California Agriculture

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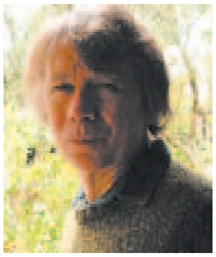
California soil quality: a closer look

University of California | Division of Agriculture and Natural Resources | Research in Agricultural, Natural and Human Resources



Garrison Sposito
Professor,
Ecosystem Sciences,
UC Berkeley

How to manage "soil quality" key question for farmers and scientists

Every grower and UC Cooperative Extension farm advisor appreciates the importance of soil quality to farm management. But remarkably, few soil scientists agree on how this key component is to be assessed or monitored. Soil is a complex natural resource that is subject to multiple beneficial uses, giving rise to debate about how it should be managed. However, experts do concur on the goals of a soil quality evaluation. It must:

- reflect what is known about the behavior of the surrounding ecosystem, including its responses to climate variation and human impacts;
- integrate the biological, chemical, geological, hydrological and physical properties of field soils,
- and translate scientific understanding into effective decision-making for soil resource management.

UC research teams have made recent strides in evaluating soil quality for production agriculture. One group of soil scientists seized a unique opportunity to examine a large number of archived California soil samples that had not been disturbed for close to 60 years, comparing their chemical fertility properties (pH, nutrient levels, carbon content) with those of soil samples collected only 2 years ago from the same field sites (p. 38). Their results may surprise some readers.

Another team has added to our understanding of how natural vegetation enhances soil quality as reflected in the same chemical properties — plus an additional physical property, bulk density, which is connected to soil aeration and permeability (p. 42). They have documented the many beneficial effects of blue oak stands, concluding that oak preservation deserves consideration as part of the optimal management of the urban–wildland–agriculture interface.

Other soil scientists extend these ideas to cover crop and tillage management on agricultural soils, pointing out in their careful study that, to ensure optimal crop yields, the positive effects of cover crops must be balanced with the well-known advantages of tillage (p. 48). Yet another research group continues the theme of balancing impacts and trade-offs in their timely study of how incorporating rice straw into soil, a management practice adopted to mitigate the known air quality impacts of rice straw burning, can produce toxic substances, notably sulfides, that reduce rice yields.

The research performed by these UC teams provides valuable insight into which soil properties are good indicators of soil quality: organic carbon content, nutrient levels, pH, salinity levels and bulk density, to name the more prominent ones. But how well does soil quality as measured by these properties correspond to growers' perceptions of their own soils?

A recent study put exactly this question to a group of San Joaquin Valley farmers participating in the West Side On-Farm Demonstration Project.* Out of a maximum high score of 10 for perfect agreement between soil quality as rated by growers and soil quality as rated by indicator properties (see list above), the average score was a remarkable 8 (±1 standard deviation). There was a close correspondence between scientific measurements of soil quality and growers' own perceptions based on their experience with the land. Another result was that growers were more likely to support alternative management practices (for example, organic matter amendments) on soils perceived already to be of lower quality. This choice reveals a belief that alternative practices are better for curing "sick" soils than sustaining "healthy" ones. Perhaps the most significant grower viewpoint expressed was that soil quality assessment is deemed useful only if it increases crop yield and farm profitability.

It is evident from these studies that, although much is to be learned about soil quality assessment, organic matter management is emerging as a critical factor in the control and maintenance of agricultural soil quality. The current 5-year mission of the Kearney Foundation of Soil Science, "Soil Carbon and California's Terrestrial Ecosystems," recognizes this factor in a multifaceted research program focusing on four broad goals:

- to understand the mechanisms governing the storage and flow of carbon pools in soils that support California's diverse ecosystems;
- to quantify the impacts of anthropogenic inputs of water, nutrients and pollutants on the transformations of carbon in soil;
- to assess the roles soil carbon may play in emissions of greenhouse gases, and
- to analyze strategies and policy options for soil carbon management that optimize natural resource utilization and mitigate adverse effects of global climate change.

Ongoing Agriculture and Natural Resources (ANR) research directed toward these goals and the elusive connection between soil quality and farm profitability is essential to the development of long-term policies that will keep California competitive in agricultural production while maintaining the rich diversity of ecosystem services that have benefited its people for more than two centuries.

** Source: Andrews SS, Flora CB, Mitchell JP and Karlen DL. 2003. Farmers' perceptions and acceptance of soil quality indices.* Geoderma *special issue, "The Assessment of Soil Quality." (G. Sposito and A. Zabel, Editors)* **)** *In press.*

Editor's note: *Garrison Sposito was Director of ANR's Kearney Foundation of Soil Science from 1996 to 2001. Under his direction, the Foundation supported studies investigating"Soil Quality in the California Environment," four of which appear in this issue.*

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News departments

Research articles

COVER: Soil is the essential building block for sustainable agriculture and healthy ecosystems. In this issue, UC scientists examine how production agriculture, natural vegetation, and environmental regulation have affected California soil. One study finds that the state's soil has maintained its chemical quality over the last six decades, although erosion appears to have accelerated. Scientists working in oak woodlands report that blue oaks significantly enhance the fertility of the soil. Others performing field trials in the Salinas Valley assess the trade-offs of different cultural practices. In addition, researchers provide helpful information to rice growers incorporating rice straw into soil, and to managers seeking to meet environmental regulations while using public lands to graze livestock.

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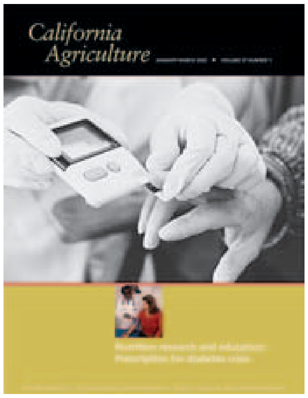
Editor's note:
Due to cutbacks related to the state's budget deficit, *California Agriculture* will publish two issues (rather than three) during the first half of 2003. This issue covers April, May and June of 2003. We regret any inconvenience to our subscribers and contributing scientists.

Letters

Politics of overconsumption



The value of the otherwise useful editorial by Joanne Ikeda and Patricia Crawford in the January-March 2003 *California Agriculture* is undermined by its failure to dig into the institutional structures in our society that contribute to overeating and overweight. While properly identifying the problem and its two main causes — overconsumption and underexercising — the article avoids a discussion of the socio-economic and political factors contributing to overeating. The authors briefly cite the issue of serving size, but they don't get at the underlying dynamic, namely the strenuous activities of food corporations through advertising, public relations, and political activity to pack more food into us individually and collectively. These same corporations consistently resist regulation and lobby for increased deregulation.

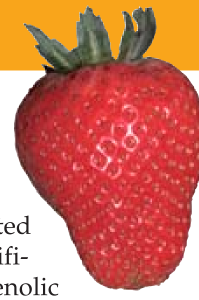
William H. Friedland
Research Professor and Professor Emeritus
UC Santa Cruz

Pat Crawford and Joanne Ikeda (co-authors of the editorial "Californians face weight and health care crisis," California Agriculture *57(1):2) respond:*

We regret that we had insufficient space in our editorial to fully discuss the pathogenesis of obesity. A comprehensive examination of the factors associated with energy intake must include institutional influences, one of which is the food industry, the corporations that grow, process and sell foods. The success of this industry depends on consumers consuming more. National food intake surveys show that Americans today are eating significantly more than they did in 1980. For example, an average woman today consumes nearly twice the calories needed (3800 kcal/day) while leading an increasingly sedentary lifestyle. It is not known to what degree the increase in intake is a result of changing varieties of foods, larger portion sizes, increased availability of foods, or aggressive food marketing and advertising campaigns. Dr. Friedland is correct that the lobbying of the food industry for less regulation can be at odds with the consumer's best interests. At the Center for Weight and Health, we are keenly interested in all factors influencing weight, including those of the family, the community and finally the larger society with its norms, laws, regulations and mass media influences.

WHAT DO YOU THINK? The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at calag@ucop.edu or 1111 Franklin St., 6th floor, Oakland, CA 94607. Include your full name and address. Letters may be edited for space and clarity.

Science briefs



Pesticide-free produce may contain more antioxidants

Berries and corn that are culti-vated without pesticides contain a significantly greater amount of polyphenolic antioxidants than conventionally grown fruits and vegetables, UC Davis scientists report. The marionberries (a type of blackberry), strawberries and corn researchers studied contained as much as 58% more polyphenolics.

The researchers, led by Alyson Mitchell, assistant professor of food science, found that the produce grown organically or sustainably — with fertilizers but without pesticides — measured higher levels of ascorbic acid, or vitamin C, as well.

The fruit and corn were grown in matched plots by a farm in Oregon, then were frozen, freeze-dried or air-dried before the nutrients were measured. Frozen sustainably grown and organic marionberries and corn contained 50 to 58 percent more polyphenolics than conventionally grown crops from neighboring plots. Sustainably grown frozen strawberries contained 19 percent more polyphenolics than conventional fruit. These levels were nutritionally significant.

While researchers know that a diet high in polyphenolics can reduce the risk of some cancers and heart disease, they aren't sure how. "We know they're beneficial, but we don't know what types of polyphenolics are beneficial, or in what quantities," Mitchell said.

Mitchell hypothesized that crops grown without pesticides or herbicides might make more polyphenolics because they are more likely to be stressed by insects or other pests. Polyphenolics are natural chemicals produced by plants as byproducts of other processes. When plants are stressed, they produce higher levels of the bitter-tasting polyphenolics and drive away pests.

Microorganisms break down toxic pesticide

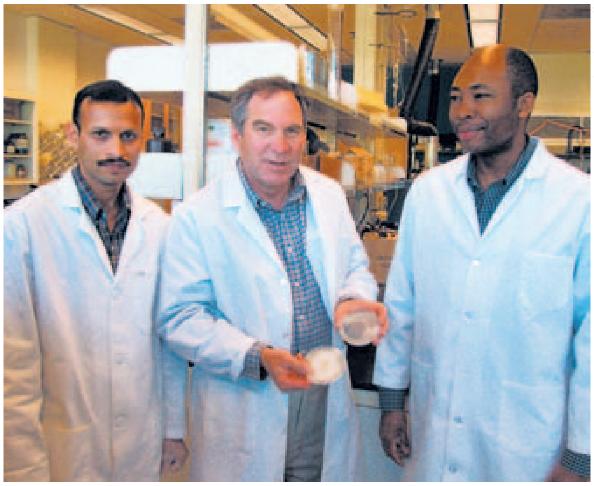
UC Riverside scientists have isolated microorganisms that can break down endosulfan, a persistent insecticide used on crops around the globe. The microorganism strains can be added to soil or water to significantly reduce levels of the insecticide.

"We have been successful in isolating strains that can use endosulfan as a carbon and energy source," said William Frankenberger, director of the UCR Center for Technology Development and professor of soil science at Riverside. He added that microorganisms will rapidly degrade pollutants when they are able to use them as an energy and carbon source.

Endosulfan, an organochloride in the same family of pesticides as DDT and dieldrin, has a half-life of 9 months to 6 years. Because it lingers so long, it can enter the food chain and cause damage to the central nervous system, kidneys, liver, blood and parathyroid gland. It can also cause birth defects and genetic mutations. The pesticide is registered for use on 60 crops in the United States and is found in waters in 38 states.

Frankenberger's findings indicate that the microorganism strains could be added to contaminated soils, bodies of water, insecticide waste dumps, wastewater and stockpiles of endosulfan. His research found that one strain, *Fusarium ventricosum,* was able to degrade about 90% of 100 ppm endosulfan within 15 days. Another strain, *Pandoraea sp*., degraded about 83% within 15 days.

The research was conducted at UC Riverside in 2001 and 2002 and published in the *Journal of Environmental Quality*.


Judy Chappell

UC Riverside researchers Tariq Siddique, William Frankenberger and Ben Okeke with samples of isolated purified bacterial and fungal strains that decompose endosulfan.

Lake Tahoe clearest in a decade

Lake Tahoe's renowned blue waters were clearer last year than they've been in 10 years, UC Davis researchers said. The clarity of the lake is good news for scientists who have been trying to reduce Lake Tahoe pollutants for the past four decades.

"These are encouraging results, and we hope they indicate the beginning of the lake's recovery," said Charles Goldman, director and founder of the UC Davis Tahoe Research Group. "However, 10 years is a short time, and it is too early to say if the recent improvements will continue. We must keep up our efforts to prevent water and air pollution, or we may still end up with a green lake."

In 2002, a white disk lowered into the lake approximately once a week was visible down to an average of 78 feet. Those are the best results since 1992, when the average visibility depth was 78.3 feet. The lake still has a ways to go, however: In 1968, when researchers began measuring the clarity, the dinner-plate-size disk could be seen down to 102.4 feet.

Goldman noted that 2001 and 2002 received less rainfall than average, which reduced runoff and could have helped clarity. But efforts to improve the lake's clarity may have contributed. These include reducing the runoff of fine sediment, which makes the water cloudy; limiting nutrients such as fertilizers that promote algae growth, which makes the water green; and minimizing the air pollution that is deposited into the lake.

"Whether or not runoff was reduced by low precipitation or by improvement projects, or both, the lake may be showing that it can recover," Goldman said.

West Nile vaccine for horses

UC Davis equine experts recommend that horses be vaccinated in March and April this year for West Nile virus. Horses should receive two doses three to four weeks apart from a licensed veterinarian before the mosquito season begins.

Horse owners are advised to consult with their veterinarians for the vaccination of individual horses. Pregnant mares and foals less than one year, for example, should receive modified treatments.

West Nile virus is much more deadly in horses than in humans — one out of three horses infected will die from it. Signs of infection in horses vary markedly but can include twitching or flaccidity of the lips, listlessness, stumbling and lack of coordination, leg weakness and a tendency to startle easily.

The experts also encourage ranchers to eliminate standing water around horses to reduce mosquito populations and to stable horses during active mosquito feeding times — dawn and dusk.

The vaccine, manufactured by Fort Dodge Animal Health, a division of Wyeth Laboratories, in Overland Park, Kan., is named West Nile — Innovator. It has received unconditional approval from the U.S. Department of Agriculture and is available only from licensed veterinarians.

Looking back 60 years, California soils maintain overall chemical quality

The quality of California's soil chemistry has not declined significantly since the mid-20th century, although a greater proportion of clay indicates accelerated erosion.

Fabrice DeClerck
Michael J. Singer

To learn whether soil properties important to production agriculture and environmental quality have changed significantly in the past half-century in California, we analyzed archival samples and samples collected in 2001 from the same locations. Comparisons of organic matter content, pH, electrical conductivity, total nitrogen, total carbon and plant-available phosphorus showed significant changes since the mid-1900s. Across the state we found increases at the 95% confidence level for plant-available phosphorus, total carbon, pH, and percent clay, and increases at the 90% confidence level for percent silt and total nitrogen. We measured significant decreases at the 95% confidence level for electrical conductivity and percent sand. Based on this sample of 125 soils, we believe that California's soil chemical quality has not decreased significantly over the past 60 years. However, increased clay percentages may be interpreted as a sign of accelerated erosion, which is a sign of decreased soil quality.

Our goal was to assess how California's agricultural soils have changed during the past half-century using laboratory analysis to measure soil quality indicators. In agricultural terms, soil quality is defined by the ability of the soil to sustain elevated yields of plant production. In an agricultural context, soil quality can be managed to maximize production without adverse environmental effects, while in a natural ecosystem, soil quality may be observed as a baseline value or a set of values against which future changes in the system may be compared (Singer and Ewing 2000)

We recovered 125 surface samples collected before 1959 by California's Natural Resources Conservation Service (NRCS) soil survey staff. The samples were taken in California's primary agricultural valleys: Sacramento, San Joaquin, Sonoma, Napa, Salinas and Imperial. In addition, soil samples collected in 1945 by UC Berkeley professor Hans Jenny, and archived at UC Berkeley and UC Davis were found. The two groups of archival samples presented an ideal opportunity to assess soil properties from 50 to 60 years ago. We refer to all these samples as the "1945" samples. The archival samples were collected as part of early investigations to determine the soil's agricultural potential and as part of soil surveys that were done by the University of California in cooperation with the USDA Soil Conservation Service. Samples were stored in closed glass bottles from the time of collection until we opened them. The samples were preserved because they represented widely distributed soil types at the time.

Using the known locations of the archival samples, we returned to the sites sampled by Jenny and the NRCS and took samples again in 2001. By combining landowner information, legal description, and soil survey mapping units, we were able to identify each site to within 40 acres from the old descriptions. Once on the site, using modern soil maps, we were able to find what appeared to be the same general location as the original sample site. In the field, we collected three surface samples at a 0-to-10-inch (0-to-25 cm) depth from the site and noted the current land use.

We combined counties that shared land-use practices and environmental conditions into larger geographic regions (fig. 1). Samples were air-dried prior to determining pH using a 1:1 soil-water ratio with a 20-gram subsample of soil. Electrical conductivity was measured on the solution from the pH measurements. We used 20-milligram subsamples to measure both total carbon (C) and total nitrogen N on a Carlo-Erba gas analyzer. Soluble phosphorus (P) as an indicator of plant-available P was measured using the Olsen and Sommers (1982) method. We measured particle size distribution using a Coulter LS230 particle size analyzer.

