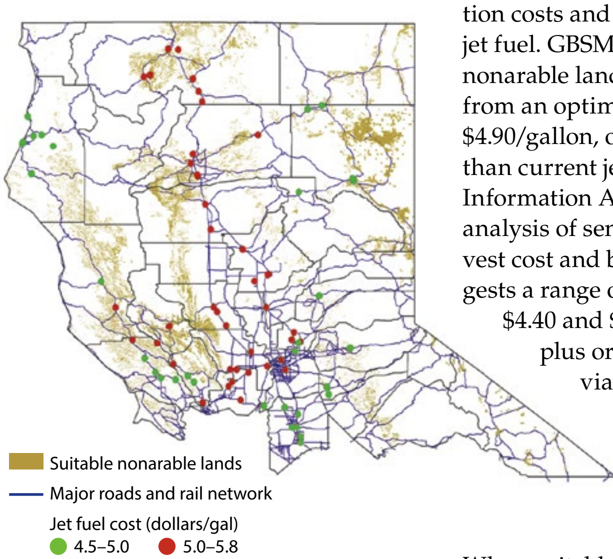


**Fig. 4. Possible sites for independent 100-million-gallon per year (MGY) biorefineries in Northern California and optimum jet fuel price for each site based on biomass supply from suitable nonarable lands (nonirrigated pasture and grasslands).**

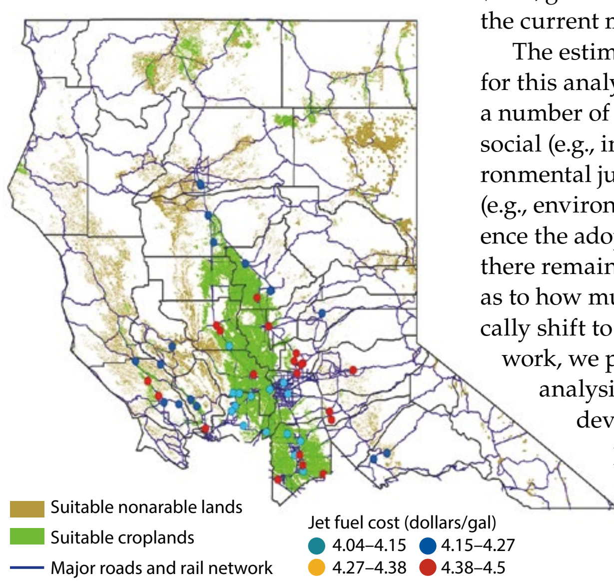


**Fig. 5. Possible sites for independent 100-million-gallon per year (MGY) biorefineries in Northern California and optimum jet fuel price for each site based on biomass supply from both suitable croplands and nonarable lands (nonirrigated pasture and grasslands).**

As mentioned earlier, suitable nonarable lands in Northern California are widely scattered across the region and are characterized by lower biomass yields. These factors lead to substantially higher biomass acquisition and transportation costs and impact the final cost of jet fuel. GBSM results indicate that for nonarable lands, the average jet fuel price from an optimized 100-MGY facility is $4.90/gallon, or about $2.78/gallon higher than current jet fuel price (U.S. Energy Information Administration 2015). An analysis of sensitivity to poplar yield, harvest cost and biorefinery capital cost suggests a range of optimized costs between $4.40 and $5.40 per gallon (average plus or minus one standard deviation). Thus, under current market conditions, poplar from nonarable lands alone may not be enough to support a poplar-based biofuel industry. When suitable croplands are considered along with nonarable lands for poplar production, jet fuel might be produced at a significantly lower cost — $3.60 to $4.50 per gallon with an expected value of $4.04/gallon — but one that is still above the current market price.

The estimate of adopted croplands for this analysis is strictly economic, but a number of other elements, including social (e.g., individual perceptions, environmental justice) and regulatory factors (e.g., environmental policies), also influence the adoption of new crops. As such, there remains substantial uncertainty as to how much cropland might realistically shift to poplar production. In future work, we plan to use the life-cycle analysis and IMPLAN models to develop a clearer picture of the prospects for poplar as a viable biofuel crop.

## Conclusions

Even though there is a reasonable amount of suitable nonarable land available, lower biomass yields on nonirrigated land and the dispersed geographic distribution of suitable lands are major barriers to

***Even though there is a reasonable amount of suitable nonarable land available, lower biomass yields on nonirrigated land and the dispersed geographic distribution of suitable lands are major barriers to poplar adoption.***

poplar adoption. Continuing research efforts to improve poplar biomass yields may be able to reduce production costs. Developing technology that utilizes additional biomass resources such as crop residues (e.g., wheat straw, rice straw) and forest residues for jet fuel at the same facility could improve prospects for the biofuel industry. Poplar feedstock also can be used to produce other bio-based products (e.g., organic chemicals, adhesives) that may be economically more promising due to the lower costs of feedstock conversion and higher value in the marketplace.

Policy measures, particularly higher value carbon credits, could also improve prospects for a larger biofuel industry in California. Companion research from the University of Washington indicates that the global warming potential of poplar-based jet fuels produced using lignin gasification technology is 27% to 71% lower than that of petroleum-based jet fuels. Thus, carbon credits could help a poplar-based jet fuel industry to become an economically competitive alternative. The modeling framework outlined here is designed to provide important decision support capacity in the analysis of agronomic, technology and policy alternatives not only for biofuel production, but for other resource management questions, including crop and livestock development, and soil and water conservation, more generally. CA

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# Are double trailers cost effective for transporting forest biomass on steep terrain?

*by* Rene Zamora-Cristales *and* John Sessions

***Transportation of forest biomass on steep terrain involves logistical challenges. Trucks with large single trailers are often unable to travel on forest roads due to their narrowness, tight curves, adverse grades and limited areas to turn around. A shorter trailer must be used but then transportation capacity is limited by the trailer volume due to the low bulk density of the processed biomass, particularly when the biomass is dry. With double trailers, transportation capacity can be limited by allowable legal weight based on axle number and spacing. We developed a simulation model that explores the economic feasibility of using double-trailer configurations to transport forest biomass to a bioenergy facility from the grinder at a landing or from a centralized yard in Washington, Oregon and California. Results show that double trailers can be a cost effective alternative to single trailers under limited conditions in Oregon and Washington, but they are not a competitive option in California due to the state's transportation regulations.***

In the United States, comminuted forest biomass from harvest residues is mainly transported from the forest to bioenergy facilities using truck-tractors pulling single trailers of different capacities. Trailer capacity is a function of the truck power train, trailer dimensions, transportation regulations and bulk density of the processed biomass. Transportation cost is a major component of biomass delivered cost. High diesel prices have increased transportation costs, triggering interest in effective strategies to reduce the unit cost per transported ton.

One strategy is to increase the dry weight per trip by reducing the moisture content of forest residues through natural drying in the forest before comminution (Ghaffariyan et al. 2013; Roser et al. 2011). But, when material is dry (moisture content < 30% wet basis), trailers frequently become limited by volume capacity and not by allowable gross weight (Roise et al. 2013). This is due to the low bulk density of the dry wood particles and problems associated with the loading method in the traditional conveyor-fed (gravity drop) system used with horizontal grinders (Zamora-Cristales et al. 2014).

Increasing hauling capacity by using larger trailers is often the intuitive alternative. However, in mountainous terrain, steep adverse grades, weight-restricted bridges and tight curves can limit the feasibility of driving large single trailers to the comminution site (Angus-Hankin et al. 1995; Zamora-Cristales et al. 2013). Several trailer designs have been developed to improve access for large single trailers, including sliding-axle trailers, stinger-steered trailers and self-steered trailers (Sessions et al. 2010). Also, decision support systems based on mathematical programming and heuristic techniques have been developed to help decide where road improvements might be made to accommodate various types of single trailers (Beck and Sessions 2013).

An alternative to larger or modified single trailers is the use of double trailers — one truck pulling two short trailers — which are common on major highways for

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**A double-trailer configuration traveling on a forest road near Roseburg, Oregon. In Washington and Oregon, double trailers can be more cost effective than single trailers for transporting forest biomass, but they are not competitive in California due to restrictions on load weight and trailer length.**

Rene Zamora-Cristales

moving many types of bulk products. In mountainous terrain, double trailers can either be loaded directly at a centralized site that provides adequate access for double trailers, or they can be decoupled at a hook-up site and transported singly to the processing site. The lower-weight, shorter trailers can negotiate tighter curves and steeper grades, and they can turn around in shorter spaces.

The maximum gross load for any truck-trailer configuration in Oregon and Washington is 105,500 pounds and for California 80,000 pounds (CALTRANS 2014; ODOT 2014; WSDOT 2014), but it can be lower depending on the truck-trailer configuration. The legal limit for each truck-trailer configuration is determined by the number of axles and axle spacings, load per axle and tire width. The use of double trailers compared to single trailers offers an alternative to avoid being volume limited and can maximize load capacity up to the legal gross weight limits. Legal load limits for double trailers usually are higher than for single trailers due to their greater number of axles and axle spacing.

Double trailers are rarely used in biomass operations because moisture content of the residues is often high enough that trucks pulling single trailers are weight limited, but as moisture management strategies are implemented we expect more trailers to become volume limited. Our goal was to examine under what conditions double trailers might be economically competitive compared to single trailers in forest biomass operations on steep terrain in Oregon, Washington and California, considering the legal restrictions in those states on load weight and capacity. We analyzed also the potential operational disadvantages and limitations.

We applied a simulation model to understand the dynamic of truck arrivals and quantify the effect of waiting times on productivity, which are difficult to estimate using a static cost method. In steep terrain, usually only one truck can access the processing site at a time, and if another truck is entering the site it must wait for the other truck to be loaded first. The amount of wait time depends on the arrival time of each truck.

## Operational parameters

A biomass operation in steep terrain usually consists of a grinder that is placed at a landing where forest harvest residues have been piled by a swing-boom loader as part of the logging operation. Trucks arrive at the landing to be loaded and travel back to the bioenergy facility. We developed a simulation model that explores the productivity and performance, in terms of operational costs, of grinder and truck operation. The information for the simulation model was obtained by observing current operations in southwestern Oregon. We recorded 58 productive cycles using GPS units in each truck. We also applied the continuous time method (Pfeiffer 1967) to record in-forest loading. Truck-trailer configurations were modeled in the Java programming language using a simulation library developed by Helsgaun (2000). The system dynamics were modeled as discrete events for each activity in the transportation cycle time.

In these operations we analyzed productivity of a tri-axle truck tractor pulling two 32-foot trailers and a tri-axle tractor pulling single trailers of different lengths, ranging from 32 to 45 feet long. A 45-foot trailer is the longest conventional single trailer commonly used in steep terrain. It requires about the same road width around curves as two 32-foot double trailers, depending on how the two trailers are coupled.

In all harvest units, the roads were single-lane gravel, with road gradients ranging from 5% to 20%. Parameters analyzed for double and single trailers and the respective units were (1) travel speed loaded on paved roads (miles per hour, mph), (2) travel speed unloaded on paved roads (mph), (3) travel speed loaded on gravel roads (mph), (4) travel speed unloaded on gravel roads (mph), (5) hook-up time for tractor to trailer (min), (6) hook-up time for first trailer to dolly to second trailer (min), (7) loading rate at the forest (tons/min) and (8) unloading rate at the bioenergy facility (tons/min) (table 1).

In general, the traveling speed for double trailers was 11% lower than for singles on paved roads, and the unloading rate for single trailers was 1.5 times faster than for doubles. The slower traveling speed can be related to the increased weight and the length of double trailers; their length may limit maneuverability, resulting in lower speed. The longer unloading time is due to the fact that the second trailer must be decoupled before unloading since only one trailer can be unloaded at a time using typical trailer designs and unloading facilities in the Pacific Northwest. Furthermore, the double trailers require additional time for the hooking and unhooking of each trailer to get them to the processing landing. We analyzed whether the increased volumetric and weight capacity offered by the doubles can compensate for the increased time (and cost) per trip compared with the use of single trailers.

**TABLE 1. Average operational parameters for single and double trailers in forest biomass operations**

| Activity | Double-trailer configurations | Single-trailer configurations |
|---|---|---|
| Traveling loaded paved (mph) | 41.7 (1.36)* | 46.9 (1.74) |
| Traveling unloaded paved (mph) | 43.4 (1.34) | 49.5 (0.81) |
| Traveling loaded gravel (mph) | 15.0 (1.85) | 14.9 (0.37) |
| Traveling unloaded gravel (mph) | 15.5 (1.73) | 15.6 (0.73) |
| Hook up tractor to trailer (min) | 4.0 (0.47) | — |
| Hook up trailer to dolly to trailer (min) | 6.4 (0.85) | — |
| Loading (tons/min) | 0.97 (0.05) | 0.99 (0.05) |
| Unloading (tons/min) | 0.50 (0.06) | 0.72 (0.04) |

* Standard deviations in parentheses.

## Transportation, grinding costs

The economics of transportation were analyzed by calculating the hourly costs by state (traveling unloaded, traveling loaded or idle) and multiplying them by the time spent in each of the activities in the transportation cycle (traveling loaded, traveling unloaded, loading and unloading times). Truck fuel consumption and cost were calculated using an engineering approach that looks at the vehicle performance in order to calculate the power required to overcome rolling and air resistance. The power required to

TABLE 2. Truck-trailer capacity limiting factors

| | Double-trailer configurations | | Single-trailer configurations | | |
|---|---|---|---|---|---|
| Item | 32 + 32 ft | 28 + 28 ft | 45 ft | 42 ft | 32 ft |
| Truck-trailer weight (tons) | 20.5 | 18.0 | 16.0 | 15.6 | 14.3 |
| Maximum legal weight (tons) | 52.5 | 40.0 | 44.0/40.0* | 40.0 | 36.8 |
| Maximum payload (tons) | 32.0 | 22.0 | 28.0/24.0* | 24.5 | 22.5 |
| Trailer volumetric capacity (cubic feet) | 5,400 | 4,400 | 3,510 | 3,240 | 2,700 |
| Trailer adjusted capacity at 12.4 lb/ft$^3$ (tons) | 32.0 | 22.0 | 21.8 | 20.1 | 16.7 |
| Limiting factor | Weight | Weight | Volume | Volume | Volume |

* Limits apply to California only.

overcome these two forces was then translated into fuel consumption (Douglas 1999; Wong 2001).