We statistically analyzed data from the entire state, as well as by land use and geographic location using JMP 4.0

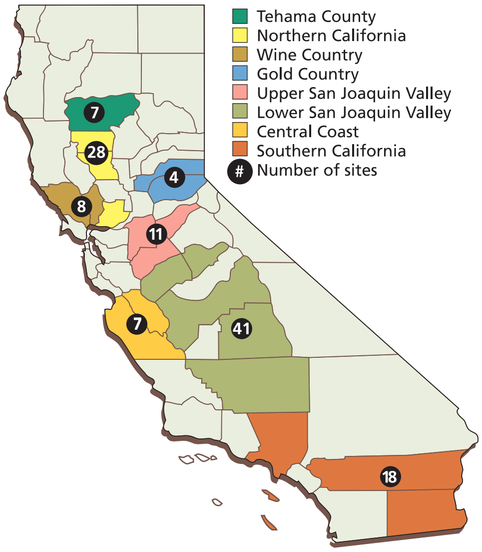


Fig. 1. Geographic location of counties and number of sites sampled in each agricultural region.

statistical software. Parametric t-tests were used to compare 1945 and 2001 values. The four land uses evaluated were tree crops such as almonds, walnuts and apples (25 sites); row crops (44 sites); rangeland (48 sites), and viticulture (8 sites). These statistics are the most effective way of demonstrating changes in soil quality since they evaluate change that has occurred at each site based on its 1945 state.

Changes in properties

pH levels. The average pH in 1945 for the 125 sites was 6.87, compared to 7.10 in 2001 (fig. 2). Across all sample locations, the increase in pH was significant at $t < 0.01$. Stratification of the data by location indicates a significant increase in pH in Southern California, the lower San Joaquin Valley, the Central Coast and Gold Country. No change was found in the upper San Joaquin Valley. When stratified by crops, pH increased significantly only in row crops.

Electrical conductivity. The average electrical conductivity (EC) for all the samples in this study was 0.85 deciSiemens/meter (dS/m) in 1945 and decreased significantly to 0.44 dS/m in 2001. Regionally, decreases in EC were limited to the 90% confidence interval but were found in all regions. Among the regions, only the EC in the Central Coast had a significant decrease at $t < 0.01$. The EC increased in soils being used for viticulture but decreased in row crops with no apparent change in pasture and tree crops (fig.3).

Phosphorus. The statewide plant-available phosphorus average of 71.8 ppm in 1945 increased to 84.6 ppm in 2001. When geographical regions were considered, the lower San Joaquin Valley had significant increases in plant-available phosphorus, as did Southern California and Wine Country. The upper San Joaquin Valley, Northern California and Gold Country did not have significant changes in plant-available phosphorus. When land use is considered, significant increases in plant-available phosphorus levels were found in tree crops, row crops and viticulture ($t < 0.1$) (fig.4) .

Nitrogen and carbon. Total nitrogen and total carbon also increased significantly statewide, with total nitrogen at 0.09% in 1945 and 0.29% in 2001 (fig. 5). Total carbon increased from 1.06% in 1945, to 1.34% in 2001 (fig. 6). There were no significant changes in the carbon-to-nitrogen ratio with a mean of 11.48 found in the 1945 samples and 12.63 in 2001. However the range of the carbon-to-nitrogen ratio decreased between 1945 and 2001. Total carbon percentages increased significantly in all regions except Southern California, the Central Coast, Gold Country and Tehama County (fig. 6). Total nitrogen increased in the Northern California, the upper San Joaquin Valley and Gold Country regions. Carbon and nitrogen significantly increased in pasturelands. Nitrogen but not carbon increased significantly in tree cropping systems ($t < 0.1$).

Clay, silt and sand. Clay percentages increased from 10% to 27% (fig. 7) and silt percentages increased from 50% to 55% while sand percentages decreased from 40% to 30% statewide. The laser grannulometer used to measure particle-size distribution underestimates clay percentages and overestimates sand percentages, but because the same method of analysis was used on both the 1945 and 2001 samples, we feel that the relative change is meaningful. Clay increases were found across the state in Northern California, lower San Joaquin Valley and Southern California ($t < 0.05$). Silt increases were significant in the lower San Joaquin Valley while decreases in sand percentages were found in the lower San Joaquin Valley, as well as in Southern California. No statistically significant changes in clay content were found in either Gold Country or Wine Country. Silt content increased significantly in Southern California and the lower San Joaquin Valley. Clay percentages significantly increased with reciprocal decreases in sand percentages in row crop, range and viticulture systems. Silt content increased significantly in row crops.

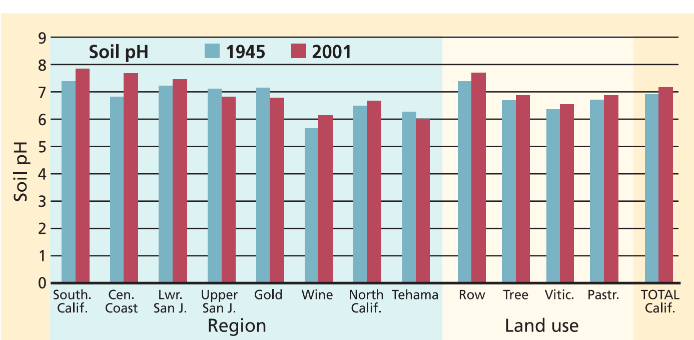


Fig. 2. Soil pH in 1945 and 2001 samples.

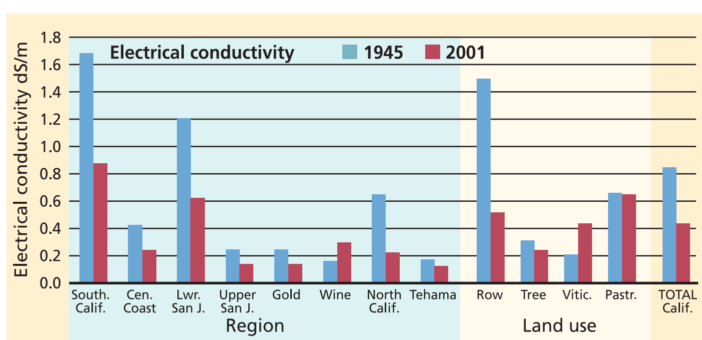


Fig. 3. Electrical conductivity in 1945 and 2001 samples.

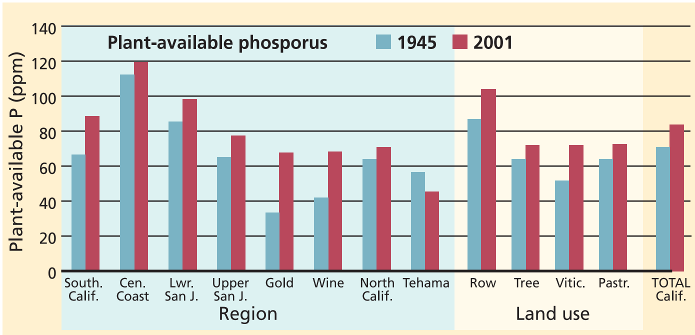


Fig. 4. Plant-available phosphorus in 1945 and 2001 samples.

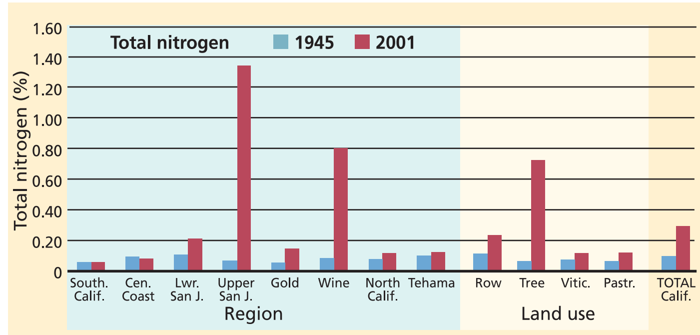


Fig. 5. Total nitrogen in 1945 and 2001 samples.

Has soil quality changed?

The scientific community, as well as regulators and the general public, has recently raised concerns that human uses of soil may be unsustainable, and that soil quality may be declining (Fournier 1989; Doran et al. 1996). Parr et al. (1992) state that "soil degradation is the single most destructive force diminishing the world's soil resources base." Within the last decade, inventories of soil productive capacity indicate severe degradation on more then 10% of the world's vegetated land as a result of soil erosion, atmospheric pollution, excessive tillage, over-grazing, land clearing, salinization and desertification (Lal 1994; Sanders 1992). However, there is continued controversy over the definition and methods used to evaluate soil quality. We discuss our results as they relate to changes in each individual measure of soil quality

Soil pH. Based on soil survey classifications of pH levels (Soil Survey Staff 1993), any change in category away from neutral (a reading either more or less than 7.0) can be viewed as a negative change in soil quality. Based on this interpretation, 25% of the sites had positive changes in pH, in the sense that the pH became more favorable by moving closer to neutral or 7.0. Another 43% had negative changes, becoming less favorable by moving farther away from 7.0, either becoming more acidic or more basic, and 28% showed no change. Soil pH is not much of a concern to plant growth when it is within the range of 5.5 to 8.2, but it becomes a management concern when it is outside of this range (Singer and Munns 2002). The results of this study suggest that pH changes do not indicate a change toward either extreme acidification or sodification (sodium increase) of the soils studied. No doubt there are unsampled areas within California where acidification or sodification have reduced plant nutrient availability, where aluminum and manganese toxicity limit plant growth, or where exchangeable sodium negatively impacts soil physical properties and water management. However, based on the results of this study, no trend in pH change was found that could be interpreted to indicate a statewide change in soil quality. Although 68% of samples showed some change, the changes were within the acceptable range for plant growth so they should not be construed as problems. (It is unlikely that pH in the range found will be managed using chemical amendments.)

Salinity. Soil salinity is a major constraint to plant production in arid and semiarid regions of the world (Tanji 1990). Salinization is indicated by an increase in electrical conductivity. Electrical conductivity classes are clearly identified in the Soil Survey Manual (Soil Survey Staff 1993). Based on these values, 87% of the sites were nonsaline to begin with, and remained nonsaline. Nine soils were very slightly saline to moderately saline in 1945, and became nonsaline by 2001. Four percent of the sites were nonsaline in 1945 but became very slightly saline to slightly saline by 2001. This soil quality parameter indicates a small improvement in soil quality over the sampling interval. We note that approximately 4.5 million acres of California's irrigated croplands — primarily on the west side of the San Joaquin Valley — are known to be affected by saline soils or saline irrigation water, with salinization increasing at a debatable rate. However, these areas are a relatively small percentage of the state's 100 million acres in total, and salinization in these soils may be underrepresented in our sampling. Even with new salinization problems, the total area of saline soils in California is likely to be less now than it was in 1945 and much less than in 1900, because many acres were drained, amended and improved for agriculture during the twentieth century.

Phosphorus. Twenty percent of the sampled soils exhibited decreases in plant-available phosphorus, 39% showed no change and 41% showed an increase. Phosphorus is an essential element that is used in large quantities by plants and it is a major component in most fertilizer. It comes as no surprise that the intense agriculture found in California has led to increases in plant-available phosphorus in the soils tested, due to the routine application of phosphorus-based fertilizer in agricultural regions. Does this indicate a change in soil quality? For those in conventional agriculture who view mineral fertilizer favorably, the increase in plant-available phosphorus can be interpreted as beneficial. For those who advocate against the use of mineral fertilizer, an increase in plant-available phosphorus might be interpreted as the presence of extra pollution and a decrease in soil quality. We interpret the changes to indicate no significant decline in soil quality.

Organic matter. Soil organic matter (SOM) contributes to soil fertility, aggregate stability and susceptibility to erosion (Seybold et al. 1998). The largest changes in total carbon were in the Wine Country and the Gold Country. Overall, the change from 1.05% to

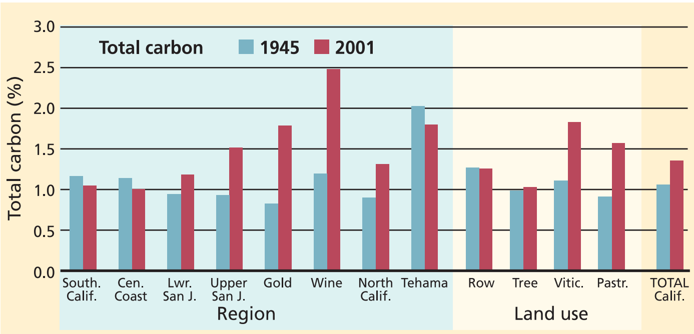


Fig. 6. Total carbon in 1945 and 2001 samples.

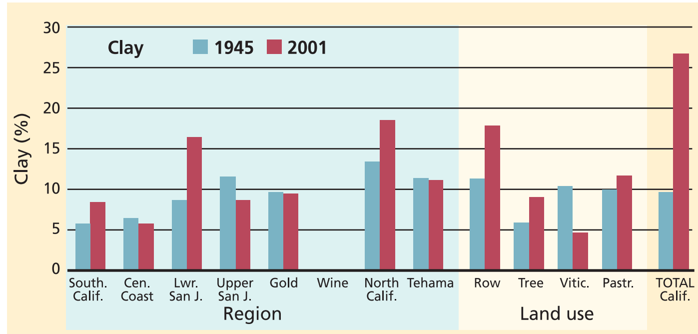


Fig. 7. Clay percentage in 1945 and 2001 samples.

1.35% total carbon in California is larger than we expected. This may reflect sample variability as well as a real increase in total carbon due to the return of crop residues to the soil. We interpret the increased carbon and nitrogen found in 2001 compared to 1945 as a statewide increase in soil quality.

Texture. Texture is important in the retention and transport of water and chemicals (Seybold et al. 1998; Arshad and Coen 1992). In turn, crop yield frequently is directly related to the amount of available soil water. Soil texture and the amount and type of clay minerals and organic matter are the major factors affecting cation (positively charged ion) exchange capacity (Arshad and Coen 1992). Texture usually changes little with use, and is considered to be use-invariant (Grossman et al. 2001). Soils with relatively high clay contents tend to stabilize and retain more organic matter than those with low clay contents, possibly indicating an increase in soil quality. However, why would a variable that is usually considered time invariant, such as texture, change so dramatically over the past 50 years? Two explanations are possible. First the increased clay percentage is an indicator of soil erosion as the surface soil layer (A horizon) is lost, and the clay-rich subsoil (B horizon) becomes incorporated into the surface horizons. Second, clay particles are less susceptible to erosion due to their ability to form more stable aggregates, leaving the clay behind as more erodible fractions are removed. In either case, the increased clay percentages may be interpreted as a sign of accelerated soil erosion, a decrease in soil quality. In dense clay-rich subsoil, both water and root penetration decrease.

". . . increased clay percentages may be interpreted as a sign of accelerated erosion, a decrease in soil quality."

For purposes of this study, we conclude that most of the properties we have measured do not indicate a loss of soil quality in California. The properties measured representing soil fertility have changed positively. Carbon, which is of growing interest and concern has increased overall. Clearly, the small sample we used to measure changes cannot represent all the soils in the entire 43 million agricultural acres (including grazing land of about 45 million acres, irrigated farmland of about 10 million acres) of California. There may be unsampled areas where soil quality has declined, due to increased salt and sodium (e.g. the west side of the San Joaquin Valley and the Imperial Valley), decreased organic matter or pollution from excessive application of chemicals or inadvertent spills. While increased clay percentages may indicate accelerated soil erosion, we conclude that the soils of California have maintained their chemical quality over the past 50 to 60 years.

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Blue oak enhance soil quality in California oak woodlands

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Blue oaks create islands of enhanced soil quality and fertility beneath their canopy. The quality of soil beneath the oak canopy is considerably better than that of the grasslands adjacent to the trees. We found evidence of improved soil quality under blue oaks for physical, chemical and biological soil properties. The type of vegetation (oak versus annual grasses) has a much stronger influence on soil organic matter and nutrient pools than does soil parent material. Removal of oak trees results in a rapid deterioration of soil quality with the majority of the loss occurring within 10 to 20 years after tree removal.

Islands of enhanced soil fertility beneath the oak canopy are especially noticeable during the spring. Note the luxuriant growth of annual grasses beneath the oak canopy compared with the adjacent open grasslands.

Oak woodlands occupy 7.4 million acres (3 million hectares [ha]) in California (Griffin 1977) and represent the landscape where California's urban-wildland-agricultural interface is most pronounced (Standiford et al. 2002). In the oak woodlands, scattered trees create a mosaic of open grasslands and oak/understory plant communities.

These ecosystems are used extensively for livestock grazing, firewood production, wildlife habitat and watersheds — and, increasingly, the development of suburban communities. Land-use practices associated with these activities, such as tree removal, often result in severe ecosystem disturbances that affect soil and water quality. In turn, changes in soil quality may affect oak regeneration success and ecosystem stability (Pavlik et al. 1991; Barbour et al. 1993).

Evidence indicates that oaks create islands of enhanced fertility beneath their canopy due to nutrient cycling processes. These spatial patterns of nutrient availability may in turn influence the success of future regeneration and the structure of the plant community. Removing oak trees has been shown to increase forage production in areas beneath the former canopy, as opposed to adjacent open grasslands; however, this benefit is often short term — less than 20 years (Kay 1987). These observations suggest that oak trees are an important component of the ecosystem and that they play an important role in maintaining soil quality and fertility.

Our primary objectives in studying oak woodlands were to examine the differences in quality between soils beneath blue oak canopies and in adjacent open grasslands. We also wanted to determine what happens to soil quality when the trees are removed. These studies were conducted in three oak woodlands in the Sierra Nevada foothills (Madera and Yuba Counties) and Coast Ranges (southern Mendocino County). At two of the sites, we examined the effects of oak removal on soil quality and fertility at intervals between 5 and 34 years following tree removal.