A frontal area of the truck of 100 square feet was assumed and an air drag coefficient equal to 1 (Caterpillar 2006). Using this approach, we accounted for differences in weight and travel speed by state (traveling unloaded or loaded) and between configuration types (double or single trailers). We also accounted for the truck standing cost, when the truck was being loaded or unloaded. This standing cost included labor, insurance and taxes expenses only, since it was assumed that the driver turned off the truck's engine when the truck was idle.

Grinding cost was estimated at $454 per hour when processing and $119 per hour when standing, waiting for trucks to arrive. Similar costs are reported by Coltrin et al. (2012). Total costs were then divided by the dry tonnage processed and transported to obtain the dollars per bone dry ton ($ per BDT).

## Performance, limiting factors

Two double-trailer and three single-trailer configurations were selected to compare their performance. The double-trailer configurations were selected because they maximize legal weight and length and at present are the largest configurations used to carry forest biomass in Oregon and Washington. In California double trailers are not often used to transport forest biomass but we identified the configuration that maximizes the legal weight and length that could potentially be used in biomass operations.

The first double-trailer configuration consists of a 6 × 6 tri-axle tractor (510 hp) pulling two 32-foot trailers with a single trailer capacity of 2,700 cubic feet, or 5,400 cubic feet total. In Oregon, this configuration can carry up to 105,500 pounds with a low-cost extended weight permit. In most routes in Oregon, there is no limit to the overall length of the tractor-trailer combination; however, each trailer must not be longer than 40 feet and the two trailers must not measure more than 68 feet from front to rear (including the space between the trailers). Similar length restrictions are in effect in Washington State, with one difference: two trailers measuring more than 61 feet need a special permit up to 68 feet. In terms of weight, Washington Department of Transportation establishes a limit of 105,500 pounds and no extended weight permit is needed.

The second configuration takes account of the regulations in California. It consists of a 6 × 6 tri-axle tractor (500 hp) pulling two 28-foot trailers with a single trailer capacity of 2,200 cubic feet, or 4,400 cubic feet total. This configuration has a maximum allowable weight of 80,000 pounds. Doubles are allowed to operate on California roads as long as each trailer's length does not exceed 28 feet 6 inches. Maximum overall length is restricted to 75 feet (CALTRANS 2014).

Maximum legal weight for the two double-trailer configurations was calculated on the basis of the state regulations, the number and distance between axles and a network programming model formulated by Sessions and Balcom (1989) using the Federal Bridge Gross Weight Formula (Federal Highway Act of 1974, as amended). Maximum volumetric capacity was calculated using the trailer manufacturer's volume specifications and the bulk density of the material. The parameters obtained for the double-trailer configurations were compared to those for three single-trailer configurations — with trailers 32, 42 and 45 feet long, which reflects the available range of trailer sizes across the region.

The limiting capacity (volumetric and weight) for each trailer configuration was determined for Douglas fir grindings at a bulk density of 12.4 pounds per cubic foot, with an average moisture content of 20% (wet basis). This density was estimated from 64 samples of field-dried biomass and calculated by adapting ASTM standard E873-82 (ASTM International 2013). At the assumed density, the limiting factor for all three single-trailer configurations was volume. For the double-trailer configurations, the legal weight was the limiting factor (table 2).

## Two operational scenarios

Results from the truck-costing model allowed us to calculate the transportation costs for each of the single- and double-trailer configurations (table 3). We analyzed two scenarios: double trailers at the forest landing and double trailers at a centralized yard. In each scenario, we modeled the productivity, in terms of processing and transportation costs, of the 32 + 32–foot double-trailer configuration (for Oregon and Washington), 28 + 28–foot double-trailer configuration (for California) and the 32-, 42- and 45-foot single-trailer configurations.

TABLE 3. Transportation costs ($/hour) for double- and single-trailer configurations

| Trailer configuration | Paved | Gravel | Standing |
|---|---|---|---|
| **Double 32 + 32 ft** | | | |
| Empty | 99.42* | 78.06 | 41.32 |
| Loaded | 126.09 | 88.30 | 41.32 |
| **Double 28 + 28 ft** | | | |
| Empty | 95.32 | 74.96 | 40.74 |
| Loaded | 113.51 | 81.67 | 40.74 |
| **Single 45 ft** | | | |
| Empty | 90.27 | 70.30 | 40.44 |
| Loaded | 108.30 | 77.01 | 40.44 |
| **Single 42 ft** | | | |
| Empty | 87.75 | 68.36 | 39.86 |
| Loaded | 104.37 | 74.56 | 39.86 |
| **Single 32 ft** | | | |
| Empty | 85.35 | 66.49 | 39.28 |
| Loaded | 101.89 | 81.63 | 39.28 |

* Higher hourly costs on paved roads than on gravel roads were related to higher speeds and fuel consumption per hour.

**Grinding at the landing.** This first scenario modeled used four double trailers to reach the processing/grinding landing in the forest and, for comparison, four single trailers. In the double-trailer configurations, one trailer had to be decoupled at an accessible hook-up point and then single trailers were transported to and loaded at the processing landing (fig. 1).

Using double trailers to reach the grinding landing (comminution site) in steep terrain involves these 11 steps: (1) drive unloaded to harvest unit hook-up point and unhook one of the single trailers, (2) drive the first single trailer unloaded to the comminution site, (3) load the first single trailer, (4) drive the first loaded trailer from the comminution site to the hook-up point, (5) detach the first loaded trailer, (6) hook up the second unloaded trailer, drive it to the comminution site and load it, (7) drive the second loaded trailer from the comminution site to the hook-up point and attach the dolly and hook the first loaded trailer, (8) drive the loaded double trailers to the bioenergy facility, (9) unhook one of the trailers and unload the other one, (10) unhook the empty trailer and hook up the loaded trailer and unload it (11) and hook up the second empty trailer and drive back unloaded to the hook-up point in the forest.

Under these conditions, double-trailer configurations spent an average of 34% more time than single-trailer configurations on a round-trip. The majority of the extra time was due to the time double-trailer configurations spent in the forest decoupling and transporting individual trailers from the hook-up point to and from the processing site. Additional time was also involved in decoupling at the unloading site at the bioenergy facility.

The two key variables affecting the economics of double-trailer configurations are the distance from the hook-up point to the bioenergy facility and the distance from the hook-up point to the grinding

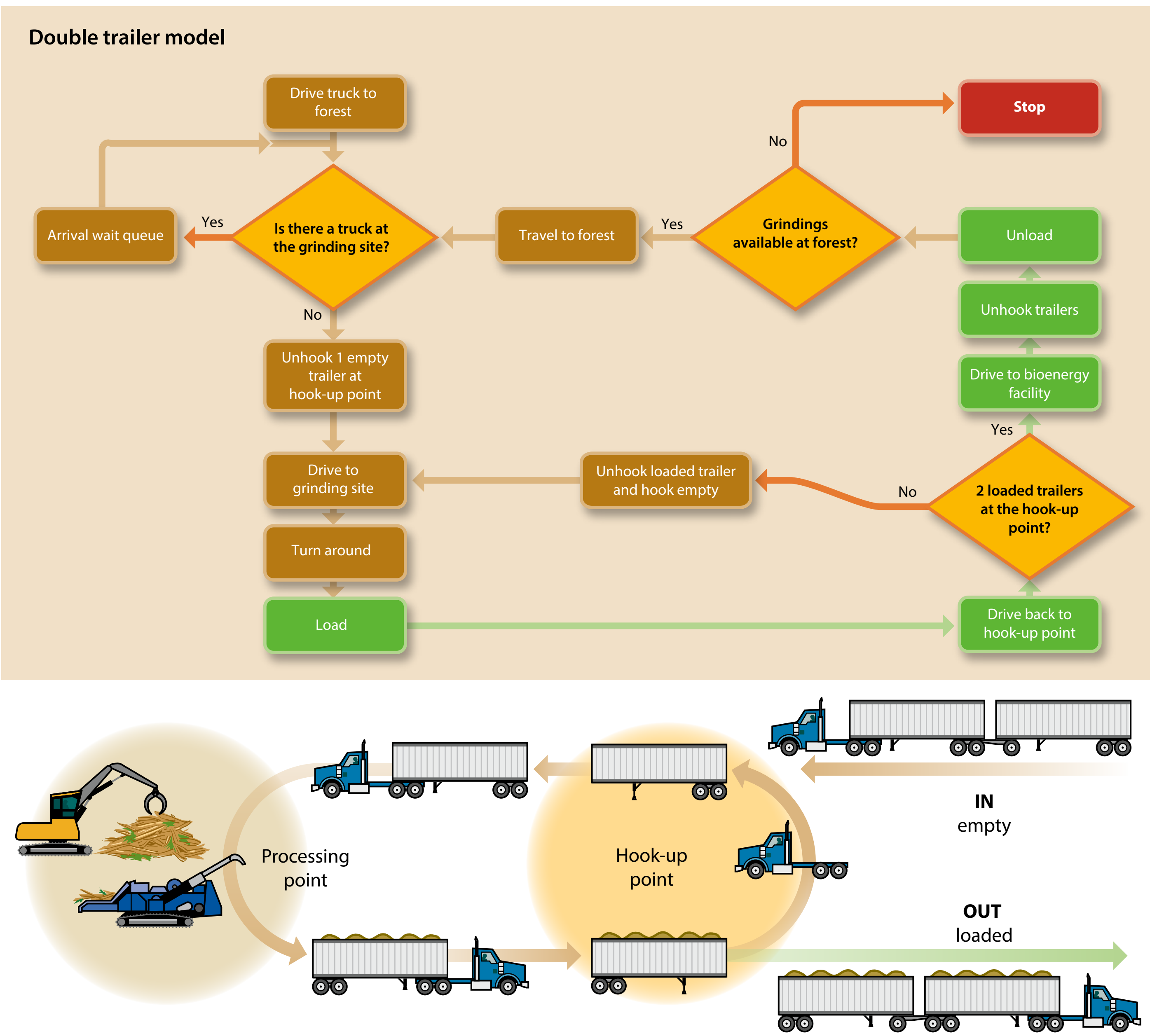


**Fig. 1. Double-trailer configuration model with hook-up point and grinding at the landing.**

landing. We performed a sensitivity analysis of productivity and transportation cost by adjusting one of the variables and leaving the other fixed.

Assuming a fixed distance of 1 mile from the hook-up point to the grinding landing, we varied the distance from the hook-up point to the bioenergy facility from 10 to 100 miles. For Oregon and Washington, results indicated the 32 + 32–foot double-trailer configuration can be cost effective at distances from the hook-up point greater than 35 miles when compared with the single 32-foot trailer, 56 miles for the single 42-foot trailer and 70 miles for the single 45-foot trailer (fig. 2). Although the hourly cost of double trailers is higher (21% higher) and the time spent in a single trip is higher (by 34%), their higher capacity (92% higher than the single 32-foot trailer; 59% higher than the single 42-foot trailer and 47% higher than the single 45-foot trailer) makes them a cost-effective option at greater distances.

For California, however, 28 + 28–foot double trailers do not appear to be a cost-effective alternative to a single trailer, mainly because the gain in payload (32% compared with a single 32-foot trailer, 9% compared with a single 42-foot trailer and 1% compared with the 45-foot trailer) does not compensate for the increased hourly cost and time spent per trip (fig. 3). Although the volumetric capacity for this configuration could accommodate up to 27.3 tons of payload, regulations allow only 22 tons after accounting for the tractor and trailer weight. Lighter trailers would increase capacity, but legal weight may still be the limiting factor.

We used the upper breakeven mileage bound as the fixed value for the distance from the hook-up point to the bioenergy facility (70 miles), and we varied from 0.5 to 5.0 miles the distance from the hook-up point to the landing to analyze the sensitivity of the double-trailer economics to this factor. For Oregon and Washington, the choice of a double-trailer configuration versus the 42- and 45-foot single trailer alternatives is sensitive to small distance changes. If distance between the hook-up point and the grinding landing is greater than 1 mile, then the single 45-foot configuration becomes more cost effective. Similarly, if we increase the distance to 2 miles, then the double-trailer configuration becomes more expensive than the single 42-foot option (fig. 4).

**Grinding at a centralized yard.** This second scenario uses a centralized yard to process the harvest residues and thereby avoids grinder wait times for trailer

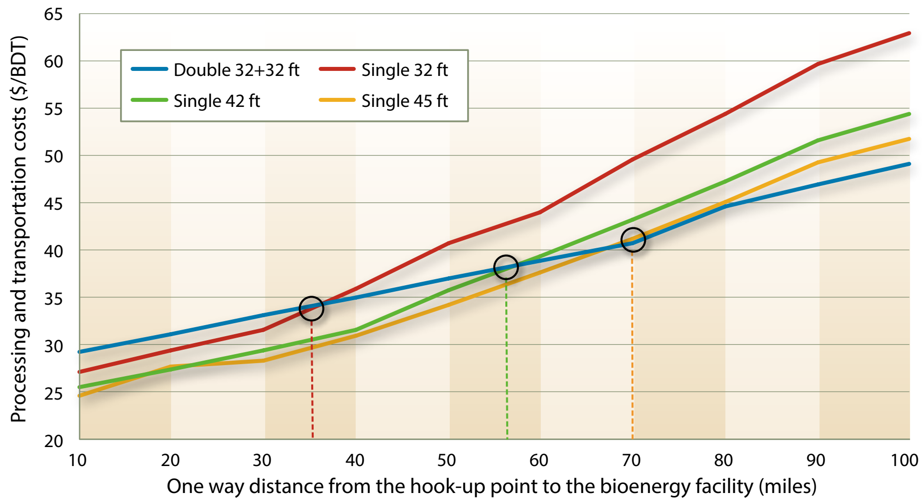


**Fig. 2. Sensitivity of cost to distance for single-trailer configurations and the 32 + 32–ft double-trailer configuration suitable for Oregon and Washington.**

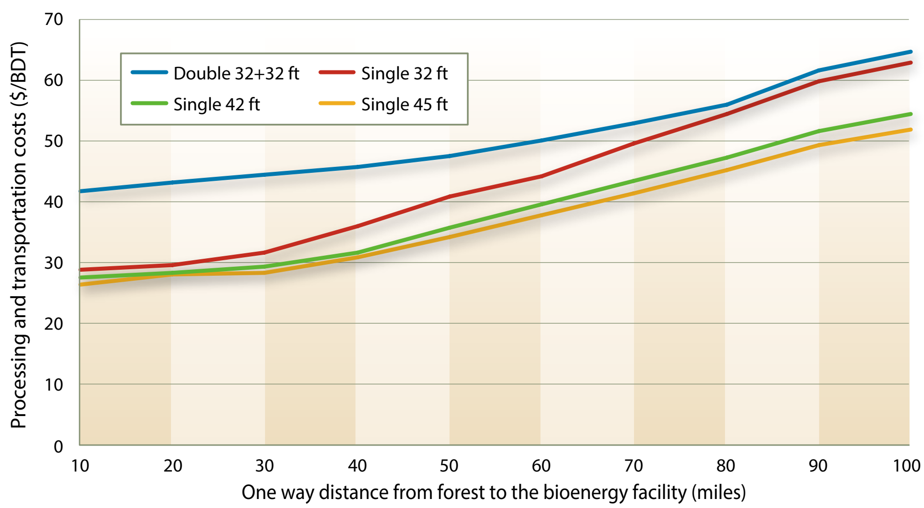


**Fig. 3. Sensitivity of the California 28 + 28–ft double-trailer configuration economics to changes in distance between the hook-up point and the bioenergy facility, for biomass at 20% moisture content.**

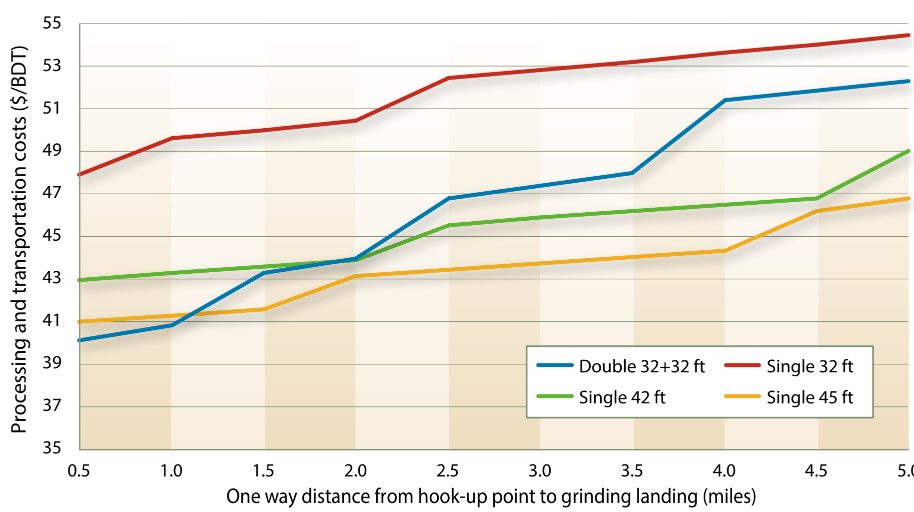


**Fig. 4. Sensitivity of cost for 32 + 32–ft double-trailer configuration to changes in distance between hook-up point and grinding landing.**

arrival and trailer exchange time. The grinder processes and dumps the material directly into a pile (no waiting on trucks), and trucks are loaded when they arrive with material from the pile using a front-end loader. It was assumed that the double-trailer configurations can be loaded on-site without the need to unhook the trailers, and the centralized yard has enough space to allow the double trailers to turn around (fig. 5). Unprocessed residues are transported from the forest to the centralized yard using short trucks such as bin trucks or hook-lift trucks. In this scenario, the key variable is the distance from the centralized yard to the bioenergy facility. We varied this parameter from 10 to 100 miles.

Productivity and cost of the double-trailer configurations using a centralized yard were compared to those of single-trailer configurations at standard grinding operations at a landing. From the comparison, we were able to calculate the marginal benefit of using double trailers. Transporting the material from the centralized yard to the bioenergy facility is cheaper than loading a trailer at the forest landing and transporting it to the bioenergy facility. However, of course, the centralized yard option requires transport of the unprocessed residue from the forest to the yard for grinding.

Results showed that the 32 + 32–foot double-trailer configuration, for Oregon and Washington, had savings ranging from $4.4 per BDT to $12.4 per BDT, depending on the distance from the centralized yard to the bioenergy facility to the forest (fig. 6). These values can be interpreted as the maximum amount that could be paid for transporting the unprocessed residues from the forest to the centralized yard. In Oregon, bin trucks cost about $70 per hour and have a capacity ranging between 5 and 10 tonnes; similar hourly costs for California have been reported by Harrill et al. (2009). Bisson et al. (2015) in a study in Northern California reported that a converted articulated dump truck carried about 5.6 BDT per load of unprocessed residues at a cost of about $4.5 per BDT per mile plus about $6.5 per BDT to load the dump truck. The 28 + 28–foot double-trailer configuration for California offers few improvements, and it is only cost effective when compared with the 32-foot single-trailer configuration.

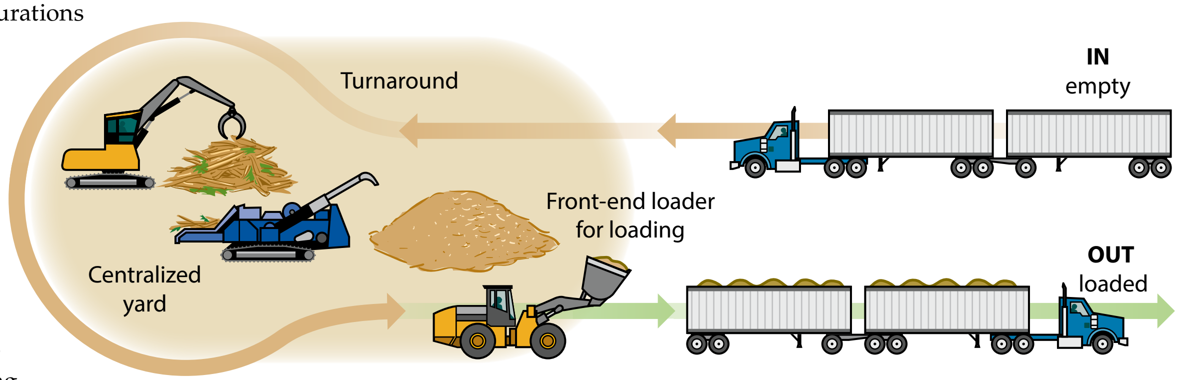


**Fig. 5. Double-trailer configuration model with centralized yard.**

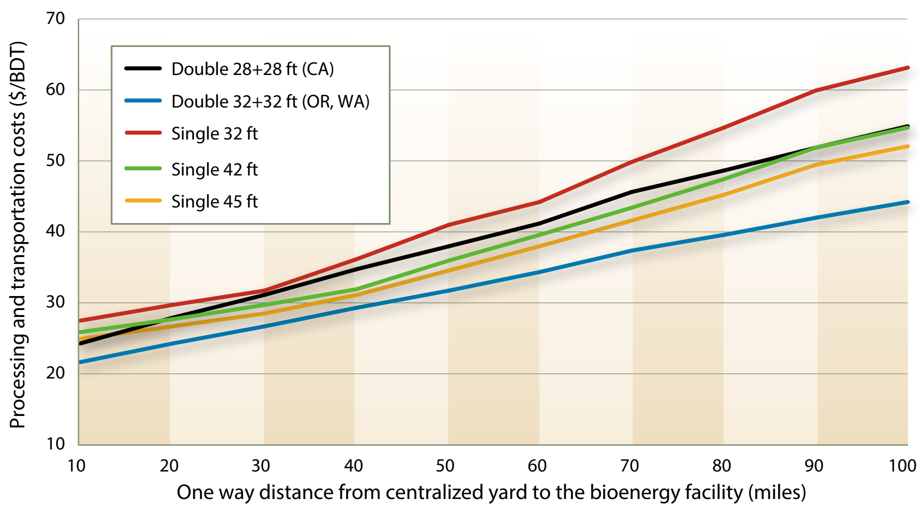


**Fig. 6. Sensitivity of processing and transportation costs to distance for the 32 + 32–ft double-trailer configuration with grinding at a centralized yard and single-trailer configurations with grinding at the landing.**


**A grinding operation in western Oregon.**

A 32-foot single trailer in western Oregon.


## Potential use of double trailers

Both double-trailer configurations analyzed in this paper offer a gain in volumetric capacity; however, the current regulations in California severely impact the potential use of double trailers for transporting forest biomass. Lighter trailers could help to increase the potential payload but probably not up to the tonnages allowed in Oregon and Washington.

When processing at the grinding landing, the key variables affecting the performance of double trailers are the distance from the hook-up point to the bioenergy facility and the distance from the grinding landing to the hook-up point. For Oregon and Washington, it is clear from the results that as distance from the hook-up point to the bioenergy facility increases, double trailers have the potential to become cost effective. This is because transport time increases with the distance, so the relative cost per ton favors doubles in long-distance hauls. On the other hand, as distance from the hook-up point to the grinder landing increases, double trailers become less feasible because of the lower payload between the landing and the hook-up point and the additional hooking-up time.

In the case of the centralized yard, savings are reported because the grinding does not depend on transportation and double trailers do not need to be decoupled, thus, they function as single trailers. However, the transportation of unprocessed residues is expensive because of the heterogeneous nature of the residue (branches, tops and log butts) and productivity can be affected by the traveled distance. Also, if material is not already piled at the roadside, additional collection costs may apply.

In summary, the future of doubles on steep terrain seems limited to long hauls between the forest and the bioenergy facility, and then only if hook-up points are close to the grinding landings. The current efforts in improving trailer maneuverability for larger single trailers, 48 to 53 feet long, and in increasing dry bulk density may offer more potential for reducing transport cost than using double trailers. CA

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# Biomass power plant feedstock procurement: Modeling transportation cost zones and the potential for competition

*by* Anil R. Kizha., Han-Sup Han, Timothy Montgomery *and* Aaron Hohl

*Transportation of comminuted (processed) woody biomass from the production site to a utilization point is one of the most costly operational components in feedstock procurement. This study identified potential sources of feedstock based on transportation cost from which three woody biomass power plants in Humboldt County, California, could economically obtain their supply. We conducted service area and location-allocation network analyses for timberlands and sawmills, respectively, and created inclusive and exclusive networks to model three transportation cost zones (TCZs). The area within the $20/bone dry ton TCZ had the highest potential supply of woody biomass in the county (709,565 acres). All sawmills in the county were within an economically viable distance of the power plants. Even though there was no competition for raw materials at the time of this study, a competition risk analysis suggested that this could change with shifts in the demand for biomass or the price of electricity. The methods we developed for this study could be adapted to other regions with managed timberlands and a strong forest products industry.*

Humboldt County, California, has approximately 1.7 million acres of forestland and maintains a strong forest products industry. Electrical power imports to the county are constrained by its remote location and lack of infrastructure. Consequently, it is a prime location for wood-based biomass energy plants. However, transportation costs have been a fundamental barrier to woody biomass utilization (Han and Murphy 2012). Even at 50 miles or less, transportation costs can be $10 to $30 per bone dry ton (BDT) (Galik et al. 2009). The fixed maximum weight limit on a chip truck of 40 tons in California increases transportation cost compared to neighboring states, which allow an increase of weight limits with an increase in the number of axles and axle spacing in a truck.

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Therefore, the first objective of this study was to determine the transportation cost zones (TCZs) for procuring woody biomass (the byproducts, or residues, of forest management and sawmill operations) from various timberlands and sawmills to fuel wood energy power plants in the county.

Humboldt County has three power plants that are primarily fueled by woody biomass: DG Fairhaven in Samoa, Blue Lake Power in Blue Lake, and Green Leaf (Eel River plant) in Scotia. Together, the plants have the ability to generate 54 megawatts (MW) of electricity (table 1). However, in the recent past, the Blue Lake Power and Green Leaf power plants have shut down temporarily due to the low price of electricity, emission permit issues and the inability to secure supply at an economical price (Sims 2012). Even though competition for raw materials among these three power plants does not seem severe in this region, high demand for renewable energy (e.g., woody biomass) or entry of an additional competitor for fuel resources can lead to increased competition for resources (Walter Nystrom, Blue Lake Power LLC, pers. comm.). Consequently, the second objective was

Forest residues are fed into a grinder at a centralized site and then loaded into a container for transport to the power plant. In Humboldt County, power plants use approximately 472,500 bone dry tons of biomass per year to generate electricity.

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to understand the potential competition for wood residues within the wood-based power production industry. To address this objective, we obtained information on the market and supply of wood residues from personal interviews with industry professionals.

The results provided by this study could be utilized by biomass contractors for maximizing their profit and for cost-effective delivery of wood residues from sawmills and timberlands to power plants. Furthermore, the methods developed for this study could easily be adapted to other locations where timberlands are actively managed and a strong forest products industry exists.

**TABLE 1. Demand for wood residue for wood-based energy production in Humboldt County, CA**

| Power plant | Utility company in contract | Capacity | Estimated biomass demand |
|---|---|---|---|
| | | *MW** | *BDT/year†* |
| DG Fairhaven | Pacific Gas & Electric Company | 16 | 140,000 |
| Blue Lake Power | San Diego Gas & Electric Company | 10 | 87,500 |
| Green Leaf Power | Pacific Gas & Electric Company | 28 | 245,000 |
| **Total** | | **54** | **472,500** |

* Megawatts.
† Bone dry ton per year.

**TABLE 2. Costs and average travel speeds for a chip van transporting forest residues and total distance associated with the various roads types in Humboldt County, CA**

| Road types | Average speed | Transportation cost | Round-trip distance |
|---|---|---|---|
| | *miles/hour* | *$/BDT-mile* | *miles* |
| U.S. highway | 55.0 | 0.116 | 7 |
| Paved (double lane) | 29.7 | 0.215 | 98 |
| Gravel (single lane) | 26.8 | 0.238 | 19 |
| Dirt (single lane) | <10.0 | >0.638 | 5.2 |

Information presented in this table is based on recent studies on wood residue transportation (Bisson et al. 2015; Han and Murphy 2012; Harrill and Han 2012). The cost of operating the truck (i.e., machine cost) was assumed to be a constant regardless of road type and distance.