The sites

We conducted this investigation in oak woodlands with contrasting soil parent materials: granite, sandstone/shale and greenstone (metamorphosed basalt). The dominant oak species at all sites was blue oak *(Quercus douglasii)*, and tree age was estimated to range between 75 and 120 years. Average oak stocking ranged between 50 and 500 trees per acre with average canopy coverage between 20% and 70%. The oak understory community and adjacent grasslands (areas not affected by oak canopy) were dominated by annual grasses and forbs. For the purpose of this study, we standardized our sampling to blue oaks growing on slopes that were less than 15%. The climate at all sites is Mediterranean, with cool, moist winters and hot, dry summers. All study sites have been historically grazed by sheep or cattle at a low to moderate grazing intensity.

The San Joaquin Experimental Range (SJER) is located in Madera County (central Sierra Nevada foothills) about 25 miles north of Fresno. Elevations of the sampling sites range between 394 and 492 feet. Mean annual precipitation is about 22 inches and mean annual air

Shown are the upper 3 feet of a typical soil profile from a California oak woodland at the SFREC. Annual grass roots are limited to the upper 18 inches of the profile while oak roots are found throughout the entire soil profile (typically 4 to 6 feet).

temperature about 63° F. Soils were formed from granite and their textures were sandy loams (sand = 68%, silt = 20%, clay = 12%). Clay mineralogy was dominated by mica and kaolinite with small amounts of vermiculite.

The Hopland Research and Extension Center (HREC) is located in southern Mendocino County (northern Coast Ranges) about 5 miles east of Hopland. Elevations of the sampling sites range between 656 and 1312 feet Mean annual precipitation is about 37 inches and mean annual air temperature about 57° F. Soils formed from mixed sedimentary material of the Franciscan formation consisting of sandstone and shale with interspersed basalt and serpentine. Soil textures were loams (sand = 40%, silt = 35%, clay = 25%). The clay mineralogy contained a wide range of minerals including interstratified vermiculite-chlorite, vermiculite, illite, smectite, kaolinite and gibbsite.

The Sierra Foothill Research and Extension Center (SFREC) is located in Yuba County (foothills of the northern Sierra Nevada) about 19 miles east of Marysville. Elevations of the sampling sites ranged between 656 and 984 feet. Mean annual precipitation is about 29 inches and mean annual air temperature about 59° F. Soils formed from greenstone (metamorphosed basalt) and their textures were silty clay loams (sand = 18%, silt = 50%, clay = 32%). Clay mineralogy was dominated by interstratified vermiculite-chlorite, vermiculite, chlorite and kaolinite with small amounts of smectite.

At each site, five replicates of a composite soil sample (consisting of four subsamples) were collected for the 0-to-2-inch and 2-to-6-inch (0-to-5 cm and 5-to-15 cm) depth increments from beneath an oak canopy and in adjacent grasslands not affected by the oak canopy. At the HREC and SFREC sites we also collected soil samples from areas where trees were removed (at known times) between 5 and 34 years before sampling. Tree removal times were 5, 15, 21 and 34 years at SFREC and 5, 10 and 30 years at HREC. We will refer to sampling locations as (1) oak canopy (beneath tree canopy), (2) oak removed and (3) grassland (open grassland sites not affected by oak canopy). For the oak canopy and tree removal sites, soil samples were collected 6 to 7 feet from the tree or stump.

Soil samples were analyzed for the following parameters using standard methods of soil analysis (Soil Survey Staff 1984; Weaver et al. 1994):

- Bulk density (quantitative pit or soil cores)
- Soil pH (1:2, soil:0.01 M calcium chloride [$CaCl_2$]solution)
- Total carbon and nitrogen (dry combustion with Carlo Erba C/N analyzer)
- Microbial biomass carbon (chloroform incubation)
- Plant-available phosphorus (Bray extraction)
- Mineral N (ammonium [NH_4^+] and nitrate [NO_3^-]; extracted with 2 M potassium chloride [KCl]).
- Potentially mineralizable N (hot KCl)
- Cation exchange capacity and exchangeable cations (extraction with 1 M ammonium acetate [NH_4OAc]).

All statistical analyses were performed at a $P = 0.05$ significance level using SYSTAT for Windows, Version 9 (SYSTAT Inc., Evanston, Ill.).

Better soil quality and fertility

Blue oaks were shown to enhance soil quality and fertility beneath their canopies for all the soil parameters examined in this study (fig. 1). Islands of

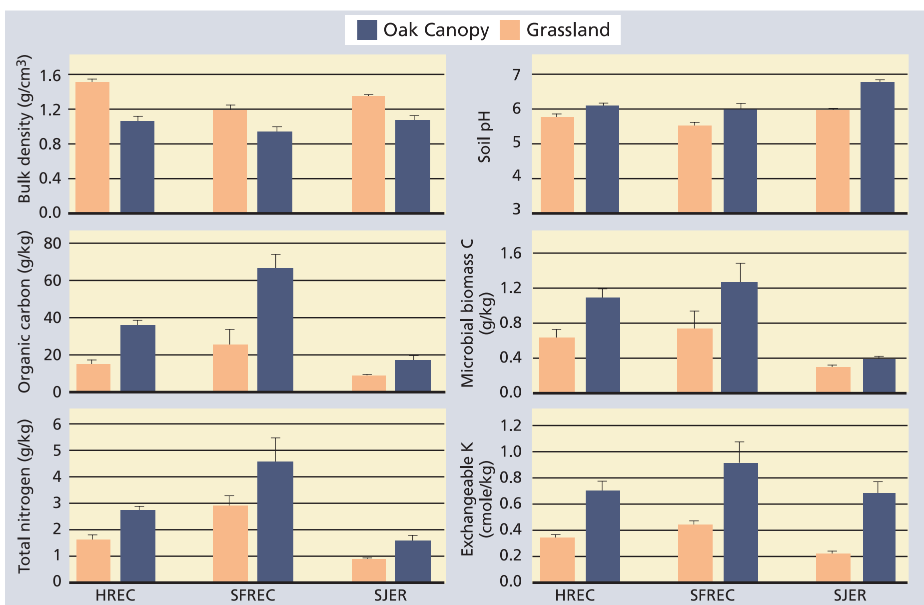


Fig. 1. Selected soil quality and fertility parameters (mean ± standard error; n = 5) for the 0-to-2-inch- (0-to-5 cm-) depth increment of soils beneath the oak canopy and adjacent grasslands for sites at HREC (sandstone/shale), SFREC (greenstone) and SJER (granite). All vegetation type comparisons (oak versus grassland) at a given site were statistically different at *P* = 0.05.

enhanced soil quality and fertility were apparent beneath the oak canopy for both sites that were grazed and sites that weren't, indicating that grazing is neither responsible for formation of these islands nor does it destroy these islands (Camping et al. 2002). Soils beneath the oak canopy generally had thicker A and AB horizons (organic-rich topsoil horizons), suggesting that oak trees promote the development of thicker topsoil horizons through enhanced organic matter production. Because of enhanced soil quality beneath the oak canopy, soil fauna (e.g., earthworms, ants) may also preferentially inhabit the soils beneath the canopy (based on casual field observations), leading to greater physical mixing of organic matter into the mineral soil profile.

Among soil physical properties, bulk density was decreased as much as 1.4-fold beneath the oak canopy. Increased mixing of soil by biota, coupled with enhanced soil structure due to increased organic matter and soil fauna/flora activity, contribute to lower bulk densities, improved water infiltration rates and improved gas exchange in upper soil layers. The resulting improvement in water infiltration and gas exchange in turn promotes an improved environment for soil organisms.

Enrichment of organic matter and nutrients beneath the canopy of oak trees results in large part from litterfall (dropping leaves, twigs and acorns) and its associated nutrients. The cycling of base cations (positively charged calcium, magnesium and potassium) by oaks often leads to higher base saturation in the surface horizons beneath the oak canopy (Dahlgren et al. 1997). The higher base saturation leads to higher soil pH values beneath the oak canopy. At SFREC, blue oaks return an average of 8,100 pounds per acre per year (lb/acre/yr) (9,100 kilograms per hectare per year [kg/ha/y]) of litterfall to the soil surface with its associated nutrients (Dahlgren et al. 1997). The added organic matter contains nutrients within its structure (nitrogen = 75 pound/acre/yr [84 kg/ha/yr], phosphorous = 7 pound/acre/yr [8 kg/ha/yr], potassium = 34 pound/acre/yr [38 kg/ha/yr]) and provides nutrient storage capacity in the form of cation exchange capacity.

Additionally, canopy throughfall (precipitation dripping from the canopy) contributes appreciable fluxes of nutrients, such as nitrogen (N = 4.6 pound/acre/yr [5.2 kg/ha/yr]), phosphorus (P = 1.1 pound/acre/yr [1.2 kg/ha/yr]), calcium (Ca = 28.5 pound/acre/yr [32 kg/ha/yr]) and potassium (K = 34.7 pound/acre/yr [39 kg/ha/yr]) (Dahlgren and Singer 1994). Nutrient fluxes in canopy throughfall originate from the capture of atmospheric aerosols and particulate matter, as well as from root uptake. Because oak roots are found at greater depths (more than 3 feet) than

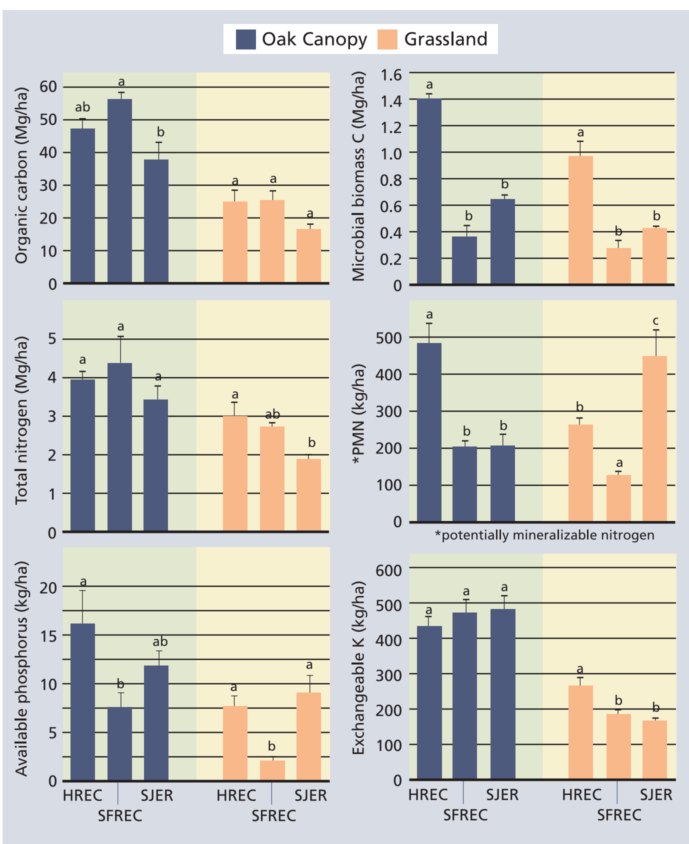


Fig. 2. Organic carbon and nutrient pools (mean ± standard error; n = 5) for the 0-6-inch- (0-15 cm-) depth increment of soils beneath the oak canopy and adjacent grasslands for sites at HREC (sandstone/shale), SFREC (greenstone) and SJER (granite). Means with same lower case letters within each vegetation type (oak versus grassland) are not statistically different at $P = 0.05$.

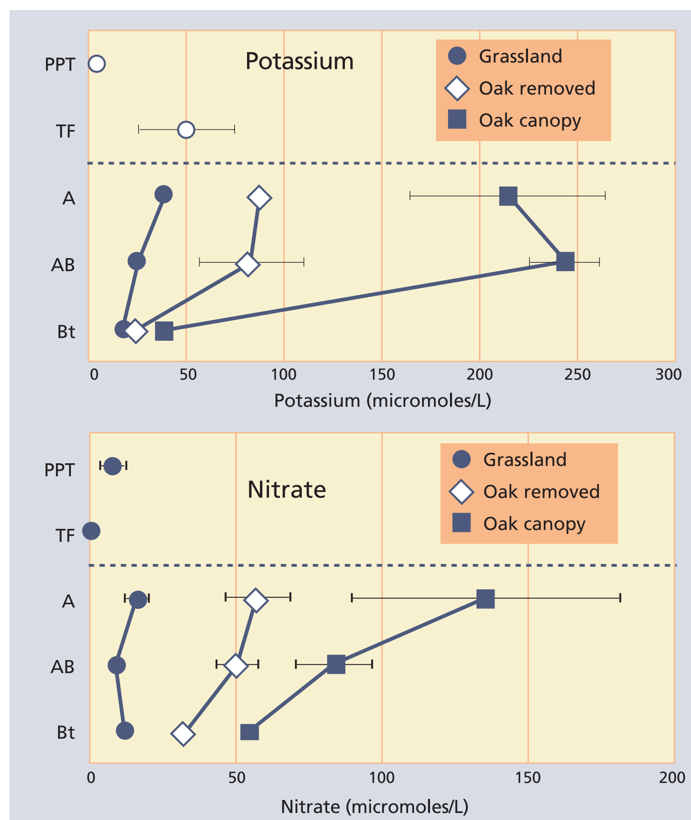
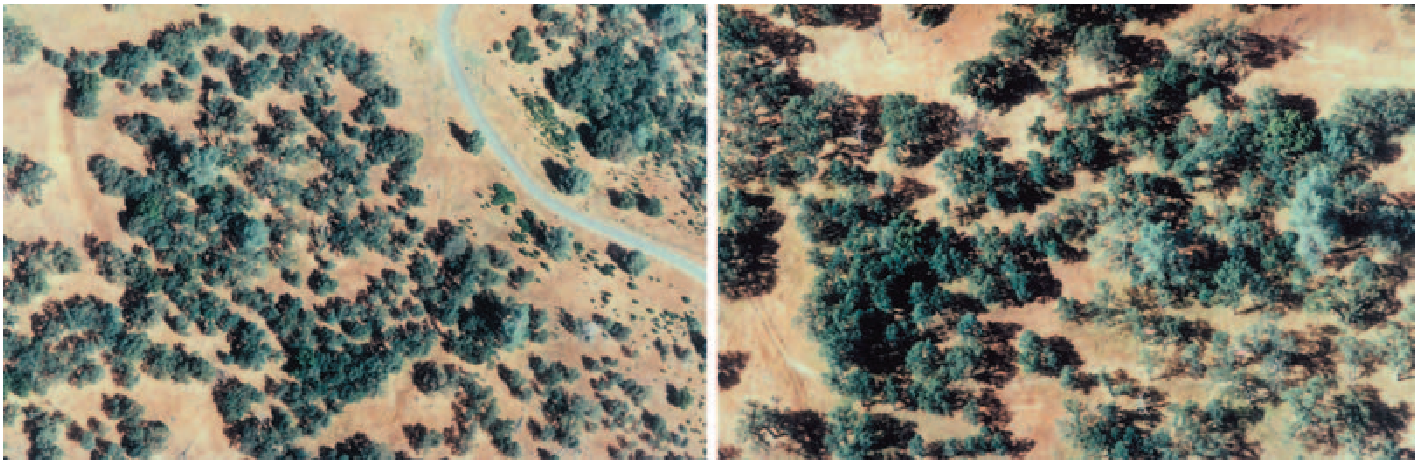


Fig. 3. Concentrations (mean ± standard deviation) of potassium and nitrate in precipitation (PPT), canopy throughfall (TF) and soil solutions from A, AB and Bt horizons of soils at SFREC. Soil solutions were collected from soils beneath the oak canopy, from adjacent grasslands and from sites where blue oaks were removed. Solutions were collected monthly from December through May following removal of the oak trees the previous September.



Courtesy of Sam Bledsoe

Scattered oak trees create a mosaic of open grasslands and oak understory plant communities on the landscape.

those of annual grasses (generally less than 1.5 feet), nutrient uptake by oak roots lessens leaching losses of nutrients from the soil profile. The extension of oak roots beyond the edge of the canopy also contributes to nutrient differences between soils beneath the oak canopy and open grasslands. The selective uptake of nutrients by oak roots will remove nutrients from the open grasslands and concentrate them beneath the oak canopy. Cattle seeking shade and defecating under trees more than in open areas does not appear to be an important factor because similar levels of nutrient enrichment are found on both grazed and non-grazed sites (Camping et al. 2002).

A further beneficial effect of the oak canopy on nutrient cycling occurs through reduced leaching and erosion, which results in more nutrients being retained in the upper soil layers (Dahlgren and Singer 1994; Dahlgren et al. 1997). Reduced leaching of nutrients and erosion of soil materials have a beneficial effect on water quality in streams draining these watersheds. At SFREC, evapotranspiration (loss of water vapor from soil and plant surfaces and through plant stomata) is approximately 30% greater in the oak system as compared with the open grasslands. This is because of the greater extraction of water from the soil profile by deeply rooted oak trees and because precipitation is intercepted by the oak canopy (and then evaporates). This loss of water reduces the leaching intensity beneath the oak canopy more than in the grassland sites. In addition, higher organic matter concentrations lead to lower soil bulk density and increased infiltration rates, which reduce surface runoff and loss of nutrients through erosion. Thus there are several biogeochemical processes by which oak trees concentrate nutrients and create islands of enhanced soil quality and fertility beneath their canopy.