## Data collection

All forested areas in the county, along with nine sawmills, were considered as potential wood residue sources. While the cost of acquiring sawmill residues was largely dependent on the transportation cost from sawmills to power plants, forest residues (tree tops, branches and non-merchantable whole trees) from timberlands had variations in the operational costs associated with in-woods processing, which were also considered. For this study, in-woods operational (stump-to-truck) costs to harvest, process (grinding or chipping) and haul were based on typical practices for the region.

Harvesting amounts and operational cost differences in the county have been directly influenced by the type of harvesting methods used, which varied by landowner type (Hohl et al. 2013; Morgan et al. 2012). Hence, using spatial data obtained from the Humboldt County Planning and Building Department, we classified the timberlands based on their ownership. Industrial timberlands were privately owned forests characterized by active forest management including timber harvesting. Land owned by tribal governments was also treated as industrial timberland for this study, as it was managed similarly to privately owned forestland. In the national forests (Six Rivers, Klamath and Shasta-Trinity), biomass harvesting was typically conducted via relatively expensive thinning operations to achieve environmental benefits such as fire hazard reduction and forest restoration. As a result, industrial timberlands generated forest residues at a lower stump-to-truck cost range of $26 to $30/BDT (Bisson et al. 2015; Harrill and Han 2012), while in the national forests, stump-to-truck biomass costs were approximately $52/BDT (Vitorelo et al. 2011). Both of these costs represent the direct cost of the operation in the field and did not accommodate any allowance for mobilization of equipment, overhead or profit.

## Transportation model for biomass feedstocks

**Forest residues.** While primary transportation (moving the forest residues from the stump to the landing, where the biomass is stacked and processed) was incorporated in the in-woods operational cost, secondary transportation (movement of the forest residues from the landing to the power plants) was modeled using road networks obtained from the U.S. Census's Topologically Integrated Geographic Encoding and Referencing (TIGER) data set. The service area tool of ArcGIS (10.1) Network Analyst was used to model the area for secondary TCZs. Information on average travel speeds over different road types and associated costs for the region were gathered from existing literature (table 2).

We assumed an average secondary transportation cost based on road types from a recent study in the region (Bisson et al. 2015) of 42-foot chip trailers carrying an average of 23.17 green tons of 25% moisture content wet basis hog fuel (wood chips and shavings). At this unit hauling cost, the TCZ thresholds of $10/BDT, $20/BDT and $30/BDT fell at 20, 41 and 61 miles. Each TCZ was associated with a range of costs: in the $30/BDT zone, the transportation cost ranged from $20.01 to $30.00/BDT based on a one-way distance between 41 and 61 miles. The TCZs were generalized to increments of $10; more refined TCZs (e.g., in increments of $1) would have complicated the model and yielded results with more or less the same utility.

To determine the actual area available for each power plant, we created two transportation networks: The inclusive transportation network, in which TCZs were classified based on the cost to provide biomass to any of the three plants (fig. 1); and the exclusive transportation network, in which the three power plants were considered individually to allocate the timberland available for each plant. The three exclusive TCZs were later intersected with the respective three inclusive TCZs to determine the actual timberland available for each plant. This also helped in determining exclusive and shared timberland zones (figs. 2 and 3).

Exclusive timberland zones were regions around a power plant from which

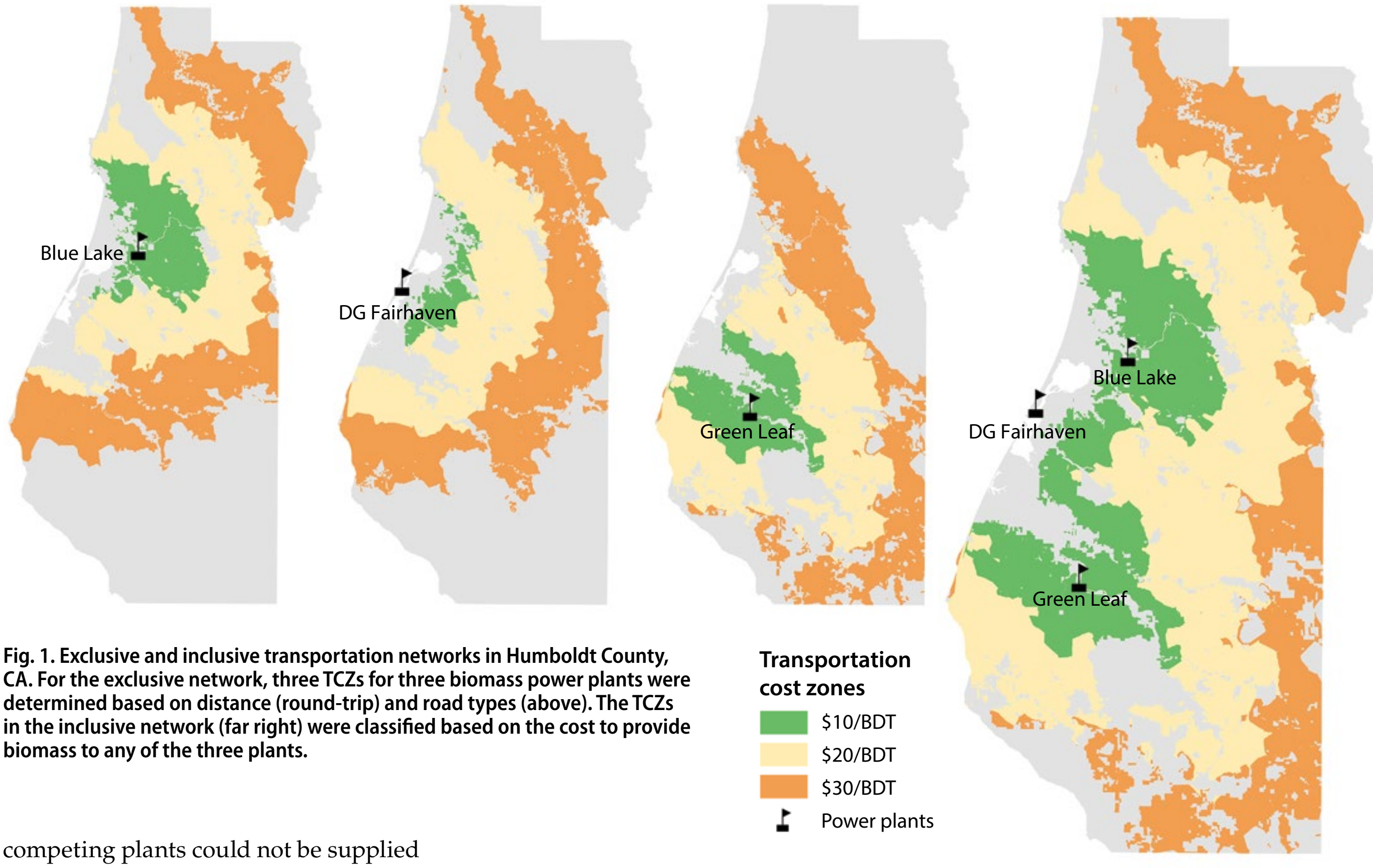


**Fig. 1. Exclusive and inclusive transportation networks in Humboldt County, CA. For the exclusive network, three TCZs for three biomass power plants were determined based on distance (round-trip) and road types (above). The TCZs in the inclusive network (far right) were classified based on the cost to provide biomass to any of the three plants.**

competing plants could not be supplied forest residues at lesser or equal price (with all conditions equal), due to the secondary transportation cost. Access to these timberlands could give the power plants an advantage if competition became an issue. Overlapping timberlands were regions within the same TCZ of two or more plants (i.e., multiple plants could be supplied at approximately the same cost). We made the following assumptions for areas where TCZs overlapped:

1. The plant with lower TCZ claims the area over the plant with higher TCZ. For example, if 30 acres of timberland fell in both the exclusive network model of the $20/BDT zone of Green Leaf power plant and the $30/BDT zone of DG Fairhaven power plant, the region would be taken out of the total area of the $30/BDT zone for Fairhaven because Green Leaf could have the material supplied at a lower cost.
2. When overlapping $/BDT TCZs are equal (shared timberland), the area is considered a "hot spot," indicating a high risk of competition (fig. 2).

Hierarchical order was assigned to road type to give preference to existing

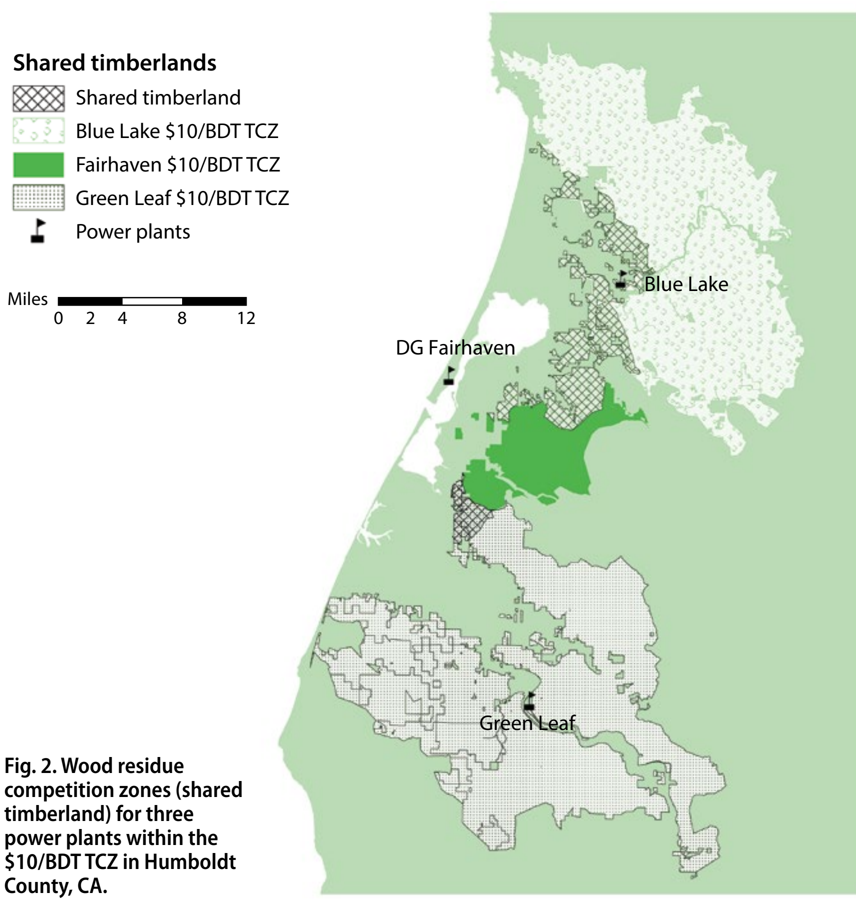


**Fig. 2. Wood residue competition zones (shared timberland) for three power plants within the $10/BDT TCZ in Humboldt County, CA.**

highways ($0.12/BDT-mile), followed by paved roads ($0.22/BDT-mile), gravel roads ($0.24/BDT-mile) and dirt roads (more than $0.64/BDT-mile) to reduce the cost of transportation (table 2). Each TCZ was later intersected with the timberland ownership data in order to exclude non-timberlands and incorporate timberland ownerships into the TCZs.

**Sawmill residues.** The location-allocation tool of ArcGIS (10.1) Network Analyst was used to estimate the transportation cost associated with sawmills and evaluate the relative advantage for each power plant to procure sawmill residues. This analysis is based on a proximity approach (competitive facility location) for estimating market share (Drezner 2014). All facilities (sawmills) in the county were selected such that the allocated demand for transporting the sawmill residues to the power plant was maximized in the presence of competitors based on a spatial interaction model (ESRI 2012). This method was used in determining the optimal sawmill(s), based on road types and distance, from which power plants could import sawmill residues within a maximum one-way haul distance of 61 miles (W. Nystrom, pers. comm.). Based on the theory of duopoly in a linear market situation, in which consumers (power plants) do not see any difference between the products (mill residues) sold by different producers (sawmills) and there is zero production cost for the producers (Drezner 2014; Hotelling 1929), Network Analyst created a weighting factor we called mill residue procurement (MRP) to assign the demand for sawmill residues from a particular sawmill to a power plant in the presence of competitors as a function of distance. Greater MRP implies a more favorable condition for obtaining sawmill residues for a particular plant. The sum of MRP for all sawmills reflects the overall advantage for a given power plant, relative to other plants, to procure available sawmill residues.

## TCZs for forest residues

**$10/BDT zone.** The $10/BDT TCZ was the region that provided forest residues from the timberlands at the lowest cost level due to proximity to the power plant. When stump-to-truck biomass costs were taken into account, more expensive forest residues close to a power plant were in many cases more economically feasible to procure than cheaper resources farther away. This zone included only industrial timberlands, with Green Leaf having the largest acreage (table 3). Our analysis of the risk for competition (fig. 2) showed that DG Fairhaven shared almost 53% of all its timberland with the other two plants (table 4), giving it little specific advantage in collecting forest residues over the other plants. Blue Lake and Green Leaf shared 15.5% and 2% of their timberland with DG Fairhaven, respectively. While all the facilities had an exclusive

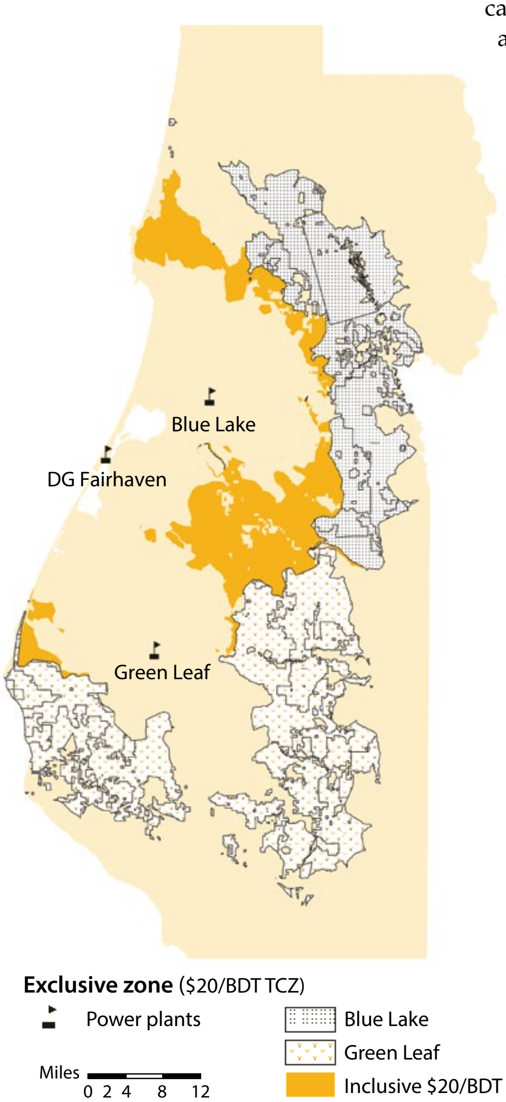


**Fig. 3. Exclusive zone of timberlands for each power plant within the $20/BDT TCZ (round-trip) in Humboldt County, CA.**

**TABLE 3. Area potentially available to supply forest residues within each timberland ownership class for each TCZ within inclusive and exclusive transportation networks in Humboldt County, CA**

| | Industrial timberlands | National forest | Total* |
|---|---|---|---|
| | *acres* | | |
| **Inclusive transportation network** | | | |
| $10/BDT | 367,108 | - | 367,108 |
| $20/BDT | 644,276 | 65,290 | 709,565 |
| $30/BDT | 335,418 | 154,591 | 490,009 |
| Total | 1,346,802 | 219,881 | 1,566,683 |
| **Exclusive transportation network** | | | |
| **$10/BDT** | | | |
| Blue Lake | 168,707 | - | 168,707 |
| DG Fairhaven | 55,837 | - | 55,837 |
| Green Leaf | 171,334 | - | 171,334 |
| **$20/BDT** | | | |
| Blue Lake | 365,351 | 65,290 | 430,641 |
| DG Fairhaven | 51,725 | 1,760 | 53,485 |
| Green Leaf | 440,321 | - | 440,321 |
| **$30/BDT** | | | |
| Blue Lake | 422,631 | 139,584 | 562,215 |
| DG Fairhaven | 497,319 | 98,431 | 595,751 |
| Green Leaf | 416,993 | 24,164 | 441,157 |

* Total of the row, showing the total area for each TCZ and power plant.

zone within this TCZ, Green Leaf had the largest exclusive area (table 4).

**$20/BDT zone.** This zone had 709,565 acres of total timberland, with 644,276 acres of industrial timberlands (table 3). Approximately 17% of timberland was shared. Within this zone, DG Fairhaven had no exclusive timberland (fig. 3). Among the three TCZs, this zone had the highest acreage and supply of forest residues.

**$30/BDT zone.** The $30/BDT TCZ is currently regarded as the outer limit for cost-effective procurement. Given the current cost of supply and market price for biomass in Humboldt County, this zone would typically generate zero profit margins for biomass contractors supplying the raw material, unless additional compensations were offered (e.g., government subsidies). In this zone, feasibility was highly dependent on hauling distance.

## Supplies from TCZs

Industrial timberlands constituted 86% of the 1,566,683 acres of timberland within the three TCZs (table 3). The $30/BDT TCZ had a smaller area and supply of forest residues than the $20/BDT TCZ for the following reasons:

1. The $30/BDT TCZ was smaller than anticipated because much of the potential land base in this zone was actually in the ocean.
2. A large proportion of the acreage falling in the $30/BDT exclusive TCZ overlapped with the inclusive $20/BDT zone of other plants and had to be removed from the former TCZ and added to the latter.
3. Our analysis was carried out exclusively for Humboldt County. Much of the timberland outside the county that would have been in the $30/BDT zone was not included. However, even if these regions outside the county within the $30/BDT were considered, transportation would still not be feasible in the current market.
4. The $30/BDT TCZ had the highest amount of national forest acreage, almost 31% (table 3), compared to 9% in the $20/BDT TCZ.

**TABLE 4. Competition hot spots (shared timberland) and exclusive zones available within each TCZ for the three power plants in Humboldt County, CA**

| | | $10/BDT | $20/BDT | $30/BDT | Total* |
|---|---|---|---|---|---|
| | | acres | | | |
| Blue Lake | Shared | 26,192 | 177,288 | 46,811 | 250,291 |
| | Exclusive | 142,782 | 253,353 | 246,489 | 642,624 |
| DG Fairhaven | Shared | 29,763 | 175,623 | 118,234 | 323,620 |
| | Exclusive | 26,228 | - | - | 26,228 |
| Green Leaf | Shared | 3,571 | 107,806 | 24,904 | 136,281 |
| | Exclusive | 167,763 | 332,516 | 191,894 | 692,172 |
| TCZ† | Shared | 30,542 | 123,697 | 51,627 | 205,865 |
| | Exclusive | 336,772 | 585,869 | 438,383 | 1,361,024 |
| Percentage‡ | Shared (%) | 8 | 17 | 11 | 13 |
| | Exclusive (%) | 92 | 83 | 89 | 87 |

* Total of the row, showing the total shared or exclusive for each power plant and TCZ.

† Total area shared or exclusive within each TCZ. The total shared acreage of TCZ is less than the shared acreage for some individual power plants because shared acreage for each plant is calculated by summing the acres shared with each of the other two plants; by this method, land shared with the other plants is counted twice.

‡ Ratio of shared or exclusive zone to the total timberland area within the TCZ.

**TABLE 5. Distance from sawmills and mill residue procurement (MRP) weighting factor for three power plants in Humboldt County, CA**

| | DG Fairhaven | | Blue Lake | | Green Leaf | |
|---|---|---|---|---|---|---|
| | MRP | Distance | MRP | Distance | MRP | Distance |
| Korbel Sawmill | 0.123 | 21.0 | 0.820 | 3.2 | 0.057 | 45.2 |
| Britt Lumber | 0.319 | 11.9 | 0.576 | 6.6 | 0.105 | 36.1 |
| Mad River Lumber | 0.343 | 11.4 | 0.547 | 7.2 | 0.110 | 35.6 |
| Sierra Pacific Industries | 0.579 | 6.4 | 0.306 | 12.1 | 0.115 | 32.2 |
| Schmidbauer Lumber | 0.598 | 6.9 | 0.242 | 17.1 | 0.160 | 25.8 |
| Humboldt Redwood Company | 0.017 | 33.0 | 0.013 | 43.2 | 0.971 | 0.6 |
| C W Wood Products | 0.193 | 25.7 | 0.138 | 35.9 | 0.669 | 7.4 |
| Redwood Lumber Company | 0.527 | 8.2 | 0.331 | 13.1 | 0.143 | 30.3 |
| Freshwater Pulp Inc. | 0.842 | 2.1 | 0.102 | 17.0 | 0.056 | 31.0 |
| **Average distance** | | **14.1** | | **17.2** | | **27.1** |
| **Total MRP*** | **3.54** | | **3.07** | | **2.35** | |

* High values indicate a favorable condition for obtaining sawmill residues.

## Procurement of sawmill residues

Sawmill residues added an additional 408,000 BDT annually to the local supply of wood residues (Hohl et al. 2013). Unlike forest residues that were seasonal in nature, residues from sawmills could potentially be available all year long. Furthermore, this resource was less expensive ($10/BDT) when compared to the forest residues ($50/BDT) (Mayhead and Shelly 2012).

Results from the location-allocation analysis showed that DG Fairhaven had the greatest competitive advantage in collecting their mill residues, followed by Blue Lake (table 5). DG Fairhaven had the least acreage of exclusive timberland (26,278 acres) (table 4) and depended primarily on sawmills for its supply (Bob Marino, DG Fairhaven Power LLC, pers. comm.). Blue Lake, with a total MRP of 3.07, also received most of its supply from sawmills (W. Nystrom, pers. comm.).

## Transportation model economics

Approximately 303,000 BDT of forest residues are available from Humboldt County's timberlands annually (Hohl et al. 2013). The U.S. Department of Energy reported $47/BDT as a target delivered feedstock price for 2012 to make biomass-based processes competitive with fossil fuel-based energy production (Wilkerson et al. 2008). Of this, the agency allocated $10/BDT to the landowner, leaving $37/BDT for collection and transportation (Greene et al. 2011).

In Humboldt County, the wood residues supplied to the power plant were priced around $50/BDT (W. Nystrom, pers. comm.). In the $30/BDT TCZ, there was only room to accommodate $20 to $30/BDT for the rest of the biomass harvesting operation. However, the stump-to-truck cost in industrial timberlands could account for about $26/BDT for biomass recovery operations (Bisson et al. 2015) and $30/BDT for biomass harvesting along with sawlog operations in Northern California (Harrill and Han 2012). Costs for mobilization of equipment, overhead and profit allowance were not included in the stump-to-truck cost figures. Hence, under present market conditions, we do not expect that contractors will operate outside the $30/BDT TCZ, especially in the three national forests, unless they are compensated in addition to the price paid by the power plant.

However, major industrial landowners often do compensate biomass contractors to remove forest residues from their property due to fire hazards and site preparation requirements. In Humboldt County's national forests, compensation has taken the form of stewardship funds or other grants for reducing the hazardous fuel loads and promoting biomass energy; the funds paid for long distance travel costs and allowed contractors to profitably supply woody biomass. There are similar examples from neighboring Siskiyou County, where biomass suppliers have delivered raw materials to power plants almost 75 miles away (Jim Johnson, Jim Johnson Logging, pers. comm.). In addition, a decrease in in-woods operational costs or fuel costs, or an increase in market price, could open up more areas for utilization. Harrill and Han (2012) found that a $1/gallon increase in the price of diesel could result in a $2.06/BDT increase in the stump-to-truck costs associated with a woody biomass project in Northern California; correspondingly, a drop in the fuel price would reduce stump-to-truck costs.

To evaluate the total cost of delivery (round-trip) from timberlands to power plants, we conducted a sensitivity analysis using a unit cost of $0.24/BDT-mile (Bisson et al. 2015) on distance traveled and the stump-to-truck biomass cost (table 6). As the stump-to-truck cost increased, the accessible distance to the timberlands decreased, and total delivery cost increased. Furthermore, this analysis confirmed that within a given TCZ, profit margins for contractors are directly determined by the type and efficiency of operation.

**TABLE 6. Sensitivity analysis at $0.24/BDT-mi on transportation distance (round-trip) and stump-to-truck biomass cost to determine the total cost for delivering forest residues from timberlands to power plants in Humboldt County, CA**

| Stump-to-truck cost* ($/BDT) | Round-trip travel distance (miles) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 |
| 20 | 22.5 | 24.9 | 27.4 | 29.8 | 32.3 | 34.7 | 37.2 | 39.6 | 42.1 |
| 26 | 28.5 | 30.9 | 33.4 | 35.8 | 38.3 | 40.7 | 43.2 | 45.6 | 48.1 |
| 30 | 32.5 | 34.9 | 37.4 | 39.8 | 42.3 | 44.7 | 47.2 | 49.6 | N/F† |
| 35 | 37.5 | 39.9 | 42.4 | 44.8 | 47.3 | 49.7 | N/F | N/F | |
| 40 | 42.5 | 44.9 | 47.4 | 49.8 | N/F | N/F | | | |
| 45 | 47.5 | 49.9 | N/F | N/F | | | | | |
| | Total delivery (stump-to-truck and transportation) cost ($/BDT) | | | | | | | | |

* Costs for mobilization of equipment, overhead and profit are not included.
† N/F = not financially feasible under the current market price ($50/BDT) for forest residues.

## Competition for wood residues

Areas at high risk of competition, or hot spots, were identified throughout the county based on transportation distance and road types. The $20/BDT TCZ was subject to more competition among the power plants because it had the highest percentage of timberland shared (17%) (table 4). A contractor working within this area had the choice to supply forest residues to any of the power plants sharing the region. Competition can be further intensified by an increase in a plant's capacity or the entry of an additional biomass consumer, such as another bioenergy facility, a pulp mill, or compost and mulching facilities.

In Humboldt County, Blue Lake Power shut down for almost a decade before being re-commissioned in 2009; its closure was attributed to an increase in price of biomass feedstock and decrease in the price of electricity (W. Nystrom, pers. comm.). In addition, when the Green Leaf power plant temporarily shut down in 2012, the company stated that the primary reason for the shutdown was "inability to secure stable fuel supplies" (Sims 2012). These cases show that the wood residue utilizers in the county were facing a shortage of raw materials at an economical price (W. Nystrom, pers. comm.). It should also be noted that Green Leaf, located in the southern portion of the biomass power production hub, had almost 692,172 acres of exclusive timberland zone


Will Suckow


**Blue Lake Power in Humboldt County, which utilizes 87,500 BDT per year to generate 10 MW of electricity, receives most of its biomass from sawmills.**

within the first three TCZs, making it the largest holder of exclusive timberland (table 4). However, because forest biomass harvesting operations were seasonal, in some cases operating roughly 100 days per year mainly due to weather conditions (Steve Morris, Steve Morris Logging, pers. comm.), power plants could not entirely depend on this resource. DG Fairhaven, which has the highest total MRP, did not need to shut down even though it had the least acreage of exclusive zone. Being the oldest plant in the region, the plant could secure long-term contracts with sawmills for stable feedstock supplies.

Having the highest average distance to the sawmills, the total MRP for Green Leaf was much lower than the MRP for the other two power plants (table 5); as a result, the plant had to pay comparatively more to access mill residues produced in the county. However, all three power plants were within an economically feasible distance to sawmills. Further analysis on competition, such as a target market share analysis, could have revealed more information on the supply chain based on the type of sawmill residues produced and total production. Additionally, the analysis used distance (miles) as the determining factor rather than “time” because the latter required historic traffic data that was not available for Humboldt County.

Exclusive timberland zones were created to understand a power plant’s supply advantage compared to others. The zone was determined by extracting areas that were not shared by the other power plants (or was solely available to a particular power plant) within each TCZ. The $10/BDT TCZ had the highest percentage of exclusive land (91.7%) compared to the total acreage in the TCZ, whereas the $20 BDT/TCZ had most land coverage (table 4).