Soil parent material

The primary difference between the three study sites was the composition of the soil parent material. Parent material differences resulted in large variations in soil texture (SJER, sandy loam; HREC, loam; SFREC, silty clay loam) and clay mineralogy. In addition, differences in climatic factors may result in differences in net primary production. In spite of these many differences, pools of organic carbon and total nitrogen in the 0-to-6-inch (0-to-15 cm) layer were similar among the sites (fig. 2). Microbial biomass carbon and potentially mineralizable nitrogen tended to be higher at HREC. Available phosphorus was lower at SFREC, which may be attributable to strong sorption of phosphate by iron oxides, which are found in high concentrations in soils at this site. Exchangeable potassium concentrations were generally similar across all sites.

Differences between study sites were expected to result in much larger differences between organic carbon and nutrient pools. For the most part, however, differences between sites were small. We conclude that vegetation has a much stronger effect on soil organic matter and nutrient pools than do differences in soil parent material.

Effects of tree removal

Oak tree removal has been suggested as a way to increase forage production by decreasing competition for light, water and nutrients. Short-term increases in forage production were commonly observed following tree removal in relatively open stands. However, this benefit lasts less than two decades before forage production returns to levels found in the adjacent grasslands (Kay 1987). To ascertain the reason for this observation, we examined soil from plots where oak trees were removed up to 34 years ago. We were particularly interested in determining how long the islands of enhanced soil quality and fertility persist once oak trees are removed.

A study at SFREC followed changes in soil solution chemistry in the year following oak tree removal (Dahlgren and Singer 1994). We used soil solution chemistry because it reflects the current biogeochemical processes occurring in a soil. The soil solids (solid-phase) in contrast, integrate all soil processes that have occurred during the development of the soil and as a result are not always a sensitive indicator of ecosystem disturbance. Oaks were removed during the summer prior to senescence, and all tree components were removed from the site. We compared the soil solution chemistry from the tree removal sites with adjacent soils from beneath the oak canopy and from open grasslands.

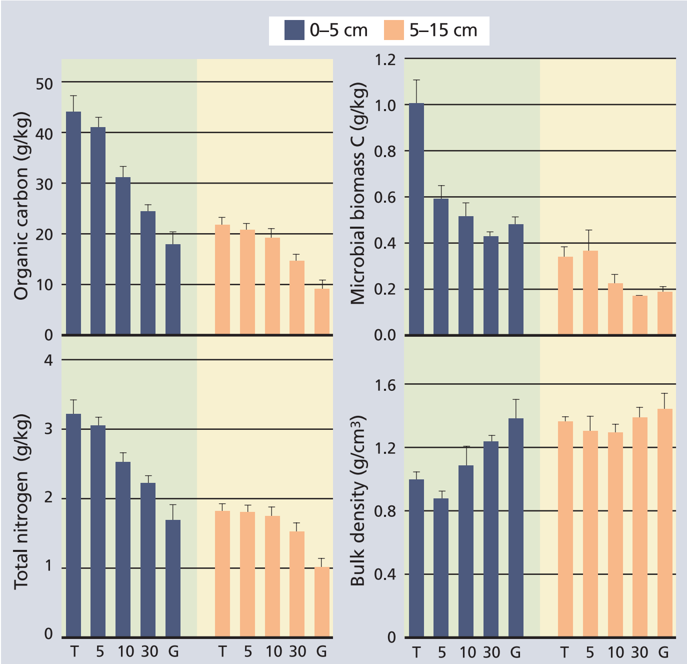


Fig. 4. Selected soil quality and fertility parameters (mean ± standard error; n = 5) for the 0-to-2-inch- and 2-to-6-inch- (0-to-5 cm and 5-to-15 cm) depth increments of soils beneath the oak canopy (T) and adjacent grasslands (G), and for soils where oak trees were removed 5, 10 and 30 years ago at the HREC site. Means with same lower case letters within each depth increment (0-to-2 inch- and 2-to-6-inch- [0-to-5 cm and 5-to-15 cm]) are not statistically different at *P* = 0.05.

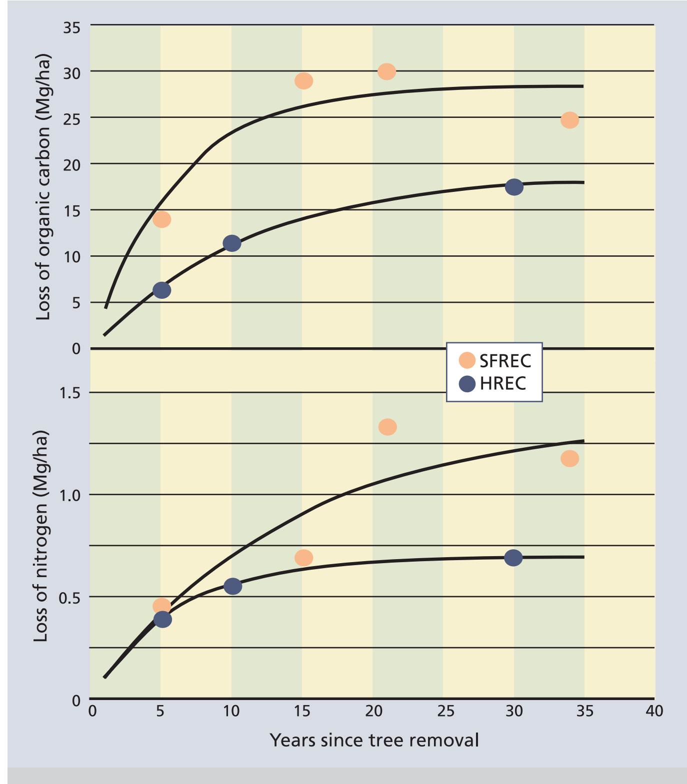


Fig. 5. Loss of organic carbon and nitrogen from the 0-to-6-inch- (0-to-15 cm) depth increment as a function of time since oak tree removal at the SFREC and HREC sites.

Concentrations of essential plant nutrients, such as potassium and nitrate, were much higher in soil solutions beneath the oak canopy compared with grassland soils, reflecting the islands of enhanced soil fertility (fig. 3). In contrast, the nonessential nutrient, sodium, displayed similar concentrations for oak canopy and grassland soils, indicating that nutrient cycling by oak trees was an important factor in enhancing essential plant nutrient concentrations in soil solutions beneath the oak canopy (Dahlgren and Singer 1994). Oak tree removal resulted in an immediate shift in soil solution nutrient concentrations toward that of the grassland soils. These data indicate that islands of soil fertility are quickly reverting to nutrient conditions similar to grassland soils following tree removal.

Given the rapid and dramatic decrease in soil solution nutrient concentrations, we subsequently examined solid-phase soil quality and nutrient parameters to determine whether differences could be detected. We focus this discussion on results from HREC; however, similar results for oak tree removal at SFREC were found (Camping et al. 2002). There was an appreciable loss of soil organic matter following tree removal at HREC. Organic carbon concentrations showed a significant decrease after 10 years in the 0-to-2-inch (0-to-5 cm) layer and approached that of grassland soils after 30 years (fig. 4). Organic carbon concentrations also decreased in the 2-to-6-inch (5-to-15 cm) layer, but at a much slower rate than in the 0-to-2-inch layer. Microbial biomass carbon showed a rapid decrease (within 5 years) in the 0-to-2-inch layer following tree removal and a much slower and smaller decrease in the 2-to-6-inch layer. Total nitrogen concentrations followed a pattern similar to organic carbon with a significant decrease after 10 years and a decline to levels similar to grassland soils after 10 to 30 years. As with organic carbon and microbial biomass carbon, concentrations in the 2-to-6-inch layer showed a slower and smaller decrease following tree removal. Bulk density in the 0-to-2-inch layer showed a significant increase over time following tree removal and is probably associated with the loss of soil organic matter.

Losses of organic carbon and total nitrogen were more rapid and larger in magnitude at SFREC than at HREC (fig. 5). After 30 to 34 years, the organic carbon pool in the 0-to-6-inch-layer decreased by about 26,720 pound/acre (30 Megagram/hectare [Mg/ha] (44% decrease) and 16,032 pound/acre (18 Mg/ha) (34% decrease) at SFREC and HREC, respectively. A similar comparison for the total nitrogen pool showed losses of about 1247 pound/acre (1.4 Mg/ha) (29% decrease) and 624 pound/acre (0.7 Mg/ha) (19% decrease) at SFREC and HREC, respectively. The majority of the organic carbon and nitrogen is lost within the first 10 to 20 years following tree removal.

The rapid and large decreases in the organic carbon and nitrogen pools result, in part, from the immediate loss of litterfall from oak trees once the tree is removed. The return of about 4,000 pound/acre/yr (4,500 kg/ha/yr) of organic carbon and 75 pound/acre/yr (84 kg/ha/yr) of nitrogen in litterfall to the soil beneath the oak canopy provides a large annual input of organic matter. The loss of litterfall inputs coupled with rapid decomposition in the tree removal soils (Ridolfi et al. 2000) result in a shift in soil organic matter concentrations until a new steady-state, less enriched with nutrients, is reached with respect to organic matter inputs from the annual grasses that dominate following oak removal. Nitrogen pools were also shown to respond quickly to oak removal resulting in the loss of 19% to 29% of the total soil nitrogen in the 0-to-6-inch soil layer within 30 years.

At this point, we do not know the exact mechanism(s) responsible for the loss of nitrogen from the soil. We speculate that nitrate leaching and denitrification are active in removing nitrogen from the soil following tree removal. Furthermore, grazing may redistribute nitrogen on the landscape as livestock preferentially graze on the more luxuriant forage growing beneath the former oak canopy. Nitrate leaching to stream water does not appear to be a major mechanism of nitrogen loss following tree removal as demonstrated by Singer and co-workers (MJ Singer, personal communication). Their results showed no increase in stream water nitrate concentrations following removal of 14% of the oak trees from a watershed at SFREC.

Oak conservation

Results from our studies show that blue oaks create islands of enhanced soil quality and fertility across a range of soil parent materials. There were no appreciable differences between islands of soil quality and fertility between grazed and non-grazed sites; this indicates that grazing is neither responsible for formation of these islands nor does grazing destroy these islands. Nutrient concentrations beneath the blue oak canopy were generally 1.5 and 3.0 times greater than those found in open grassland soils for most soil quality parameters. Within a given vegetation type (blue oak versus grassland), organic matter and nutrient pools in the 0-to-6-inch layer of soil were similar in magnitude across the range of soil parent materials. However, there were large differences in soil nutrient pools beneath the oak canopy as compared with adjacent grasslands. We conclude that vegetation type has a much stronger influence on soil organic matter and nutrient pools than does soil parent material.

In addition, oak tree removal resulted in a rapid and relatively large decrease in soil quality and fertility. The majority of these losses occurred in the 0-to-2-inch-layer, and they occurred within 10 to 20 years after tree removal. The loss of organic matter and nutrient returns via litterfall, and rapid decomposition of soil organic matter, are believed to be primarily responsible for this rapid loss of organic matter and nutrients following oak tree removal.

Our results clearly show that blue oak trees enhance soil quality in California oak woodlands. Improved soil quality was shown for physical (bulk density, aggregate stability, infiltration), chemical (pH, cation exchange capacity) and biological (microbial biomass, soil respiration) parameters. The presence of oak trees increases net primary production and may enhance species diversity (Pavlik et al. 1991; Barbour et al. 1993), water quality (Dahlgren et al. 1997), forage quality (Frost et al. 1997) and wildlife habitat (Pavlik et al. 1991; Barbour et al. 1993). Planting oaks can sequester relatively large amounts of carbon into California soils; however, the sequestered carbon may be quickly released back to the atmosphere upon oak removal. Because oak trees play many beneficial roles in the ecosystem, land managers should carefully consider oak conservation in managing California oak woodlands and savannas.

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RESEARCH ARTICLE

Scientists, growers assess trade-offs in use of tillage, cover crops and compost

Merced rye cover crop on semi-permanent beds in Salinas Valley vegetable production during the winter. Beds were retained for a 2-year period. The +OM treatment received a cover crop and a compost application each year.

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Use of cover crops and compost increased soil quality in irrigated, intensive production of lettuce and broccoli in the Salinas Valley. These methods had the beneficial impacts of increasing soil microbial biomass, increasing total soil carbon and nitrogen, reducing surface bulk density and decreasing the potential for groundwater pollution as a result of nitrate leaching below the root zone. These soil benefits did not lead to lower yields and occasionally resulted in fewer weeds and lower lettuce corky root disease. Although surface minimum tillage reduced yields, it led to reduced potential for nitrate leaching below the root zone. Use of conventional tillage, cover crops, and compost produced high vegetable yields and acceptable net economic returns over a 2-year period, but broccoli was more profitable than lettuce under this regime. Understanding the trade-offs of various costs and benefits will help growers choose management practices that optimize economic and environmental benefits.

Soil quality research focuses on soil organic matter (SOM), its activity and function, and related chemical and physical properties. It also considers the larger picture, including impacts of soil management on production, pests, and economics. Use of cover crops, compost, and reduced tillage may increase SOM, especially the active fraction of SOM that is largely composed of decaying plant material and microbial cells, and plays an important role in nutrient cycling and retention (Paul and Clark 1996). These methods may also increase nutrient availability, leading to less reliance on fertilizers that are derived from nonrenewable fossil fuel, and improve soil physical properties such as aeration and water infiltration (Reeves 1997). They can improve soil quality by minimizing nitrate leaching below the rootzone, reducing groundwater contamination (Jackson et al. 1993).

Adoption of these practices will be enhanced if: (1) farmers face few economic disadvantages due to the new procedures; (2) the start-up costs and effort are feasible; and (3) new practices do not result in onset of new problems. In this on-farm research, farmers participated in the design and implementation of experiments to assess the multiple trade-offs involved in transitioning to new management practices.

In an on-farm experiment in a vegetable production field in the Salinas Valley, a multidisciplinary approach was used to evaluate responses to tillage and organic matter (OM) management. Conventional tillage (subsoiling, disking, and surface mulching to a depth of 20 inches) was compared to minimum tillage where only the surface layer of semi-permanent beds is tilled to a depth of 8 inches. Also, organic amendment (+OM) and no organic amendment (–OM) treatments were compared. Organic matter was added to the soil in the form of both cover crops and compost, to incorporate carbon (C) and nitrogen (N) sources like plant residues, that are readily available to plants, and more resistant sources of C and N that remain after the composting of manure, municipal yard waste, and other plant materials. Many conventional and organic vegetable growers use both inputs in their crop rotations, and so these materials were used together to study their effects on SOM and other variables. Soil microbial biomass is one measure of the readily available, active fraction of SOM, and it usually represents < 5% of the total C and N in the SOM (Paul and Clark 1996). Total soil C and N contain many diverse compounds that are resistant to breakdown in soil, and typically change more slowly in response to management than the active fraction of SOM (Wander et al. 1994). The objectives of the 2-year experiment were to determine the effects of alternative tillage and OM management practices by: (1) monitoring changes in crop yield, nutrient uptake, and soil parameters throughout a 2-year period; (2) documenting effects on weeds, pathogens, and insect pests; and (3) assessing the total economic costs and net returns incurred while adopting practices conducive to increasing soil quality.

Soils and management practices

A 20.5-acre field trial site was established in April 1998 in the Salinas Valley of California. The Salinas silt loam soil had a pH of 7.0, and contained 28% sand, 52% silt, and 20% clay. The four treatments were: minimum tillage +OM inputs; minimum tillage –OM inputs; conventional tillage +OM inputs; and conventional tillage –OM inputs. Treatments were replicated four times, and each plot was 1.3 acres. Two replicate areas were sampled per plot.

Typical vegetable production with conventional tillage disturbs the soil to approximately a 20-inch depth and beds are re-made between each crop. The 'Sundance' system for minimum tillage, however, utilizes disks to incorporate crop residues, cultivate the tops and sides of the beds and lister bottoms, shanking the furrows in a single pass. This method tills to approximately 8 inches deep. No subsoiling was done in the minimum tillage treatments. The same 40-inch-wide beds remained in place in the minimum tillage treatments for the entire study, but were re-made between each crop or cover crop in the conventional tillage treatments.

In treatments receiving added OM, compost was added two times per year at 4 tons per acre per application, and a Merced rye (*Secale cereale* cv. Merced) cover crop was grown each year during the fall or winter when no vegetable crops were present. Compost was applied either immediately before or after the cover crop. The compost was commercially available and had a mean C:N ratio of 17:7. Starting materials for the compost were municipal yard waste (30%), salad packing plant waste (5%), with the remainder composed of manure, clay, finished compost, and baled straw. The amount of total N added per compost application was approximately 80 pound/acre, but this N is not readily available, and is released slowly through time. Consequently, growers apply other fertilizer materials to supplement the N supplied by the decomposition of the compost and cover crops. Currently, accurate methods do not exist for growers to monitor N availability from these materials, and trial and error is often used for determining supplemental fertilizer needs.

Four vegetable crops were grown during the course of the study. Crisphead lettuce was planted in May 1998, January 1999 and June 1999. Broccoli was planted in November 1999, on the east half of the field, and December 1999 on the west half of the field. These were counted as the same crop for the purpose of this study. All crops were direct-seeded.

Sprinkler irrigation was used during the germination and establishment stages of the crops and cover crops. After thinning the cash crops, surface drip irrigation was applied two to three times per month. The entire field received the same fertilizer applications. Nitrogen fertilizer inputs were as follows for the four vegetable crops: 134.2 pound/acre (May 1998 lettuce crop); 84.8 pound/acre (January 1999 lettuce crop); 112.5 pound/acre (June 1999 lettuce crop); and 148.4 pound/acre (2000 broccoli crop). A pre-plant fertilizer of 300 pound/acre of 5-25-25 before each cover crop and broccoli crop was applied, and one to four applications of liquid 20% ammonium nitrate through the drip tape after thinning each vegetable crop were applied. There was one application of 300 lb/acre of ammonium sulfate prior to planting broccoli.