However, given the annual production of wood residues in the county of over 711,000 BDT and a total power plant consumption of around 472,500 BDT/year, the market is relatively safe from competition at present (W. Nystrom, pers. comm.). Furthermore, major industrial timberland owners in the county have indicated that they could generate up to three times more if there was demand (Ewald 2013).

## Extending the results

The transportation cost zone concepts developed in this study could be applied to other locations where more than one power plant competes for the same raw materials.

Traditionally, forest residues are grinded, chipped, bundled or crushed to increase bulk density and enhance the transportation efficiency. Apart from these, new evolving technologies that densify woody biomass, such as torrefaction, briquetting and densification, can significantly increase the energy value of the raw materials. These energy-densified products could thereby extend the TCZ up to 100 miles (Mayhead 2010). CA

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# California's agricultural regions gear up to actively manage groundwater use and protection

*by* Thomas Harter

***New regulations are emerging in response to historic groundwater depletion and widespread groundwater quality degradation in California. They aim at long-term preservation of groundwater resources for use in agriculture, in urban areas and for the support of ecosystems in streams dependent on groundwater. The regulations are driving a historic shift in the way the agriculture sector is engaged in managing and protecting groundwater resources in California. A review and synthesis of these recent regulatory developments — the Sustainable Groundwater Management Act and new policies under the California Porter-Cologne Water Quality Control Act — clarifies key challenges for farmers, scientists and regulators and points to the need for continuing innovation in agricultural practices as well as in planning and policy.***

Groundwater is a critical resource for California water management. Stored in aquifers, water from rainy seasons can be used during dry and hot summers and supports water users through droughts if it is replenished in wet years. Aquifers also help move water from areas of recharge (often on the edge of the valley floor near the foothills) to areas dominated by extraction that are miles or — in very large aquifers — a few tens of miles away. Unfortunately, in many areas of California we have not been replenishing this account sufficiently during wet years. Groundwater resources across California's agricultural regions have been more stressed during the current drought than at any other time in history (CDWR 2014a).

In most wells, depth to groundwater has exceeded that of the same or nearby wells in the 2007–2009 drought, and exceeds the depths recorded in the mid-20th century, prior to local, state and federal water projects (reservoirs and canals) coming on-line. The demand for groundwater has been increasing due to the increased acreage of intensively grown crops, large-scale conversion of rangeland and field crops to permanent crops and uncertainty about water deliveries from the Sacramento-San Joaquin Delta, the heart of California's elaborate surface water conveyance system (CDWR 2014b).

Lower groundwater levels have significantly increased pumping costs and increased the need for constructing deeper wells where existing wells were not sufficiently deep to access falling water levels (Howitt et al. 2014; Medellín-Azuara et al. 2015). Greater reliance on groundwater during the drought has caused land subsidence on a large scale in the Central Valley (in some cases more than 12 inches of subsidence in 2014 alone), coastal basins and Southern California; it has also exacerbated seawater intrusion where pumping occurs in aquifers near the coast (CDWR 2014c).

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**The Kings River flows across a coarse gravel bed near the Sierra Nevada foothills, recharging groundwater in the Central Valley aquifer.**

Thomas Harter

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# Hazardous Fuels Reduction Demonstrations — Fall 2015

To raise awareness about alternatives for hazardous fuels treatments, the UC ANR Woody Biomass Utilization Group and its project partners will be hosting demonstrations at three locations this October and November. The program includes a demonstration day in which participants will observe operations featuring equipment that can be used on difficult terrain, as well as technology that facilitates processing for value-added uses such as soil amendments and bioenergy. Participants will also learn about monitoring for fuel and soil impacts. In addition, the demonstrations will provide an opportunity for resource managers and other stakeholders to evaluate the effectiveness of alternative treatments for their region.

**Dates and locations:**

Oct. 9 Shaver Lake
Oct. 16 Big Bear Lake
Nov. 20 Santa Rosa Indian Reservation

**To register:**

Visit http://ucanr.edu/hftd or contact Dr. Peter Tittmann at pwt@berkeley.edu or 510-665-3518.

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Review Article

# California's agricultural regions gear up to actively manage groundwater use and protection

*by* Thomas Harter

*New regulations are emerging in response to historic groundwater depletion and widespread groundwater quality degradation in California. They aim at long-term preservation of groundwater resources for use in agriculture, in urban areas and for the support of ecosystems in streams dependent on groundwater. The regulations are driving a historic shift in the way the agriculture sector is engaged in managing and protecting groundwater resources in California. A review and synthesis of these recent regulatory developments — the Sustainable Groundwater Management Act and new policies under the California Porter-Cologne Water Quality Control Act — clarifies key challenges for farmers, scientists and regulators and points to the need for continuing innovation in agricultural practices as well as in planning and policy.*

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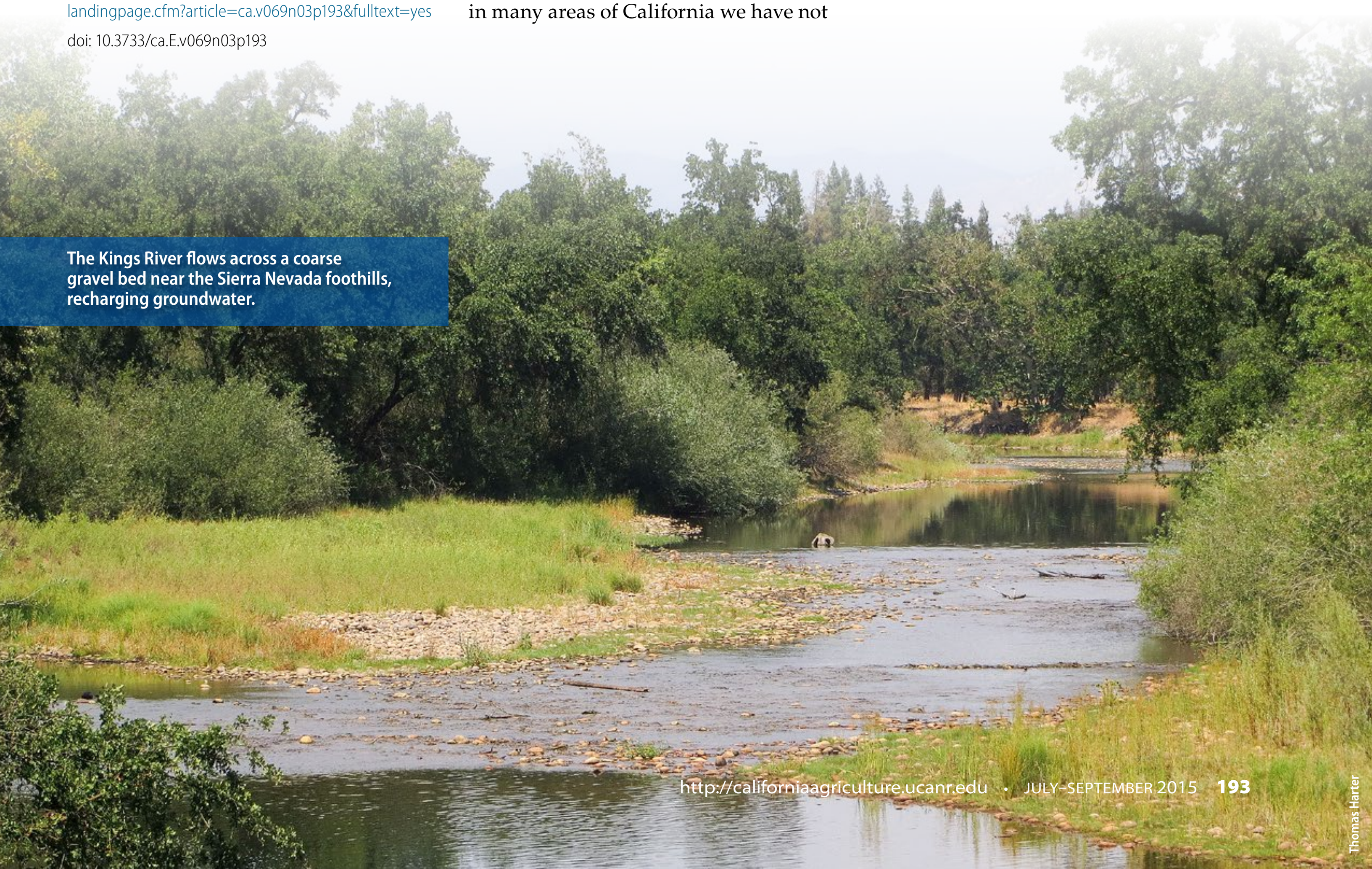

The Kings River flows across a coarse gravel bed near the Sierra Nevada foothills, recharging groundwater.

Thomas Harter

California Gov. Jerry Brown signed the new groundwater legislation into law in September 2014.


Lower groundwater levels have significantly increased pumping costs and increased the need for constructing deeper wells where existing wells were not sufficiently deep to access falling water levels (Howitt et al. 2014; Medellín-Azuara et al. 2015). Greater reliance on groundwater during the drought has caused land subsidence on a large scale in the Central Valley (in some cases more than 12 inches of subsidence in 2014 alone), coastal basins and Southern California; it has also exacerbated seawater intrusion where pumping occurs in aquifers near the coast (CDWR 2014c). As pumping lowers the water table, water quality is sometimes compromised by saline water or other naturally occurring contaminants (e.g., Jurgens et al. 2010). Rapidly falling water tables also lead to more-contaminated shallow groundwater entering drinking water wells.

Agricultural regions in California are challenged not only by dwindling groundwater supplies — a critical drought insurance for California — but also by significant groundwater quality degradation, in particular from nitrate and salt pollution. Pollutants may come from urban sources (such as wastewater treatment and food processing plants), domestic household sources (such as septic systems) or agricultural sources (such as fertilizer, animal manure and irrigation water).

A number of studies have shown a high incidence of nitrate, above drinking water standards, in domestic and public drinking water supply wells; in some counties, more than 40% of domestic wells exceed the nitrate limit for safe drinking water (Harter et al. 2012; Lockhart et al. 2013; LWA 2013; SWRCB 2013). Salt accumulation in streams and groundwater has also been found to be significant (LWA 2013), with potentially punitive economic consequences: By 2030, the combined impact of surface water and groundwater salinization to agriculture and the California economy, if current conditions continue and no preventative action is taken, is estimated at $6 to $10 billion annually in lost production costs, job losses and other impacts (Howitt et al. 2009).

The problems of groundwater overdraft and water quality degradation have been recognized for some time. Increasing public concern over the past two decades has raised the level of local, state and federal government engagement and of actions by policy- and decision-makers. Groundwater users and wastewater dischargers in the urban and the agricultural sectors face new regulatory requirements. While urban governments have a long history of dealing with limited water resources, the agricultural community is experiencing significant and historic changes in its involvement with managing groundwater extraction and protecting groundwater resources for the future.

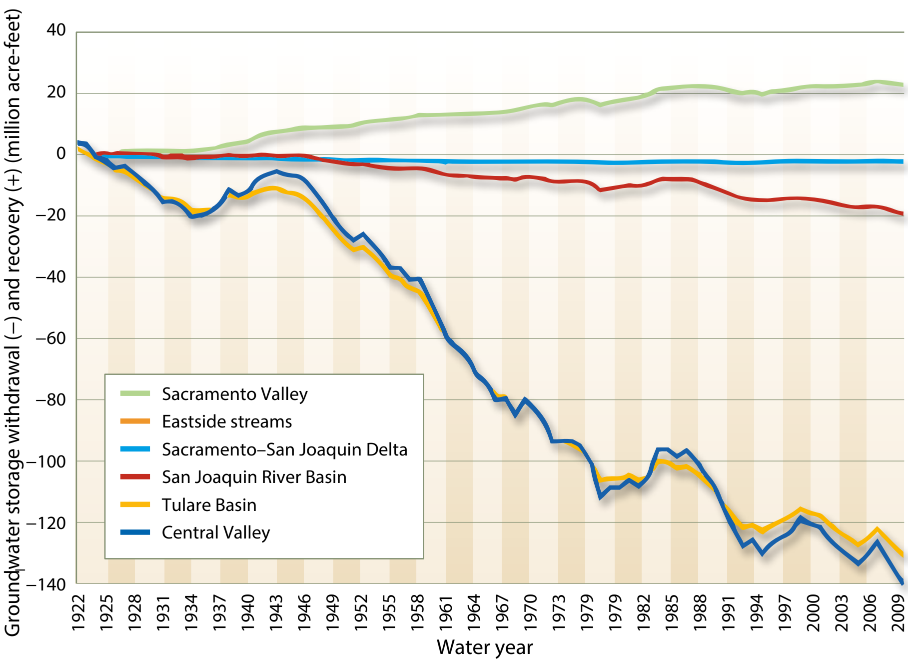


**Fig. 1. Changes in groundwater storage in the California Central Valley (dark blue) and its subregions from 1922 to 2009 (adapted from Brush 2014). The largest depletions have occurred in the Tulare Lake Basin, which includes the southern part of the Central Valley from Fresno to Bakersfield.**

### Groundwater supply management

On September 16, 2014, Gov. Jerry Brown signed the Sustainable Groundwater Management Act (SGMA), California's first comprehensive groundwater management legislation. It focused on managing groundwater supplies as part of an integrated hydrologic system for the benefit of current and future generations of Californians.

The legislation and the governor's water action plan (California Natural Resources Agency 2014) recognize the importance of groundwater for California's livelihood and its central role in California water management. The legislation seeks to put a process in place that ends decades of unsustainable groundwater use and management in some California regions and prevents future unsustainable groundwater use in other regions. For example, an estimated 140 million acre-feet were depleted from the Central Valley aquifer system (mostly in the Tulare Lake Basin) between 1922 and 2010 (fig. 1). And seawater intrusion due to groundwater pumping has migrated 8 miles into the Salinas Valley aquifer system (fig. 2).

While other Western states have statewide water rights management systems that include groundwater, California has lacked an administrative approach to managing groundwater rights. Conflicts that have arisen among groundwater users, for example in some areas in urban Southern California, have been addressed through expensive and lengthy judicial proceedings called groundwater basin adjudications.