Sampling occurred at harvest of each of the cash crops and the fall/winter cover crops (n = 32). At each sampling point, soil cores were taken to a depth of 36 inches. Soil analytical methods included gravimetric moisture, potassium chloride extractions for inorganic N, chloroform fumigation extraction for soil microbial biomass (MBC), and anaerobic incubation for potentially mineralizable N. The latter two analyses were only done on the surface soil (0 to 6 inches in depth). In addition, cores for total soil C and N were taken at the end of the experiment at this depth, and for bulk density, also at a typical plowpan depth. Aboveground plant biomass was collected from 1.2-square-yard areas. Total soil C and N and plant nitrogen were analyzed by the DANR Analytical Laboratory. Weed densities were taken during each cropping cycle in one 27-foot-by-50-foot area per plot, whereas weed seedbanks were evaluated by germination tests after washing seeds from soil at four times during the study.

Since soil management is known to affect certain diseases, such as corky root disease (van Bruggen et al. 1990) and *Sclerotinia minor* (Bell et al. 1998; Jackson et al. 2002), root-susceptible diseases were monitored. Corky root disease was evaluated on a severity scale from 1 (low severity) to 12 (high severity). For corky root, 10 plants were sampled per sampling point. The percentage of sampled plants with symp-

TABLE 1. Mean total soil C, total soil N, and bulk density in April, 2000*

OM Treatment	Tillage treatment	Total soil C at 0–6 in. depth	Total soil N at 0–6 in. depth	Bulk density at 0–2.4 in. depth	Bulk density at 18–21 in. depth
		······· % ·······		······· g/cm^3 ·······	
+	Min.	1.51	0.163	1.16	1.47
-	Min.	1.41	0.153	1.31	1.46
+	Conv.	1.48	0.160	1.25	1.33
-	Conv.	1.37	0.149	1.36	1.41
Main effect *F* values					
OM		s	s	s	ns
Tillage		ns	ns	ns	ns
OM x Tillage		ns	ns	ns	ns

* s = Data were significant at the 0.05 level.
ns = No significant differences were found.

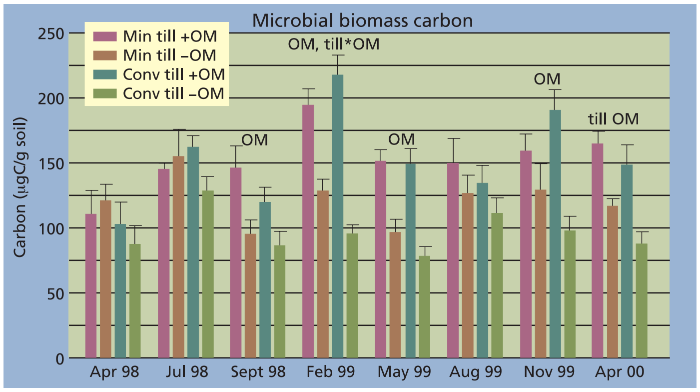


Fig.1. Soil microbial biomass carbon (MBC) in the 0-to-6-inch layer of soil. Treatment effects are labeled for each sampling date when the main effects of tillage (till) or organic matter (OM) or their interaction (till*OM) was significant at $P \leq 0.05$. Mean ± SE shown only in the positive direction.

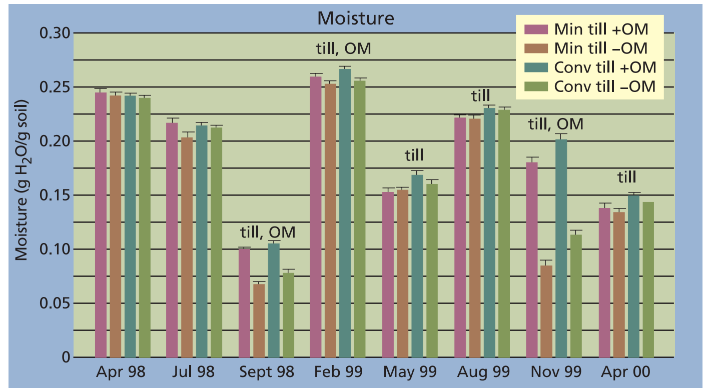


Fig. 2. Soil gravimetric moisture in the 0-to-6-inch layer of soil. Treatment effects are labeled for each sampling date when the main effects of tillage (till) or organic matter (OM) or their interaction (till*OM) was significant at $P \leq 0.05$. Mean ± SE shown only in the positive direction.

toms of *Sclerotinia minor* infection or big vein was assessed in a 695-foot-by-13-foot area per plot. Counts were made of the number of Pea Leafminers that flew and stuck to a sticky card in a bucket cage containing one plant (n = 80).

Soil responses

After 2 years of cover crop and compost additions, total soil C and N in the surface 0-to-6-inch layer were higher than in non-amended soils (table 1). The addition of OM amendments caused bulk density to decrease in the surface layer, but not at a lower depth. Lower bulk density is known to be beneficial for increasing water infiltration, soil aeration, and root growth (Russell 1973), although no measurements of these effects were conducted in this study. Tillage treatment did not have a significant effect on either total soil C or N, or bulk density.

Soil microbial biomass C, which is a measure of the active SOM, in the surface 0-to-6-inch layer was responsive to OM inputs (fig. 1). At the onset of the experiment in July 1998, when only compost had been applied in the +OM treatments, no treatment differences were observed before cover cropping occurred. After the first cover crop in September 1998, soil microbial biomass (MBC) increased in the +OM treatments, and typically remained higher than the treatments with no OM inputs. MBC in the –OM treatments was typically about 30% to 40% lower than in the +OM treatments from the fall of 1998 through spring 2000. MBC was affected little by minimum vs. conventional tillage during most of the 2-year experiment, but it was higher with minimum tillage at the end of the study, indicating that the active fraction of SOM had begun to slowly increase after this length of time.

Soil moisture content was substantially higher in the surface layer after the cover crops were grown due to irrigation (fig. 2). In 1999, this continued through the winter. Minimum tillage decreased the moisture content in the surface layer beginning with the first cover crop in September 1998. Although the differences were small (i.e., 1% to 2% gravimetric moisture), they were consistent through the rest of the experiment. Minimum tillage may have resulted in impedance of lateral and upward movement of water from lower depths in the soil, and therefore in less water in the surface layer where most of the roots of the vegetable crops are located (Gallardo et al. 1996).

Nitrate in the top 3 feet of the soil profile was lower in the +OM treatments, beginning with the first cover crop in the fall of 1998 (fig. 3), undoubtedly due to the uptake of nitrogen by the cover crop. Across both tillage treatments, differences were largest between the +OM and –OM treatments during the fall and winter (135 to 310 pounds nitrate-N/acre) and less when crops were present (approximately 70 to 90 pounds nitrate-N/acre). Minimum tillage also decreased nitrate in the soil profile. There were approximately 45 to 135 pounds more nitrate-N/acre with conventional than with minimum tillage across both OM treatments. The conventionally tilled soils without OM inputs tended to have the

TABLE 2. Mean crop dry weight and N content on four sampling dates at the time of harvest maturity of each vegetable crop*

OM treatment	Tillage treatment	Jul 98		Lettuce May 99		Aug 99		Broccoli April 00	
		Dry weight	N	Dry weight	N	Dry weight	N	Dry weight	N
		pound/acre							
+	Min.	3641.3	126.8	2504.9	92.8	2271.9	84.8	5578.4	227.9
-	Min.	3497.6	111.6	2794.2	108.0	2156.8	82.1	5406.9	220.0
+	Conv.	3477.1	113.4	2685.2	100.0	2236.2	88.4	5749.4	237.4
-	Conv.	3801.1	127.7	2639.7	103.6	2289.8	91.9	5651.7	235.7
Main effect *F* values									
OM		ns	ns	s	sss	ns	ns	ns	ns
Tillage		ns	ns	ns	ns	ns	ss	ss	sss
OM x Tillage		ss	sss	ss	ss	ns	ns	ns	ns

* ns = No significant differences were found.
s = Data were significant at the 0.05 level.
ss = Data were significant at the 0.01 level.
sss = Data were significant at the 0.001 level.

most nitrate in the soil profile, thereby increasing the potential for nitrate leaching below the root zone during fall and winter rains.

Ammonium was typically less than 20 pounds N/acre in the top 3 feet of the profile (data not shown) and so was much lower than nitrate. In the surface soil, ammonium was significantly lower after cover cropping, but otherwise did not show consistent responses to the management treatments. Since ammonium is rapidly converted to nitrate in these soils (Calderón et al. 2001), ammonium concentrations are less indicative of N availability than are nitrate concentrations.

Two minimum-tillage treatments shown side by side: at *left*, the +OM treatment (cover crops on bed tops and added compost); at *right*, the –OM treatment (no OM inputs other than unharvested crop residues).

Plant biomass and nutrient content

Lettuce and broccoli fresh weights in 1999 and 2000 were highest in the treatment receiving conventional tillage, cover crops, and compost (fig. 4). Addition of OM increased fresh weight or dry weight, or both fresh weight and dry weight, for crops produced in 1999 and 2000, compared to –OM treatments (table 2, fig. 4). For the two 1999 lettuce crops, minimum tillage decreased crop fresh weight compared to conventional tillage, but the type of tillage did not affect dry weight. There may be a relationship with soil moisture since the surface layer (0 to 6 inches) was drier in minimum tillage treatments on both sampling dates (fig. 2) as described above. Soil moisture at lower depths, however, was similar between the two tillage treatments for these lettuce crops (data not shown). For broccoli in 2000, dry weight decreased with minimum tillage, and fresh weight tended to be lower with minimum tillage.

Nitrogen in the vegetable crops did not show consistent treatment effects (table 2). For example, uptake of N by lettuce was lower with OM inputs only in the May 1999 crop. Uptake of N was also lower with minimum tillage in the August 1999 lettuce crop, and the April 2000 broccoli crop. Minimum tillage resulted in lower tissue phosphorus concentration in both 1999 lettuce crops and the 2000 broccoli crop (data not shown). Lack of disruption of lower soil layers could have resulted in lower temperatures and lower rates of net mineralization *in situ*, as is typically found in no-till soils (Silgram and Shepherd, 1999).

Cover crop biomass and N were not affected by tillage treatment in either year. Aboveground biomass was 4,142 and 2,660 pounds dry weight/acre and 131 and 122 pounds N/acre in 1998 and 1999, respectively. The C:N ratio was 14 in 1998 and 10 in 1999, assuming that carbon was 45% of plant dry weight, as is typical of most plant material.

TABLE 3. Effect of organic amendments and tillage system on burning nettle and shepherd's purse emergence densities at eight sample dates during 1998 and 1999*

OM treatment	Tillage treatment	Jul 98	Dec 98	Feb 99	May 99	Jul 99	Aug 99	Nov 99	Dec 99
Burning nettle:					*number of plants/yd²*				
+	Min.	0.0	1.7	6.2	0.6	1.8	0.6	2.3	1.8
-	Min.	0.9	6.2	8.0	1.5	4.8	0.8	nd	4.1
+	Conv.	0.8	3.6	3.3	0.4	4.8	1.1	3.6	1.1
-	Conv.	0.9	5.8	1.8	0.4	4.1	1.5	nd	4.8
Main effect *F* values									
OM		ns	s	ns	ns	ns	ns	—	ss
Tillage		ns	ns	s	ns	ns	ns	ns	ns
OM × Tillage		ns	ns	ns	ns	ns	ns	—	ns
Shepherd's purse:					*number of plants/yd²*				
+	Min.	0.8	27.5	37.2	2.6	26.2	8.4	26.3	31.4
-	Min.	3.8	97.4	68.1	6.4	78.7	16.6	nd	41.9
+	Conv.	0.9	25.9	19.2	3.2	35.7	1.7	29.8	8.6
-	Conv.	1.8	85.0	27.8	3.9	72.9	3.2	nd	45.9
Main effect *F* values									
OM		s	ss	ns	ns	ss	ns	—	ns
Tillage		ns	ns	ns	ns	ns	ns	ns	ns
OM × Tillage		ns	ns	ns	ns	ns	ns	—	ns

* The data are means.
nd = No weeds were present due to lack of irrigation in this treatment.
ns = No significant differences were found.
s = Data were significant at the 0.05 level.
ss = Data were significant at the 0.01 level.
— = No samples were taken because no weeds were present.

Weeds, insects and diseases

The most abundant weed species were shepherd's purse (*Capsella bursa-pastoris*) and burning nettle (*Urtica urens*). For samples taken in July and December 1998, and July 1999, the density of shepherd's purse plants was lower where OM inputs had been added (table 3). The density of burning nettle plants was reduced in December 1998 and December 1999 in +OM treat-

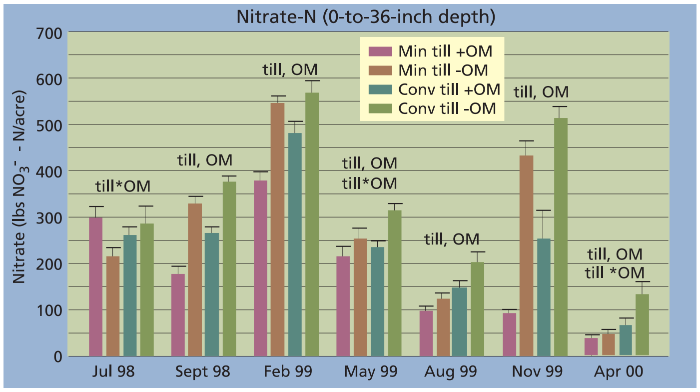


Fig. 3. Soil nitrate pools in the 0-to-36-inch profile. Treatment effects are labeled for each sampling date when the main effects of tillage (till) or organic matter (OM), or their interaction (till*OM) was significant at $P \leq 0.05$. Deep layers of soil were not sampled in April 1998. Mean ± SE shown only in the positive direction.

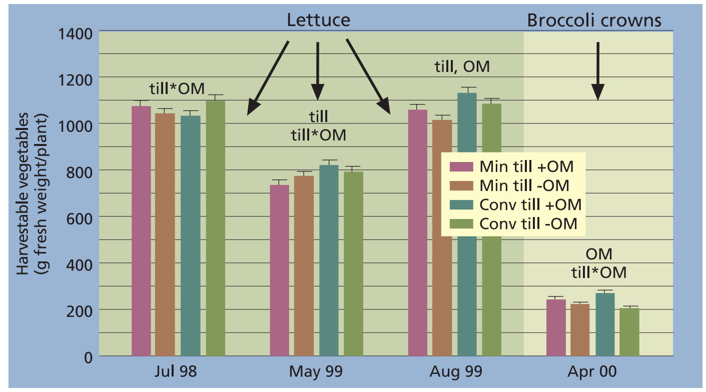


Fig. 4. Fresh weight of the harvestable vegetables. Treatment effects are labeled for each sampling date when the main effects of tillage (till) or organic matter (OM), or their interaction (till*OM) was significant at $P \leq 0.05$. Mean ± SE shown only in the positive direction.

ments, and by conventional tillage in February 1999. More extensive analysis showed negative correlations between microbial biomass and weed densities, possibly due to microbial effects on weed emergence (Fennimore and Jackson, in press). Organic amendments were associated with lower numbers of viable burning nettle seed in the soil in 1999, but no other effects of tillage or OM inputs on seedbanks of either species were observed (data not shown).

Leafminers were present on both of the lettuce crops that were sampled in 1999, but at higher densities in the fall crop than the spring crop (data not shown). All leafminers found were the pea leafminer, *Liriomyza huidobrensis*, and only a few parasites were found, mostly *Diglyphus intermedius*. There were no significant treatment effects.

Corky root disease, caused by *Rhizomonas suberifaciens*, was lower in the +OM treatments in May 1999, even though the severity of this disease was low throughout the field (data not shown). Lettuce drop symptoms caused by *Sclerotinia minor* were observed on less than 2% of the plants, and there were no treatment differences. Shallow minimum tillage, however, has been shown to increase this disease in other studies, possibly because sclerotia accumulate in the surface soil (Bell et al. 1998; Jackson et al. 2002). Downy mildew, the most important foliar disease of lettuce, was absent from all lettuce crops. Big vein disease, which is caused by a virus-like agent, was only present in the May 1999 crop. No evidence of damping-off diseases was found, although these diseases can be associated with decomposing cover crop residue.

Economic analysis and fuel use

The grower supplied information for each operation including the date, labor and time required, and materials and equipment used. Fresh yield data were also provided for the entire field. Costs and returns were then calculated from the baseline data and crop yields, using actual market prices and costs from local input suppliers. The Budget Planner program calculated total costs, gross returns, monthly cash flow and equipment schedules, and summaries of water, fertilizer, energy and labor use throughout each crop and cover crop season for each of the four management treatments. Rents were estimated to be $1,000/acre/cash crop in this district. Non-cash overhead includes equipment costs. To convert yield data from the grower (box/acre) for the whole field to yield per treatment, we used the relative differences in fresh harvestable yield in 1.2-square-yard areas that had been obtained from the same crop.

Production costs differed with each management system, depending on the amount of tillage and land preparation, the use of a cover crop prior to planting, and the harvesting costs associated with differences in crop yield due to tillage or OM management (table 4). The costs of using a cover crop resulted in additional irrigation, seed, and tillage costs, averaging $265/acre for each cover crop. The costs (not including harvest costs) of the four compost applications and two cover crops over the 2-year study period averaged $288/acre/cash crop for the minimum till +OM system, and $337/acre/cash crop for the conventional tillage +OM system. The difference in management costs between minimum tillage and conventional tillage was that minimum tillage cost $575 less per acre for the 2-year study. Approximately half of the savings was in reduced fuel use with an average reduction of 32 gallons per acre. The rest of the savings was in reduced labor and equipment ownership costs.

Fuel use was 2.2- to 3.8-fold greater with conventional tillage than minimum tillage (table 4). Fall tillage operations to disk, chisel and shape beds accounted for the largest difference between conventional and minimum tillage operations. Incorporation of the cover crop and compost utilized 10% to 30% of the fuel used for each of the crops produced in the spring.

Net returns for the lettuce crops were lowest in the conventional tillage +OM system (table 4), despite the tendency for higher harvest yields in this treatment (fig. 4). The total returns from higher yields were offset by the costs of the OM inputs and increased harvest costs compared to the conventional tillage treatment that did not receive compost and cover crops.

For the broccoli crop in 2000, net

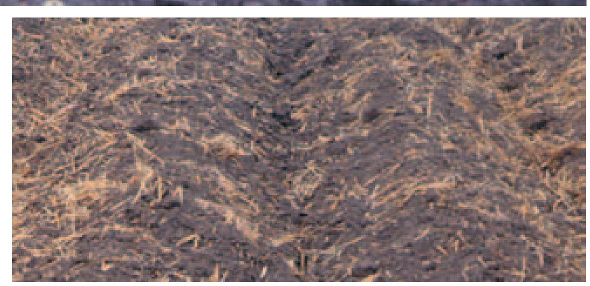
TABLE 4. Economic analysis of all management costs and returns, and fuel use for the four vegetable crop seasons*

	Lettuce Crop harvested July 1998				Cover crop + lettuce Crop harvested May 1999				Lettuce Crop harvested Aug 1999				Cover crop + broccoli Crop harvested Apr 2000			
	Min Till		Conv Till		Min Till		Conv Till		Min Till		Conv Till		Min Till		Conv Till	
Management costs per acre ($)	+OM	–OM	+OM	–OM	+OM	–OM	+OM	–OM	+OM	–OM	+OM	–OM	+OM	–OM	+OM	–OM
Fuel, lube, repair	74	74	135	135	150	117	374	254	58	58	140	140	126	84	313	275
Machine labor	81	81	102	102	150	134	235	179	73	73	122	122	115	88	205	184
Non-machine labor	497	497	497	497	470	436	470	436	440	440	440	440	470	402	467	399
Harvest costs	4588	4452	4407	4679	3623	3816	4047	3893	5764	5531	6114	5881	3586	3299	6035	3437
Irrigation	99	99	99	99	89	74	88	73	132	132	132	132	106	83	105	81
Compost	177	0	177	0	177	0	177	0	177	0	177	0	177	0	177	0
Seed	100	100	100	100	125	100	125	100	100	100	100	100	125	100	125	100
Fertilizer	119	119	119	119	151	151	151	151	142	142	142	142	240	240	240	240
Herbicide	24	24	24	24	26	26	26	26	39	39	39	39	107	107	107	107
Other pesticide	190	190	190	190	149	149	149	149	172	172	172	172	0	0	0	0
Application fees	95	95	95	95	95	95	95	95	104	104	104	104	31	31	31	31
Cash overhead	4	4	7	7	9	7	22	15	3	3	8	8	8	5	19	17
Non-cash overhead	52	52	79	79	111	83	253	172	39	39	90	90	92	58	224	197
Interest on capital	69	62	71	67	97	71	127	87	75	68	82	75	96	69	132	86
Land rent	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Total costs	7170	6849	7100	7191	6422	6257	7338	6631	8318	7902	8860	8443	6280	5567	9181	6154
Returns per acre ($)																
Total returns	8136	7894	7813	8297	5985	6304	6686	6431	9007	8643	9552	9188	6794	6251	11435	6512
Total costs	7170	6849	7100	7191	6422	6257	7338	6631	8318	7902	8860	8443	6280	5567	9181	6154
Net returns	966	1045	714	1105	-437	46	-652	-200	689	741	692	745	514	684	2254	358
Fuel (gal. per acre)																
Diesel used	28	28	61	61	52	43	162	111	22	22	61	61	43	30	129	115

* Costs for the cover crop and its incorporation are included with the subsequent vegetable crop. The calculation of returns used $7.50 (lettuce) and $9.00 (broccoli) per box, which was the Monterey County average for the sampling times of the study.

returns were highest in the conventional tillage +OM system, which produced higher fresh yields than the other treatments (table 4, fig. 4). The high management costs of this treatment were compensated for by a much greater yield increase for broccoli than for lettuce. Note that it was not possible to collect samples on all three dates when the grower harvested the broccoli crop. The small plot data are for only the second harvest date. The data can be considered a good representation of actual yield, however, because the harvest on this date was very much larger than any of the other harvests.

The ranking of net returns for the entire 2-year study is as follows (fig. 5), from lowest to highest: minimum tillage +OM inputs ($1,732/acre), conventional tillage –OM inputs ($2,008/acre), minimum tillage –OM inputs ($2,516/acre) and conventional tillage +OM inputs ($3008/acre). The typical practice, conventional tillage without OM inputs, was not the most economically advantageous for either lettuce or broccoli.



***Above,* deep subsoil tillage in the conventional tillage plots after the last lettuce crop in the fall. Large blocks of soil are brought to the soil surface, and thereafter beds are shaped and smoothed. *Right,* dried cover crop residue of Merced rye cover crop on semi-permanent beds after Sundance tillage in the minimum tillage +OM treatment.**

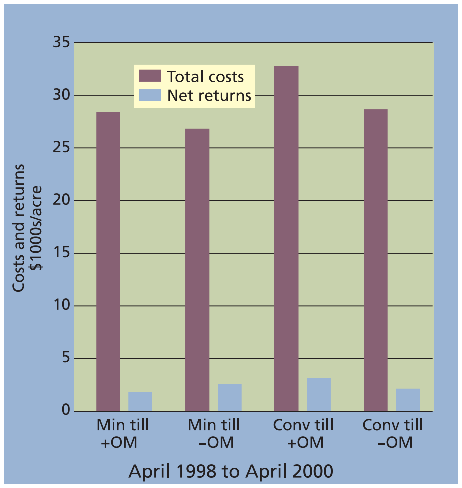


Fig. 5. Total costs and returns by treatment for the 2-year study period from April 1998 to April 2000.

Implications for management

There are trade-offs to consider with the adoption of alternative OM and tillage practices to improve soil quality. In this study, soil quality was enhanced by cover crops and compost due to increased SOM and microbial biomass, and reduced potential for nitrate loss. Lower soil nitrate was not associated with lower crop yield, as demonstrated by the fact that highest fresh weight of vegetables typically occurred in the treatment using conventional tillage, cover crops, and compost, for which nitrate tended to be lower in both shallow and deep layers compared to lower-yielding treatments.

Minimum tillage in our project involved disking the top few inches of soil on semipermanent beds. Neither SOM nor soil moisture in the surface layer increased with minimum tillage, as might have been expected if minimum tillage were similar to no-till management elsewhere in the USA (Carter 1991). Frequent surface tillage probably disrupted the surface layer in a similar fashion as conventional tillage. The lack of soil disruption in lower layers may have created differences in compaction, aeration and temperature, which could have affected water movement and N mineralization at lower depths, such that moisture in the surface layer (0-to-6-inches depth) and nitrate in lower layers (6-to-36-inches depth) were lower than with conventional tillage and could have reduced growth and N uptake of crops grown with minimum tillage. Higher soil moisture in the surface layer of conventional tillage treatments, where lettuce roots are densely congregated, may have contributed to higher fresh weight of lettuce compared to minimum tillage.

In terms of a qualitative assessment of soil quality, the system using minimum tillage with OM inputs ranks higher than other treatments. This treatment tended to be associated with higher total soil C and N, and lower bulk density in the surface soil after 2 years, and higher soil microbial biomass during much of the 2-year period. In addition, the potential for nitrate leaching below the root zone was lower than in any other treatment. Yet, minimum tillage with OM inputs did not produce high vegetable yields, possibly due in part to slight N, P and moisture limitation, nor was it economically advantageous despite low fuel and input costs.

Conventional tillage with OM inputs appears to be a more attractive option for farmers. This treatment enhances some attributes of soil quality and also produced high lettuce and broccoli yields. Although the increase in lettuce yield was not high enough to offset the costs of using the OM inputs, economic returns across the 2-year period were highest for this system, largely due to high yields of broccoli. If farmers were to use this treatment with intermittent use of minimum tillage (e.g., between summer crops or to incorporate a cover crop), they could effectively reduce tillage costs and fuel use, without the deleterious effects on productivity that were observed with continuous minimum tillage over a 2-year period.

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RESEARCH ARTICLE

Incorporating straw may induce sulfide toxicity in paddy rice

Above, **Sacramento Valley rice fields.** ***Right,*** **Rice plants with healthy roots (left) and blackened roots (right); the latter is caused by sulfide toxicity.**

Suduan Gao
Kenneth K. Tanji
Steven C. Scardaci

Sulfide toxicity to rice plants has been randomly observed in isolated sites in rice fields and experimental plots in the Sacramento Valley. Plants suffering from sulfide toxicity show signs of retarded growth and reduced yields, including the characteristic blackened roots and, in the most severe cases, death. Because the environmental conditions causing sulfide toxicity are not clear, we carried out a greenhouse pot test. The treatments included straw and sulfate additions to a rice soil to induce sulfide production. Our results contribute to an improved definition of conditions leading to sulfide production, toxicity and impact to rice plants.

In 2001, about 470,000 acres of rice *(Oryze Sativa* L.*)* were grown in California, mainly in the Sacramento Valley. Traditionally, rice straw has been burned after harvest to ease tillage and to control rice stem rot. But recently, the burning of rice straw has been restricted in California to improve air quality under the Connelly-Areia-Chandler Rice Straw Burning Reduction Act of 1991 and Senate Bill 318 in 1999. The purpose of these acts was to improve air quality.

Because commercial uses of rice straw are limited, rice growers dispose of the straw they cannot burn, most often by incorporating it into the soil (Bird et al. 2002). Rice researchers are concerned that over the long term, as incorporated straw decomposes in the soil, it might produce constituents toxic to rice, such as sulfide. Plants suffering from sulfide toxicity show signs of retarded growth and reduced yields, including the characteristic blackened roots and, in the most severe cases, death.

UC Cooperative Extension rice farm advisors have noted random, isolated cases of what appears to be sulfide toxicity in the Sacramento Valley. Field observation shows that the roots of affected plants are blackened from the accumulation of iron sulfides (and possibly manganese sulfides) formed under reducing conditions. This black coloring disappears upon exposure to the atmosphere after several hours due to oxidation, a confirmation of sulfide formation. Because the soil conditions producing sulfide and sulfide toxicity to rice plants when straw is incorporated are not clear, we conducted a greenhouse pot study.

Reactions driven by microbes

As rice straw and other soil organic matter decompose in submerged soil, a sequence of reduction-oxidation (redox) reactions occur that are driven by a variety of microbes (fig. 1) This sequence of microbially mediated reactions is shown as a redox ladder. The oxygen sufficiency of an environment can be indicated by its redox status, which can be roughly indexed by redox potential (Eh) as measured by a platinum and reference electrodes. A high Eh represents oxic (oxygen-rich) conditions and a low Eh represents anoxic (oxygen-poor) conditions. Redox status can also be classified into oxic, post-oxic, sulfidic and methanic status, as different redox reactions occur that correspond to decreases in Eh.

Microbes decompose organic matter to obtain energy, and they need oxygen or other oxidized substances such as nitrate (NO_3^-), manganese (Mn [IV or III]), iron (Fe [III]), sulfate (SO_4^{-2}) or carbon dioxide (CO_2) to serve as electron acceptors. In submerged paddy soil, the decay of organic matter will initially consume the dissolved oxygen in water. Dissolved oxygen (O_2) which is an electron-poor substance is reduced to an electron-rich substance (H_2O) because it serves as the electron acceptor while organic matter is being oxidized. (This is an example of a redox reaction.) When oxygen is depleted, microbes reduce nitrate to nitrogen gas (N_2) (denitrification), and convert the soil from

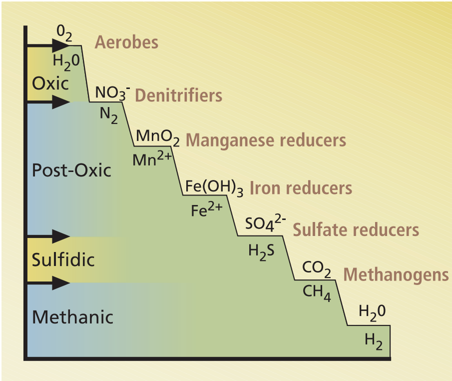


Fig. 1. Redox reactions catalyzed by microbes during decay of soil organic matter and geochemical redox classes.

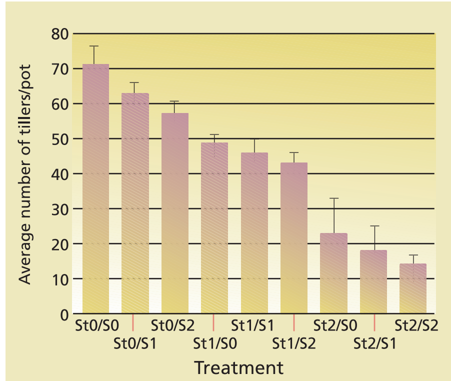


Fig. 2. Average number of tillers 6 weeks after planting.

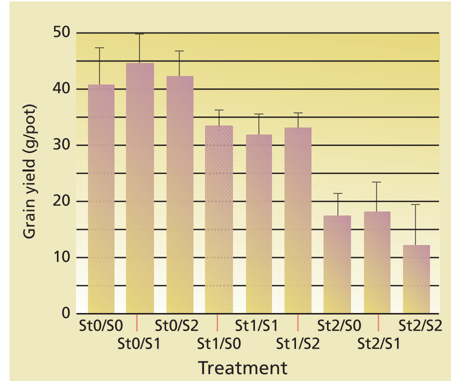


Fig. 3. Average grain yield with straw and sulfate treatments.

oxic to post-oxic status. In post-oxic status, organic matter continues to decay, and oxidized manganese and iron present in solid phases are reduced to soluble manganous (Mn^{2+}) and soluble ferrous (Fe^{2+}) ions. The continuous decay of organic matter leads to sulfidic conditions, and microbes reduce sulfate to sulfide. Under highly reducing condition (fig.1) microbes (methanogens) reduce carbon dioxide to produce methane. This process is defined as methanogenesis and the resulting condition is termed "methanic status."

Under post-oxic conditions, soluble manganous and soluble ferrous ions are produced; under sulfidic conditions, dissolved hydrogen sulfide (mainly as HS^-) is produced. When sulfides accumulate, they may precipitate out as ferrous and manganous sulfides (such as FeS and MnS), reducing the accumulation of soluble sulfides to very low concentrations. But if soluble ferric and manganic sources are depleted, sulfide may accumulate. As a result, sulfide accumulation and toxicity to rice plants may occur only under specific environmental conditions.

Greenhouse study

Experimental soil (Willows clay) was obtained from a burned-straw treatment plot at the UC Rice Straw Management Project near Maxwell. This soil is moderately alkaline. The extract from soil saturation paste had a neutral pH, electrical conductivity (EC) of 2.5 deciSiemens/meter (dS/m) and sulfate concentration of 16 milliMole/liter (mmol/L). Using the Loeppert and Inskeep method (1996), we measured the content of amorphous iron and manganese oxyhydroxides in this soil at 110 milliMole/kilogram soil (mmol/kg) and 8.0 mmol/kg, respectively.

Three levels of straw chopped into 1-inch lengths were mixed into the soil at 0, 6 and 23 tons/acre (0%, 0.6% and 2.3%, respectively). The typical annual straw incorporation in unburned rice fields is about 3 to 4 tons/acre, and any partly decomposed straw may be carried over each year (Bird et al. 2002). The purpose of choosing a much higher straw incorporation rate of 23 ton/acre was to examine the potential damage of straw return on rice with only one growing season of treatment.

The straw-incorporated soil (9.5 pounds) was placed in PVC pots (8 inches in diameter and 8 inches in height). Ammonium sulfate [$(NH_4)_2SO_4$] was added at rates of 0, 350 and 1,820 pound/acre (0, 160 and 800 milligram/kilogram (mg/kg), respectively) to ensure that sufficient sulfate was available for reduction to sulfide. The fertilization rates were 530 pound/acre of nitrogen as ammonium sulfate and urea, and 64 pound/acre of potassium and 37 pound/acre of phosphorus as potassium phosphate, monobasic (KH_2PO_4) and potassium phosphate, dibasic (K_2HPO_4). Our nitrogen fertilization rate was about three to five times greater than normal field applications (Bird et al. 2002) to ensure that the rice plants did not suffer from nitrogen deficiency due to high rates of added straw, and that nitrogen use was not a variable in the treatments.