The core principles that guided the development of the new legislation include the following:

- A vision that groundwater is best managed and controlled at the local or regional level; the state would only step in if local efforts are not successful or are not moving forward in accordance with the law.
- A broad definition of groundwater sustainability and a specific outline of what undesired effects must be avoided. The latter include continuous water level drawdown, subsidence, seawater intrusion, water quality degradation and continued (or new) impacts to groundwater-dependent ecosystems and streams after Jan. 1, 2015, when the legislation took effect.
- The state's role is focused on providing clear guidelines on requirements for local groundwater management, to be developed in 2015 and 2016 by the Department of Water Resources, as well as providing technical and financial support.
- Existing water rights will continue to be protected.

***The agricultural community is experiencing significant and historic changes in its involvement with managing groundwater extraction and protecting groundwater resources.***

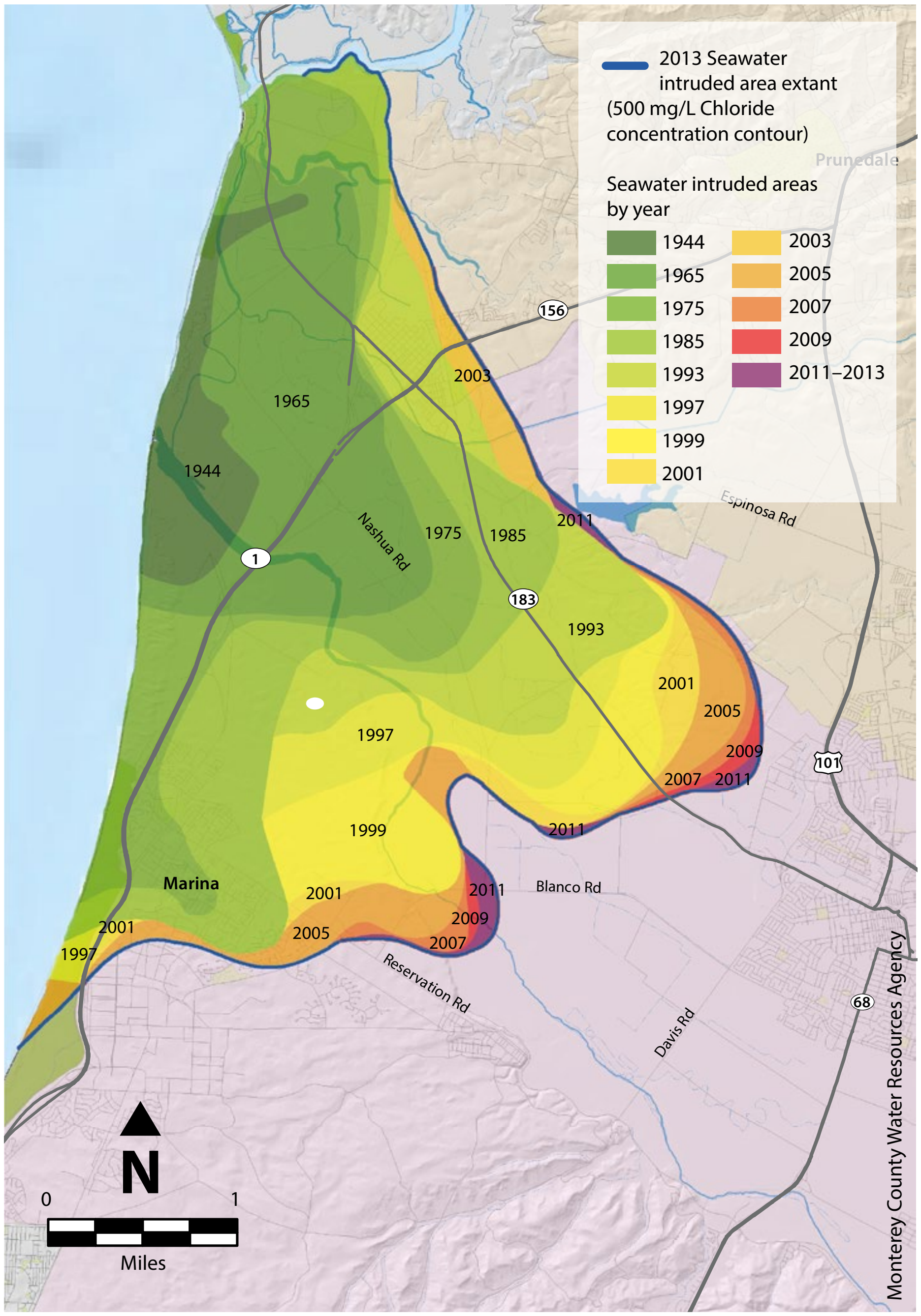


**Fig. 2. History of seawater intrusion in the Salinas Valley (Brown and Caldwell 2015).**

Based on these principles, the legislation lays out a framework for the entire state to manage its groundwater. In 127 medium- and high-priority groundwater basins (representing about 96% of groundwater extraction), groundwater sustainability agencies (GSAs) will have to be formed no later than June 2017. These GSAs will be responsible for developing and implementing a groundwater sustainability plan (GSP) that has specific objectives and meets specified sustainability targets consistent with the core principles of the SGMA. GSAs have 3 to 5 years to develop and begin implementing their GSP (by 2022, or in critically overdrafted basins by 2020). GSAs must show significant progress in implementing their plan and achieve sustainability no later than 2042.

Between 2015 and 2017, the focus of the implementation of the SGMA will be multipronged:

- GSAs will be formed that together govern all of the 127 medium- and high-priority groundwater basins, not just partially but in their entirety. This process will only be possible with significant local stakeholder involvement and will require significant outreach, facilitation and local leadership.
- The Department of Water Resources will be in charge of identifying critically overdrafted basins, developing minimum regulations for a GSP, new rules for adjusting basin boundaries and implementing basin coordination among GSAs, and regulations for determining medium- and high-priority basins that have significant groundwater-dependent ecosystems or stream flow but are not already included in the current group of 127 medium- and high-priority basins.
- Technical guidelines and financial support will be developed throughout the state.

While farmers and landowners may not see immediate impacts from the legislation, their involvement in the formation of the GSAs and in the development of the GSPs provides opportunities to shape the political process in ways typically not possible in the court-driven adjudication process. GSAs can be formed by local public agencies, such as cities, counties, water and irrigation districts, or other special acts districts (e.g., water replenishment districts).

The SGMA provides flexibility and allows for either a single agency or multiple agencies to run a GSA. A GSA in turn may govern an entire groundwater basin or just a portion of a groundwater basin. Where multiple GSAs govern a groundwater basin, GSAs have to coordinate their efforts. A basin may have a single GSP implemented by one or multiple GSAs, or a GSA may have multiple GSPs. Importantly, the GSAs must consider the interests of the wide range of groundwater uses and users, including agricultural pumpers. Given the broad authorities given by the SGMA to GSAs in managing recharge and extraction, groundwater users have strong motivation to be engaged early in the formation of GSAs to ensure political representation in the decision-making process when GSPs are developed and implemented. GSPs will rank around four key programmatic areas:

- data collection, monitoring, modeling, evaluation, assessment and reporting (on a continuous basis)
- stakeholder engagement, communication, outreach and facilitation of stakeholder-informed policy development
- development of groundwater supply projects to increase recharge as needed (e.g., intentional recharge, groundwater banking, increased recycled water use, storm water capture, surface water imports)
- reducing groundwater extraction as needed (e.g., water conservation programs, land purchases for agricultural land retirement, setting extraction limits, extraction fees)

Funding for GSP activities will likely come from a combination of state and local funding sources.

In overdrafted basins, adjudications may continue to be an alternative process to achieve sustainability, despite the high cost and often years-long legal proceedings involved. As of this writing, the Legislature is actively considering multiple bills that would create an alternative, streamlined adjudication process.

In the intermediate and long run, the main impact from this legislation will be that new recharge and groundwater storage options will be pursued, and, where needed, pumpers may see restrictions in pumping or well drilling. Where additional recharge is available, pumpers may be asked to pay additional costs to secure the recharge needed in return for their right to continue pumping. Basin boundaries may be adjusted and may include fractured rock aquifers currently not recognized as groundwater basins by the Department of Water Resources although they are subject to significant groundwater extraction in some areas.

Litigation and state intervention may be inevitable in some cases, but it remains to be seen how frequently that route will be chosen over mediation or facilitated GSP development and implementation. In either case, the new groundwater legislation marks a turning point in California water management by no longer allowing for continued depletion of groundwater resources and by requiring an active, well-informed groundwater management system that is better integrated with surface water management, water quality management and land use decisions to maintain a balance that best serves competing human, economic and environmental health interests.

## Groundwater quality regulation

The federal Clean Water Act addresses only surface water quality. By contrast, California's water quality law, the Porter-Cologne Water Quality Control Act of 1969 (Porter-Cologne Act), includes the protection of groundwater quality. The California Legislature designated the State Water Resources Control Board (SWRCB) and nine newly created regional water boards (RWBs) to implement the Porter-Cologne Act.

The primary function of the RWBs is to establish a basin plan that identifies water quality goals and to develop regulatory programs to achieve those goals. Nonpoint sources of potential groundwater pollution (urban storm water, agriculture) were long exempted from direct oversight through unconditional waste discharge waivers. However, those waivers were discontinued by the Legislature in 2002, which led to new regulatory requirements for agricultural and other nonpoint source water dischargers (Dowd et al. 2008). Focused on surface water quality in the first decade after 2002, these regulatory efforts now increasingly address groundwater quality. They require demonstrable source control and documentation of groundwater nitrate and salt discharges and also provide state and federal funds to improve the drinking water supplies of communities affected by poor groundwater quality.

The nine RWBs use different approaches to assess and control agricultural discharges. The Central Valley RWB and Central Coast RWB regions are home to large areas of California's most intensive agricultural operations and have therefore developed the most extensive regulations. But all RWBs are obligated to consider discharges from nonpoint sources to groundwater and to develop basin plan amendments for nutrient and salt management (SWRCB 2009).

In the Central Valley, three major programs have been or are being developed to control salt and nutrient discharges to groundwater and surface water: the Central Valley Dairy Order, the Irrigated Lands Regulatory Program (ILRP) and the Central Valley Salinity Alternatives for Long-Term Sustainability (CV-SALTS) program. The Central Coast has developed its own version of the ILRP, referred to as the Central Coast Agricultural Order.

With respect to groundwater protection, all of the above programs have in common that they require

- assessment of sources, groundwater pathways (hydrogeology, water quality) and potential groundwater quality impacts
- source management plans
- source management certification and reporting
- direct or indirect (proxy) groundwater discharge monitoring
- development of management practices that are protective of groundwater quality
- groundwater monitoring at the regional level

**Central Valley Dairy Order.** The 2007 Dairy Order was the first comprehensive California groundwater quality permitting program applicable specifically to farms. It sets the framework for permitting dairy discharges of nutrients and salts to surface water and groundwater. The dairy order requires dairies to prepare nutrient and waste management plans, annually report nutrient budgets for individual fields, tonnage of manure exports and water quality of on-site wells. Targeted shallow groundwater monitoring and efforts to develop improved management practices that demonstrably improve groundwater quality are implemented through the Central Valley Dairy Representative Monitoring Program. This program is led by a coalition of dairy producers that is working closely with the RWB; it offers an efficient alternative to individual dairy groundwater monitoring plans.

**Central Valley Irrigated Lands Regulatory Program.** Upon its inception in the early 2000s, the Central Valley ILRP (like a similar program in the Central Coast region) focused on surface water and watershed protection through farmer education, certification and coalition-led stream water quality monitoring and management. But since 2010, the Central Valley RWB has been expanding the ILRP to add elements that also protect and improve groundwater quality, primarily nitrate, pesticide and salt contamination, through source management on irrigated lands.

In the Central Valley, the ILRP covers about 7 million irrigated acres with several tens of thousands of individual farms. Permits (waste discharge orders) are given either to individual farms or to regional ILRP coalitions, organizations that farms can join to represent them collectively with the RWB. ILRP coalitions representing large groups of farmers include the Sacramento River Watershed, Rice Farmers, Eastern San Joaquin Watershed, San Joaquin County and Delta, Western San Joaquin Watershed, Tulare Lake Basin Area, and Western Tulare Lake Basin Area coalitions. Each coalition is subject to a separate RWB order.

Under the expanded ILRP, the first step is a Groundwater Assessment Report (GAR), which is currently being developed or has been developed by each of the coalitions. The assessment identifies

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Water well drilling rig on the UC Davis campus.

historic and current groundwater quality conditions and identifies vulnerable groundwater regions. The assessment provides the rationale for the monitoring and reporting requirements, which may differ within and between regions, and allows for a tiered program of monitoring and reporting requirements for subregions to reflect the diverse potential impacts to groundwater.

In a next step, beginning in 2015, field-specific nutrient management planning forms will need to be completed by all farmers for the first time. Generally, farmers will now be required to implement management practices, keep appropriate records (for random audits) and report some of the information collected to their coalition. The coalitions are further responsible for performing groundwater monitoring, typically in a network of domestic and monitoring wells. As in the dairy program, the coalitions are also responsible for developing management practices that demonstrably improve and protect groundwater quality. A significant focus will be on documenting field nitrogen inputs and outputs and on improving nitrogen-use efficiency.

**Central Coast Agricultural Order.** In 2012, the Central Coast RWB adopted an update to the ILRP, called the Agricultural Order (or Agricultural Regulatory Program). The program covers about 4,000 farms on about 400,000 acres. Based on its own groundwater assessment work, the RWB created three tiers of farms depending on the potential risk they pose to groundwater quality. The tiers are determined by pesticide use, farm size, nitrate occurrence in nearby public supply and farm wells, and by crop type. About one in seven farms are in the highest tier, tier three (posing the greatest risk), about half of the farms, mostly vineyards, fall in the lowest tier (posing the least risk), and the remainder are in tier two.