Microbes decomposing straw require nitrogen as a nutrient competing with nitrogen uptake by plants. Urea and ammonium are oxidized into nitrate, which can be readily assimilated by microbes during straw decomposition and/or is denitrified to form nitrogen gas, causing nitrogen loss from soil (fig. 1) (Bilal et al. 1979). The nitrate becomes less available for plant uptake, as there is competition between immobilization, denitrification and plant uptake. The treatments included three levels of straw and three levels of sulfate done in triplicate (table 1). The pots were flooded on June 27, 2000, and 10 seeds of rice (M202 variety) in germination were transplanted into each pot the following day.

At early growing stages, the 23 ton/acre straw treatment severely affected the rice plants (see photo, p. 58). At week 6 of the growing season, the average number of tillers (extra stems or culms in a rice plant that arise from its base) per pot decreased with increasing straw incorporation as well as with increasing sulfate additions (fig. 2). Likewise, grain yield decreased with increasing straw incorporation (fig. 3).

An analysis of covariance using the GLM procedure and Type II sum of

TABLE 1. Straw and sulfate treatments in greenhouse pot study

Treatment	St0 (0 ton/acre straw)	St1 (6.0 ton/acre straw)	St2 (23.0 ton/acre straw)
S0 (0 pound/acre SO_4)	St0/S0	St1/S0	St2/S0
S1 (350 pound/acre SO_4)	St0/S1	St1/S1	St2/S1
S2 (1,820 pound/acre SO_4)	St0/S2	St1/S2	St2/S2

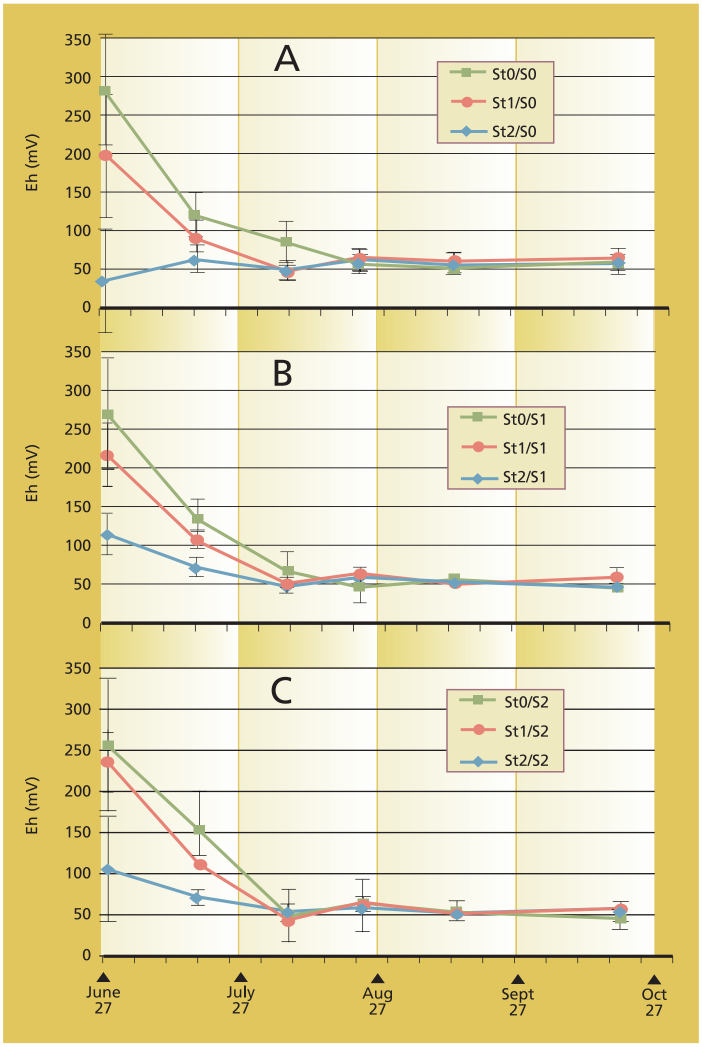


Fig. 4. Redox potential (Eh) at (A) 0, (B) 350 and (C) 1,820 pound/acre sulfate (SO_4), and 0, 6 and 23 ton/acre rice straw incorporation.

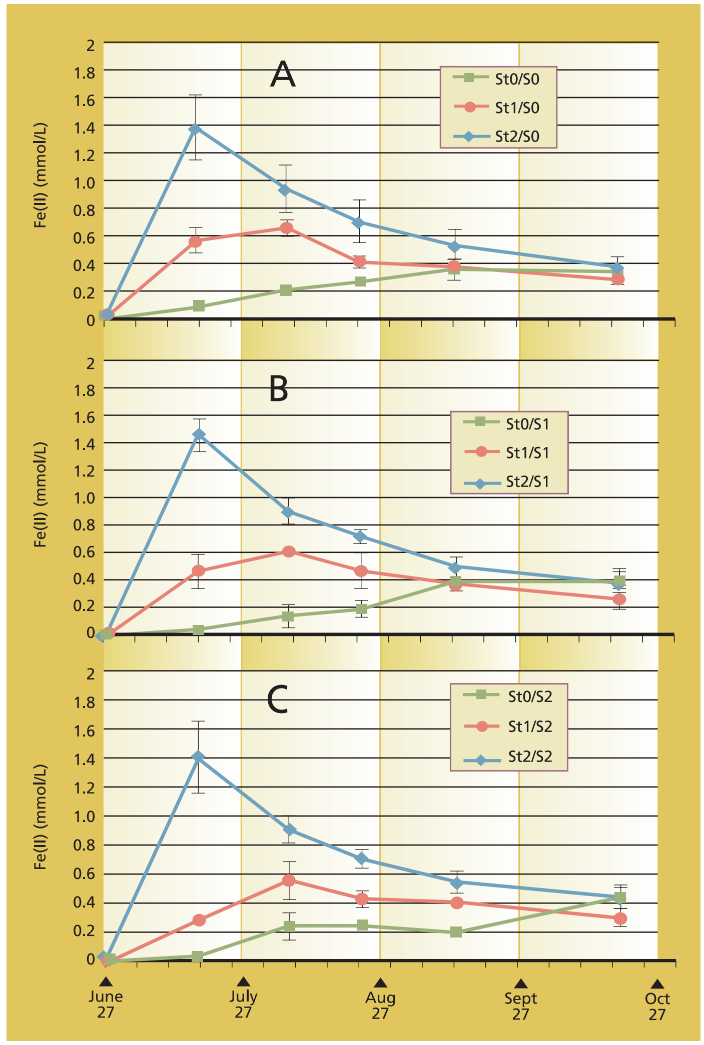


Fig. 5. Ferrous iron concentration at (A) 0, (B) 350 and (C) 1,820 pound/acre sulfate (SO_4), and 0, 6 and 23 ton/acre rice straw incorporation.

squares was performed using the SAS program (SAS Institute 1991). Statistics on the number of tillers showed that the differences among the three levels of straw treatment were all significant, as were the differences between no sulfate and the highest sulfate addition ($P < 0.0036$). The grain yield variation from straw treatment effects was significant ($P < 0.0001$), and the variations in grain yield due to sulfate addition and interaction between straw and sulfate addition were not significant. The highest straw treatment exhibited blackened roots as well as a rotten egg odor characteristic of sulfide.

Chemical monitoring

The soil solution in the pots was monitored throughout the growing season for redox status and chemical constituents. Soil solution was extracted by vacuum with online monitoring of Eh and dissolved oxygen (DO). For analysis of soluble manganous and ferrous ions (Fe^{2+} and Mn^{2+}), samples were immediately acidified. For sulfide analysis, samples were immediately treated with a reducing agent to prevent sulfide oxidation; sulfide concentration was determined using an ion-selective electrode (Model 9416; Orion Research Inc.).

The redox potentials (Eh) decreased rapidly upon flooding, and they stabilized by mid–growing season (fig. 4). Note that initially measured Eh of the highest straw treatment after 24 to 48 hours of flooding was about 100 milliVolts (mV) or lower and for no straw treatment, 250 to 300 mV. Lower Eh values indicate more reducing conditions. An Eh value of 50 to 100 mV is considered reduced (Patrick 1981). Differences among Eh values between the treatments after about 3 weeks of flooding were not readily discernible. The pH of the soil solution was near neutral after flooding (data not shown) and so did not affect Eh values.

Changes in composition of the soil water with respect to soluble iron, soluble manganese, sulfate, sulfide and methane were monitored. (Results are shown for soluble iron and sulfate only.) Ferrous iron concentrations generally increased with time (fig. 5). However, in the 23 ton/acre straw treatment with high sulfate addition, iron peaked at 3 weeks, indicating a more rapid decrease in Eh than other treatments. Eh decreased to a level similar to the other treatments by harvest time.

Meanwhile, sulfate concentrations decreased with time to very low concentrations (fig. 6). Initially measured sulfate concentrations were negatively

In greenhouse experiments, rice plants responded to straw treatment and sulfate additions. *Left to right photos,* Treatments with 0, 350 and 1,820 pound/acre sulfate (SO_4). Within each photo, pots from left to right contain 0, 6 and 23 ton/acre incorporated straw.

correlated to the level of straw treatment. It is likely that sulfate reduction occurred within the first couple of days in the straw treatment (6 and 23 ton/acre) that resulted in lower sulfate concentrations in the first sampling that was taken after 24 to 48 hours of flooding. Very low concentrations of sulfides were found, however, much lower than expected with the amount of sulfate reduced to sulfide. Most of the samples contained sulfide concentrations below 0.005 mmol/L (data not shown). The low sulfide concentrations were mainly due to formation of ferrous sulfide (FeS) which will be discussed in detail below.

Geochemical redox classes

We defined the redox status as falling within one of several geochemical redox classifications (fig. 1) of the monitored soil solutions. These were based on oxidative capacity, which, in turn, was based on equivalent concentrations of the redox constituents (dissolved oxygen, nitrate, manganic oxide, ferric hydroxide, sulfate and methane) (Gao et al. 2002; Tanji et al. 2001). The no-straw treatment was initially oxic, then post-oxic, and methanic in the last sampling. The 6 ton/acre straw treatments were initially oxic, then sulfidic at 3 weeks, and thereafter methanic. The 23 ton/acre straw treatment rapidly became methanic after an initial oxic status. Straw additions clearly resulted in the fast development of more reduced conditions. We expect sulfide toxicity to rice plants to occur when redox status is sulfidic.

Sulfide solubility, toxicity

This study indicates that elevated levels of straw incorporation may have caused sulfide toxicity effects on rice plants. The most readily apparent visual symptoms of sulfide toxicity are blackened roots, and reduced height and number of tillers. The monitored chemical data did not clearly establish a chemical diagnosis of potential sulfide toxicity. Low sulfide concentrations in soil solutions of sulfide-affected rice plants have been a diagnostic dilemma (Yoshida 1981). We hypothesize that the concentration of sulfides in the soil solution is not a good indicator of sulfide toxicity because of precipitation of sulfides with metals such as iron and manganese.

We tested this hypothesis with a geochemical computer model called WATEQ (Ball and Nordstrom 1991). This model examines the speciation of iron and sulfur in solution and predicts whether or not ferrous sulfide is precipitated based on calculations of saturation indexes. The model predicted that when the FeS was formed, the sulfide concentration was extremely low (< 0.001 mmol/L) and thus difficult to measure. This is why chemical diagnosis of sulfide toxicity is so difficult and rarely produces clear evidence. In the Sacramento Valley, sulfide toxicity is sometimes associated with water salinity, possibly because waters with higher electrical conductivity may contain higher concentrations of sulfate. Undissociated hydrogen sulfide is the toxic form to rice plants (Yoshida 1981). Hydrogen sulfide is a strong inhibitor of aerobic respiration after entering the roots, causing nutritional imbalance and physiological disorders (Kumazawa 1984). This point needs further research. At any rate, the best diagnosis for sulfide toxicity is blackened roots and rotten egg odor (hydrogen sulfide). Reduced height and number of tillers may also be an early sign of sulfide toxicity. In the most severe cases, rice plants die. Incorporating excessively high rates of straw may enhance sulfide toxicity to rice plants, but under current straw return rates, it is unlikely that sulfide toxicity could occur on a large scale. It is more likely that only randomly localized sites will exhibit toxicity.

In this study, the 23 ton/acre straw incorporation significantly reduced rice yield and induced sulfide toxicity symptoms. The 6 ton/acre straw incorporation rate, which is slightly higher than the normal field return rate (4 ton/acre), also reduced rice yield significantly. However, the reduced yield may not be solely attributable to sulfide toxicity. Decomposition of organic matter produces low-molecular-weight organic acids, some of which are toxic to rice plants. Further, it appears that salinity is another factor in reducing rice yield (Scardaci et al. 2002). For example, sulfate additions reduced the number of tillers at the early stage. All these factors may have contributed to rice yield reductions.

Under normal field conditions, straw decomposition after the fall harvest and incorporation can be promoted by winter flooding (Bird et al. 2002). Straw decomposition rates can be slowed down

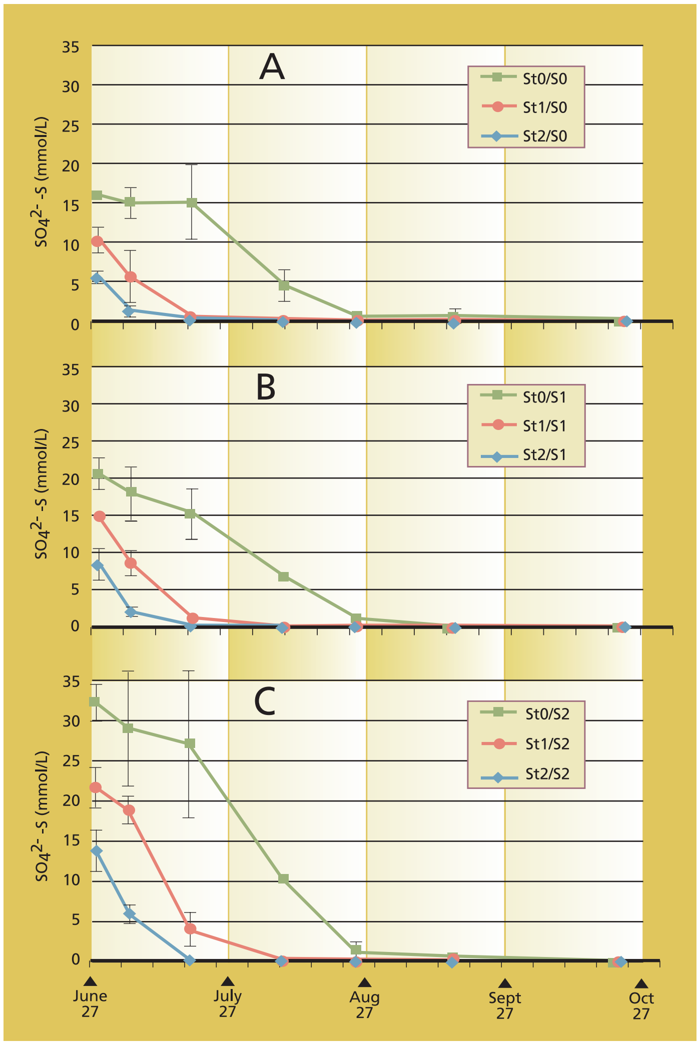
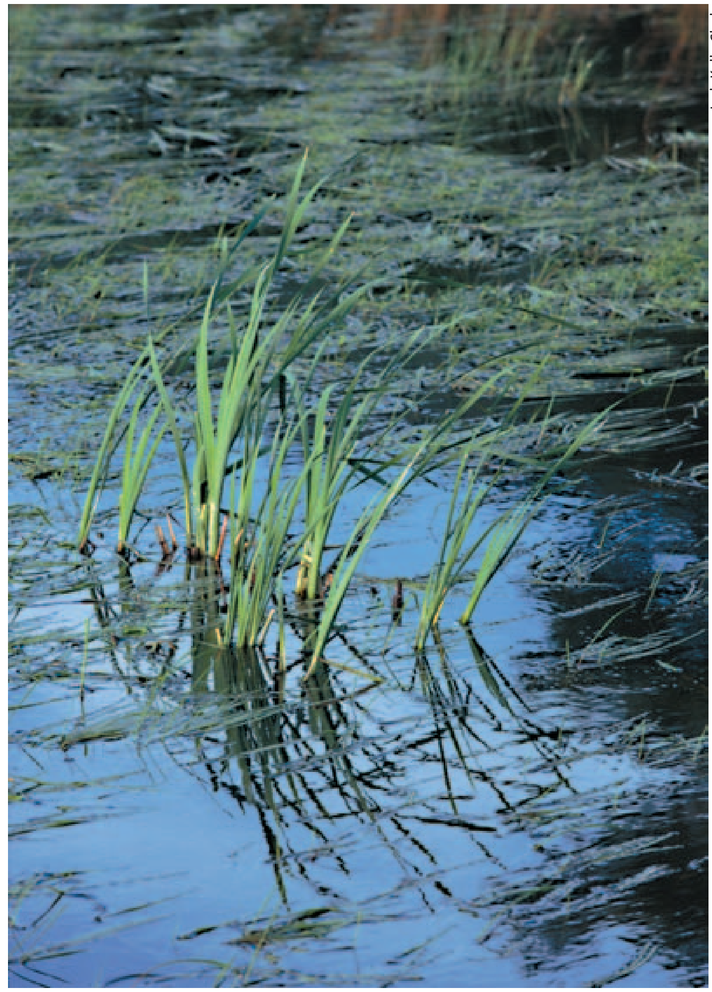


Fig. 6. Sulfate concentration at (A) 0, (B) 350 and (C) 1,820 pound/acre sulfate (SO_4), and 0, 6 and 23 ton/acre rice straw incorporation.