As in the Central Valley, farms in all tiers are required to perform proper nutrient, pesticide and irrigation management, documented in their farm plans (although the specific forms may differ from those in the Central Valley). Backflow prevention and proper well abandonment are also required on all farms. Unlike in the Central Valley ILRP, all farms need to sample groundwater from existing wells twice during the first year. Subsequent groundwater sampling frequency is greater for farms in tier three than in tier two or one. Farms can choose to implement the groundwater sampling program individually or join a coalition that has been created specifically to perform groundwater monitoring and to support farmers with the implementation of the Agricultural Regulatory Program.

**Central Valley SALTS program.** Operating at an even larger scale and affecting stakeholders beyond agriculture (e.g., wastewater treatment plants, food processing plants, urban storm water systems) is the Central Valley Salinity Alternatives for Long-Term Sustainability (CV-SALTS) program. In coordination with the RWB, it was created in 2009 by stakeholders to develop a comprehensive salt and nutrient basin plan amendment for the Central Valley that complies with the state's recycled water policy (SWRCB 2009). The development of the basin plan amendment includes a wide range of assessments by CV-SALTS: nitrate and salt source loading from agricultural, urban and industrial sources, extensive review of surface water and groundwater quality data, and development of potential management practice and infrastructure solutions.

The CV-SALTS program builds upon and is coordinated with the Central Valley Dairy Order and ILRP efforts. It focuses in particular on avoiding future salinization of the Central Valley aquifer system under SWRCB's overarching antidegradation policy. Stakeholders are organized within the Central Valley Salinity Coalition (CVSC), which is scheduled to provide its final salt and nutrient management plan (SNMP) to the RWB in 2016. As part of these efforts, a recent Strategic Salt Accumulation and Transport Study (SSALTS) compared historic water quality data to an assessment of current salt and nutrient loading in the Central Valley; it determined that approximately 1.2 million acre-feet of Central Valley groundwater needs to be desalinized annually to meet long-term irrigation and drinking water standards.

SSALTS suggests various alternatives for water treatment, including desalination and evaporation ponds. Implementation costs are estimated to be roughly $70 billion over the next 30 years, of which $20 billion can be raised by selling approximately 1.1 million acre-feet of ultraclean treated water annually to urban areas. These costs include some saline water being disposed of by deep injection and some being stored in salt accumulation areas on the Tulare Lake Bed (CDM Smith 2014).

## Challenging transitions for agriculture, science and the regulatory community

These efforts to manage groundwater supply and groundwater quality make the agricultural community subject to an evolving set of new requirements for documentation of key farm activities, training, practice improvement, monitoring and reporting. This will be a significant and in some cases expensive shift in farming practices. It is without parallel in California's agricultural history. As was the case with the development and implementation of water quality regulatory programs in the 1970s through 1990s that targeted and significantly changed practices in industrial and urban land uses, the transition period will be challenging for this newly regulated community and likely take a generation to be fully effective.

To the degree that a more centralized, region-wide effort — rather than a farm-by-farm approach — can direct the goals of these new programs, the ILRP coalitions will have a key role in providing services to help member farmers comply, at an annual cost currently ranging from about $3 to $7 per acre (including regulatory fees assessed by the RWBs). Similar coordination and funding approaches may evolve within the GSAs that implement the new sustainable groundwater management legislation, with some additional funding available also through state and federal grants. But in addition to paying monitoring and compliance fees, farmers and their employees will also participate in training and continuing education, provided through the ILRP coalitions, local GSAs, UC ANR Cooperative Extension, National Resources Conservation Service, Resource Conservation Districts and others; and on many farms, significant infrastructure improvements are needed to address groundwater quality and quantity concerns, at significant cost to the farm operation (Medellin-Azuara et al. 2013).

This is not a transition period only for farmers; it is also a transition period for scientists and educators who develop and provide innovative management practices and training to protect groundwater quality and better understand the groundwater–agriculture interface. Agronomic and crop scientists have rarely taken into account losses of contaminants to groundwater when developing best management practices and farm recommendations. Existing recommendations for fertilizer applications, for example, are in urgent need of revision to account for potential unwanted losses of nutrients to groundwater (Gold et al. 2013; Rosenstock et al. 2014). Another challenge for scientists is the design of groundwater monitoring networks. Existing groundwater research has developed many approaches to monitoring distinct contaminant plumes, typically a few acres in size (e.g., Einarson and Mackay 2001), but recommendations for the design of nonpoint source monitoring networks are currently lacking (Belitz et al. 2010).

Furthermore, this is a transition period for regulatory agencies, which for the first time are regulating nonpoint sources of groundwater pollution that involve large tracts of land with numerous individual landowners who are adjacent to each other and a wide range of crops, soils and management practices. For agencies, this is a situation that requires innovative strategies and a significant rethinking of existing programs that have been focused on point sources or surface water quality.

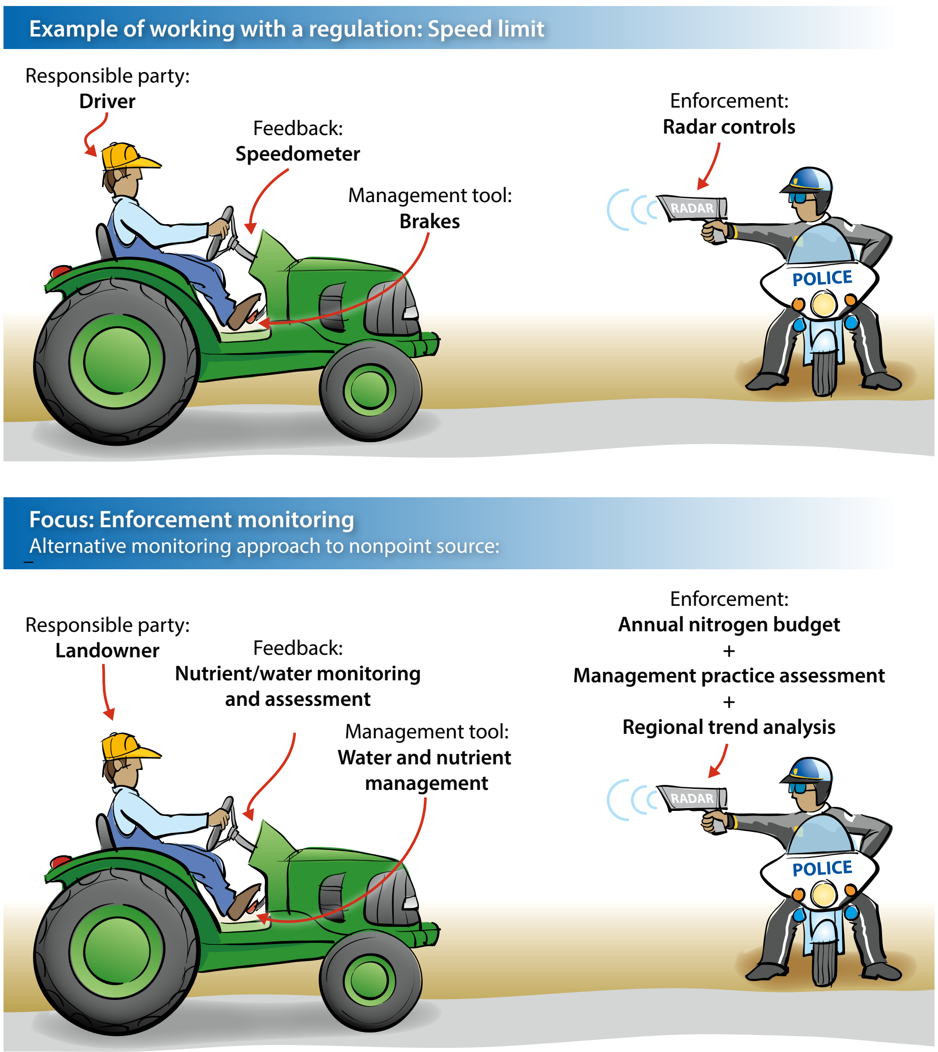


**Fig. 3. Implementation of new nonpoint source monitoring programs to evaluate discharge to groundwater. A well-known enforcement program is the speed limit, which involves the driver as the responsible party, a speedometer that provides instantaneous feedback on speed, brakes and accelerator to adjust the speed, and police radar controls for enforcement. The equivalent in nonpoint source regulatory programs is the landowner as responsible party, the nutrient and water budgets as feedbacks to the landowner, nutrient and water management as the tool to adjust discharge and a three-tracked monitoring program for enforcement (see text).**

For example, regulatory agencies have long focused on shallow groundwater monitoring wells as a key tool for monitoring potential waste discharges into groundwater and to detect inadvertent contaminant plumes from point sources, such as from underground gasoline storage tanks. Underground storage tanks are discrete point sources, and leaks from them can be detected by using down-gradient monitoring wells (Day et al. 2001). Agricultural irrigation, in contrast, leaks by design across broad landscapes, to flush salts from the root zone. Agricultural irrigation has therefore also been a significant source of groundwater recharge, especially irrigation from older non-efficient systems.

## New monitoring approaches

Regulatory agencies have come to recognize that traditional site monitoring well networks are not the most effective tool for farm discharge monitoring. In the Central Valley Dairy Order, Central Valley ILRP and Central Coast Agricultural Order, an alternative is emerging that employs a loosely integrated three-tracked monitoring approach (fig. 3):

1. Proxy monitoring, e.g., nutrient budgets: Nitrogen budgets at the field and farm scale are used to estimate potential groundwater nitrate losses, instead of groundwater monitoring wells that would more directly observe discharge of nitrate.
2. Management practice assessments: Because discharge is not measured directly, research is needed to show the relationship between the nitrogen budget (the proxy waste discharge monitoring tool), agricultural management practices and impact to groundwater quality. In the Central Valley ILRP, this step is referred to as the management practice evaluation program.
3. Regional trend monitoring: As an insurance that the first two tracks are successful, regional long-term dynamics in groundwater quality are monitored through trend monitoring programs, implemented by farm coalitions or through a regulatory agency (e.g., California Department of Pesticide Regulation domestic well monitoring program).


**Two monitoring wells (short white casings) adjacent to an irrigated, manure-treated field as part of a dairy monitoring program.**

The specific monitoring requirements under each of the three tracks are a function of groundwater conditions, potential pollution sources, proximity to public and private water supply wells and existing contamination. The role of the groundwater assessments described above is to better understand these aquifer conditions as a basis for developing these three-tracked monitoring programs effectively, efficiently and commensurate with groundwater vulnerability.

## Future directions

**New agricultural practices to manage groundwater quantity and quality.** Managing groundwater quantity in California's diverse agricultural landscape is intricately linked to protecting groundwater quality and vice versa. New practices in the agricultural landscape to recharge clean water into aquifers while maintaining high irrigation efficiencies and while also controlling nutrient and pesticide leaching will address both groundwater overdraft and groundwater quality.

Dzurella et al. (2012) and others have outlined numerous ways to improve nutrient management in California's diverse cropping systems, following largely the concept of the Four Rs: Right amount, Right time, Right place, Right form (CAWSI 2015). Significant educational efforts by universities, state and federal agencies, and industry groups will need to continue and intensify to support agriculture in moving forward with practices that better protect groundwater. There is one key complication around managing nutrients: while high nutrient-use efficiency reduces nitrate and pesticide loading, it also is typically achieved only with high water-use efficiency. In situations where irrigation water is imported to the groundwater basin rather than pumped from local aquifers, higher water-use efficiency translates into significant reductions in groundwater recharge, impacting long-term water supplies and raising the need for additional recharge of clean water.

New agricultural practices, yet to be developed, also promise to play an important role in simultaneously addressing groundwater quality and groundwater quantity issues: the agricultural landscape potentially provides a wide range of opportunities for using floodwaters and other surplus surface water to recharge groundwater, whether with recharge basins, field flooding, targeted clean recharge irrigations or other methods (e.g., Bachand et al. 2014; Harter and Dahlke 2014). The significant potential for innovation and field testing in this arena could lead to water being intentionally recharged in the agricultural landscape without degrading water quality, possibly even improving water quality. For example, in areas recharging groundwater for public supply wells ("source areas"), some nitrogen-intensive crops may be replaced with crops that are known to be relatively protective of groundwater quality. This has been shown to be an economically promising option to address long-term drinking water quality issues, especially in the source area of drinking water supplies for small, often disadvantaged communities (Mayzelle et al. 2014; Rudolph et al. 2015). More research and pilot testing are needed.

**Integrating groundwater management with surface water management and with land-use planning.** Groundwater management cannot be done without managing surface water resources. The future of groundwater use, protection and management in California's agricultural landscape will be an increasingly integrated approach to managing the quality and quantity of both surface water and groundwater. Land-use planners must also be more involved in and informed by water planning and assessment activities. New regulations for groundwater sustainability and groundwater quality protection have emphasized the engagement of landowners and local stakeholders in the planning and implementation of new regulations, providing stakeholders, including farmers, with opportunities for engagement, dialogue and education. Integration of the new groundwater regulations with existing programs in integrated regional water management (IRWM) planning and urban water management planning will be needed. This integrated strategy will employ a diverse portfolio of approaches reflecting local needs, local technical and economic capacity, and the diversity of local stakeholders and of their engagement in these efforts.

**Sharing the costs.** The new groundwater management and groundwater quality regulations and improvements involve additional costs and efforts for farmers and other local and state stakeholders and taxpayers, but they will provide long-term benefits to water users, including agriculture. Disagreements and lawsuits over how to share costs will likely continue to be part of the agricultural groundwater landscape as well.

**The global long-term view.** Despite the growing pains, sustainable management of groundwater supplies and protection and improvement of groundwater quality in California agricultural regions are a necessary and vital foundation for continued economic and ecosystem prosperity in these regions. If California continues to lead, nationally, this broad sustainability effort and if that leadership is demonstrable and transparent to the public, California agriculture may some day enjoy a significant economic advantage: sustainable agricultural produce is expected to be in demand among increasingly discerning consumers, including large food service providers (for instance, Menus of Change).

Finally, and most importantly, California is not alone in this challenge. Irrigated agricultural regions around the world produce 40% of global agricultural products. Many of these regions are struggling with overuse and water quality degradation of their groundwater resources, posing significant risks to global food security and political stability (Brabeck-Letmathe and Ganter 2015; University of California 2015). Meeting the sustainable groundwater challenge with forward thinking and integrated agricultural, scientific and policy programs has become a global endeavor. CA

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