Jack Kelly Clark

Rice straw decaying in submerged soil consumes the dissolved oxygen, sometimes leading to sulfidic conditions. Wild rice shown.

if straw is not well incorporated into the soil and winter flooding is not practiced. Then the organic matter would be subject to decomposition in spring during the rice-growing season. These conditions are more likely to result in sulfide problems. Sulfide problems were also observed in lower basins and on the sides of fields, suggesting that lack of water circulation and/or oxygen may be a contributing factor. Increasing water flow or circulation may therefore ease impacts in some fields.

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RESEARCH ARTICLE

Stubble height standards for Sierra Nevada meadows can be difficult to meet

The study site was protected from grazing by cattle during the 3-year study.

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Betsy M. Karle

Standards for the height of herbaceous vegetation remaining in meadows at the end of the growing season have been, and continue to be, implemented on public grazing lands throughout the Sierra Nevada. Although supporting research is limited, stubble height standards are intended to benefit riparian resources by limiting grazing pressure. This study illustrates how the timing and intensity of defoliation in mountain meadows can affect the stubble height of herbaceous vegetation at the end of the growing season, and compares these findings with current standards. The research also can help livestock operators and public lands managers develop grazing management strategies to meet stubble height standards and conduct local applied research to evaluate the appropriateness of general stubble height standards.

Riparian meadow systems in California's Sierra Nevada mountains perform an array of critical environmental functions. They provide wildlife habitat, aesthetic value, flood attenuation and maintenance of water quality. Many beef cattle operations rely on vegetation growing on publicly and privately owned meadows for their annual forage budget. During the summer, when low-elevation foothill and valley rangelands are dry and forage quality is low, mountain meadows provide green, high-quality forage. Cattle are moved on to mountain meadows annually for a grazing season that typically lasts from early June through late September, depending on the elevation and annual weather conditions.

On public lands, natural resource managers with the United States Forest Service and Bureau of Land Management apply several annual grazing utilization standards that livestock operators must meet as a condition of their grazing permits. There are generally four standards each permittee must address: (1) stubble height, (2) percent stream bank trampling by livestock, (3) percent utilization of woody riparian plants by cattle and (4) percent utilization of herbaceous biomass. These standards are intended to safeguard riparian resources from damage by excessive livestock grazing. They include height standards for riparian herbaceous plants such as sedges (*Carex* sp.), rushes (*Juncus* sp.) and perennial grasses and forbs at the end of the growing season (USDA Forest Service 1991, 1992; USDI Bureau of Land Management 1998). Livestock operators are required to manage the timing and intensity of grazing by their livestock to ensure that herbaceous plants are left at a certain leaf height, referred to as the stubble height, when the livestock leave the area in the fall. There are significant ramifications for the permittee if these stubble height standards are not met. These include a temporary, 25% reduction in permitted numbers of livestock. Repeated failure can lead to cancellation of the grazing permit (USDA Forest Service 1991, 1992).

Stubble height standards were selected based on the assumption that plant height is (1) a standard easily communicated to managers, (2) easily and quickly measured and (3) directly correlated to the ecological health of specific riparian resources. Anticipated benefits from stubble height standards include enhancement and/or preservation of forage plant vigor, woody riparian plant communities, stream bank stability and floodplain sediment trapping ability. (Clary et al. 1996; Clary and Leininger 2000). However, there is a shortage of research defining the correlation of plant leaf height to the suite of riparian resource values that stubble height standards are expected to safeguard. In a review of the literature, Clary and Leininger (2000) stress that direct experiments to link stubble height standards with riparian resource objectives are limited and that continued research is needed. Clary and Leininger also note that stubble height is a short-term management guide for long-term riparian resource objectives and that the stubble height standards should not be thought of as a long-term resource objective

A stubble height of 4 to 6 inches has been widely recommended and enforced as a general grazing standard on public lands for the last decade (USDA Forest Service 1991 and 1992; USDI Bureau of Land Management 1998). In some circumstances, a 3-to-5-inch stubble height has been recommended, depending on stream type and season of grazing (USDA Forest Service 1991, Hall and Bryant 1995). Additional stubble height standards for areas with wildlife species of concern have been proposed, such as a 12-inch standard for meadows within great gray owl habitat areas (USDA Forest Service 2001). On public lands in general, a 4-inch stubble height is required for meadows in "good" condition, often defined as having stable stream banks and a plant community in middle to late seral status. (The "late seral" plant community is composed of "climax" species representing the potential plant community on the site in the absence of disturbance by human activity.) A 6-inch standard is generally required for meadows in "poor" condition, often defined as having unstable stream banks and a plant community in early seral status (USDA Forest Service 2001; USDI Bureau of Land Management 1998). Though measurements are currently taken at the end of the growing season, proposed USDA forest plan amendments are not specific about the time of application of this standard during a season (USDA Forest Service 2001).

The objective of this study was to evaluate how well grazing operators can meet the usual stubble height standards under several typical combinations of timing and intensity of defoliation (by clipping) on a northeastern California mountain meadow. The results should help public-land operators develop grazing management schemes that comply with current stubble height standards. We also hope to illustrate a simple method for local resource professionals to generate site-specific information on the relationship between grazing schemes and stubble height standards.

Plant defoliation is only one component of livestock grazing, however. This study does not attempt to fully examine the effects of grazing on meadows, which would involve measuring the impacts of livestock hooves, and redistribution of nutrients.

Mountain meadow

The study was conducted within an 850-acre, moist-to-wet mountain meadow (Clover Valley) located approximately 13 miles north of Westwood in western Lassen County at an elevation of 5,830 feet. Soil type on the site is an aquoll, consisting of loam-to-silt-loam texture with 10-to-20-inch rooting depth, underlain by a gravelly-silty-clay restrictive layer (Kliewer 1994). Dominant plant species on the study site are Nebraska sedge *(Carex nebraskensis)*, rush (*Juncus* sp.), Kentucky bluegrass *(Poa pratensis)*, tufted hairgrass *(Deschampsia caespitosa)*, native perennial clovers (*Trifolium* sp.) and buttercup (*Ranunculus* sp.). Grazing management on the site for the last several decades has been typical of middle-to-late-season moderate use in the region, with stable stream banks and an herbaceous plant community in mid-seral status as determined by USFS Region 5 ecological score cards (USDA Forest Service 2001).

Twenty-eight 2-by-12-foot (24-square-foot) plots were placed in a 4- by 7-plot grid with a 2-foot buffer strip between plots. Plots were located within a moist, productive meadow site adjacent to a first-order perennial stream (a headwater stream that flows -year around) flowing through the meadow where plants receive adequate subsurface soil moisture through the growing season from the adjacent stream. The site was fenced to prevent grazing by livestock for the duration of the study.

Clipping treatments

We simulated grazing by hand-clipping plots to desired levels (2 and 4 inches) at different times (early and mid-season) during the growing season (June through September). The scope of our project was limited to evaluating how well stubble height standards can be met under different combinations of timing and intensity of defoliation, and for these purposes hand-clipping provided an inexpensive, straightforward and repeatable approach.

Seven combinations of timing and intensity of grazing treatments were replicated four times and randomly applied to the 28 plots during the growing seasons of 1997, 1998 and 1999 (table 1). Each plot received the same treatment each year. All clipped vegetation was removed from the plots at the time of clipping. Clipping times for each year were based on annual weather and growth stage of perennial grasses rather than a set date (table 2). Early-season clipping occurred during the period of active vegetative growth (early June to mid-July) just prior to boot stage (seedhead emergence) of perennial grasses (tufted hairgrass and Kentucky bluegrass). Mid-season clipping occurred from mid-July to mid-August, at the onset of the bloom stage of perennial grasses**.**

TABLE 1. Clipping treatments applied to plots in Clover Valley

Treatment	Timing and intensity of clipping
E2	Early-season clipping to 2 inches
E4	Early-season clipping to 4 inches
M2	Mid-season clipping to 2 inches
M4	Mid-season clipping to 4 inches
EM2	Clipped to 2 inches both early and mid-season
EM4	Clipped to 4 inches both early and mid-season
Unclipped	No clipping

End-of-season herbaceous plant heights were determined for all plots each year at the time of the first killing frost of the fall. Plant height in the unclipped plots was measured at the time of the early- and mid-season clipping treatment application each year. Mid-season plant heights were measured for each of the early-season clipping (E and EM) treatments. At each sample time, five random readings per plot of plant leaf height were taken with a ruler following standard interagency methodology (USDI Bureau of Land Management 1996). Repeated measures analysis of variance was used to determine significance of treatment, year and treatment-by-year interac-

TABLE 2. April 1 snowpack at the Norvell Flat (3 miles east of study site, elevation 5,700 feet) and Silver Lake Meadows (4.5 miles west of study site, elevation 6,450 feet), a USFS Lassen National Forest snow survey location, and clipping dates at Clover Valley for 1997, 1998 and 1999

	April 1 snowpack		Clover Valley clip dates	
Year	Norvell Flat	Silver Lake Meadows	Early season	Mid-season
	. . . .% of average.			
1997	0.0	56	June 5	July 16
1998	152	145	July 22	Aug 13
1999	116	127	June 22	July 28

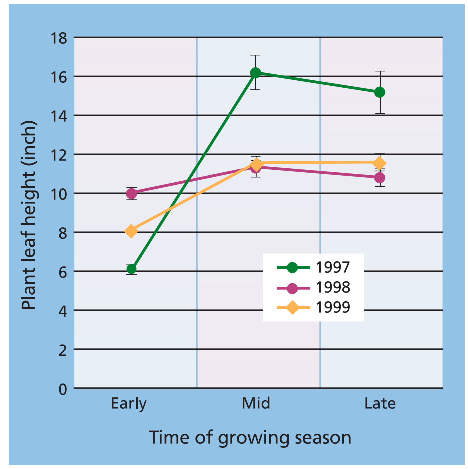

Fig. 1. Mean unclipped treatment plant leaf heights recorded early, mid- and end of season from 1997 to 1999. Sample size for each year is four. These data display potential plant height accumulation on the Clover Valley study site for the study period. Error bars represent one standard error of the mean.

tions. The clipping treatment (seven levels) was the fixed factor, and the end-of-season stubble height was the repeated measurement taken each year (1997, 1998, 1999) from all 28 plots (7 treatments × 4 replicates). Pairwise contrasts were used to separate significant treatment and year differences.

Weather and plant growth

Annual snowfall and the onset of growing season (and therefore clipping dates) varied during the study (table 2). April 1 snowpack in 1997 was below normal, and the onset of the growing season was much earlier than in 1998 and 1999. The 1998 El Niño anomaly provides insight into the effect of grazing timing and intensity on stubble height during a year with high snowfall and a short growing season. Snowpack and growing season onset in 1999 were slightly above average, but approximated long-term average conditions better than 1997 or 1998.

Statistically significant year differences existed in mean unclipped plant leaf height at early season, mid-season and end of season (fig. 1). These data illustrate the effect of variable annual snowfall and onset of growing season on plant height, in the absence of defoliation. The general trend across all years was an increase in plant height from early to mid-season followed by no increase — even a slight decrease — following mid-season as plants set seed and began to senesce. Despite a late onset of the growing season in 1998, there was rapid growth in plant height from the early to middle portion of the growing season. This is likely due to extremely favorable soil moisture conditions following the prolonged melt of the El Niño snowpack.

Treatment effects

There were significant treatment and year effects, as well as a year-by-treatment interaction effect, on the mean end-of-season stubble height ($P < 0.05$) (fig. 2). Unclipped plots generated a significantly ($P < 0.001$) higher end-of-season stubble height compared with all six clipping treatments. The early-season, 4-inch treatment (E4) generated a significantly higher ($P < 0.05$) end-of-season stubble height than all other clipping treatments. There were no significant differences ($P > 0.05$) in end-of-season stubble height between the early-season clip to 2 inches (E2), mid-season clip to 4 inches (M4) and early- and mid-season clip to 4 inches (EM4), but these treatments were significantly different ($P < 0.05$) from all other treatments. The mid-season clip to 2 inches (M2) and early- and mid-season clip to 2 inches (EM2) treatments were not significantly different ($P > 0.05$) from each other, but were significantly different from all other treatments.

The year-by-treatment interaction can be seen by examining the response of end-of-season stubble height across years and across treatments (fig. 2). For example, end-of-season stubble height for the early-season clip only (E2 and E4) was reduced in 1998, while it increased under several other treatments (EM4, M4, unclipped) for the same year. An interesting year effect is the steady reduction in end-of-season stubble height from 1997 to 1999 for treatments with a mid-season clip to 2 inches (M2 and EM2). While this

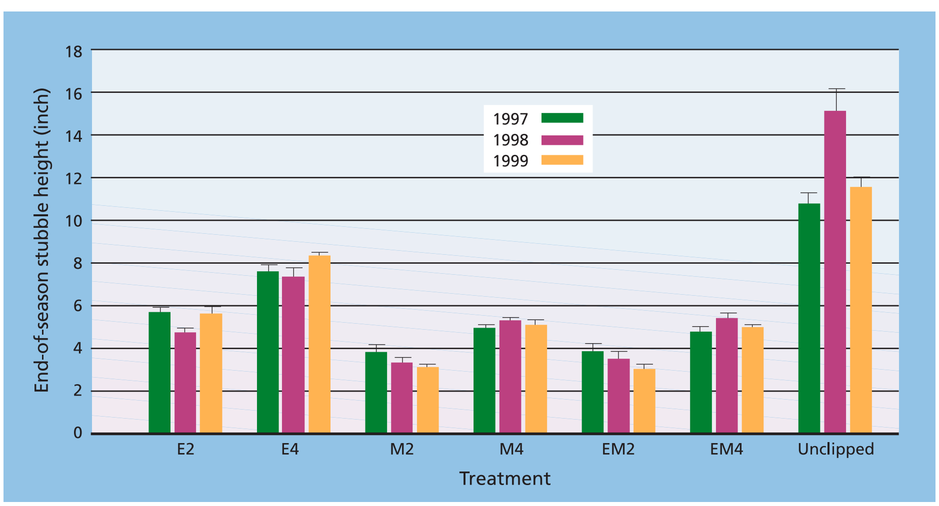

Fig. 2. Mean end-of-season stubble height for seven clipping treatments (E = early-season clip; M = mid-season clip; EM = early- and mid-season clip; 2, 4 or 6 = clip height in inches) applied annually to plots in Clover Valley from 1997 to 1999. Sample size for each treatment per year is four. Results can be compared with stubble height standards for meadows in late seral status (4 inches), in early seral status (6 inches), as well as for great gray owl habitat (12 inches). Error bars represent one standard error of the mean.

trend could indicate a cumulative treatment effect over time, without additional data on seasonal rainfall patterns and total biomass production it is difficult to interpret. For example, more rainfall could have occurred later in the season in 1997 than in 1999.

Left, **Vegetation at the study site was a mixed community composed of sedges, grasses, rushes, native clovers and other forbs.** ***Right,*** **Specialist Tate and advisor Lile hand-clip one of 28, 7-by-12-foot plots. Clipped vegetation was removed from the plot.**

Public land standards

Of particular interest to the grazing operator and public lands manager is how end-of-season stubble height generated by the clipping treatments compares with current public lands stubble height standards. These include standards for meadows in early (4 inches) and late (6 inches) seral status, and for locations inhabited by the great gray owl (12 inches) as established by the US Forest Service (USDA Forest Service 1991, 1992, 2001).

Unclipped plots achieved the 4- and 6-inch stubble height standards in all 3 study years. However, the unclipped plots achieved the 12-inch standard for great gray owl areas only in the 1998 El Niño year. This raises questions about the appropriateness of this particular standard for similar meadows in the region. The 12-inch standard may not be achieved even with the complete removal of livestock. There is a need for continued investigation of stubble height standards by regions and across different site conditions (elevation, moisture regime, soil type, and so on).

Treatment plots with early-season clipping to 2 and 4 inches (E2 and E4) met the 4-inch end-of-season stubble height standard across all years. However, only plots receiving the E4 clipping treatment achieved the 6-inch stubble height standard. In fact, E4 was the only clipping treatment in any year that met the 6-inch standard recommended on low seral meadows (fig. 3). Significant recovery of plant height occurred prior to mid-season (seed set in perennial grasses) in plots clipped in the early season (prior to boot stage in perennial grasses). Little, if any, recovery of plant height occurred during the late growing season on these plots. This indicates that early season grazing benefits the grazing operator by allowing sufficient time prior to seed set for the plant height to recover after grazing.

Clipping treatments that include a mid-season clip to 2 inches (M2 and EM2) did not achieve the 4-inch stubble height standard due to the limited regrowth potential of herbaceous meadow vegetation following seed set. Even during 1998, there was essentially no recovery of stubble height following mid-season clipping. To graze mid-season, the intensity of grazing must not lower plant leaf height below the standard for the site, because very little recovery can be expected following seed set.

The importance of carefully managing mid-season grazing intensity is also illustrated by the results for the mid-season clip to 4 inches (M4) and the early- plus mid-season clip to 4 inches (EM4). Plots receiving these treatments achieved the 4-inch standard, but due to the slight regrowth they experienced after mid-season clipping, they were not able to attain the 6-inch stubble height standard recommended for meadows in early seral stage. In order to meet a 6-inch standard, mid-season grazing must leave 6 inches of stubble height.

Grazing options

While the difference between a 4- and 6-inch end-of-season stubble height standard seems slight on paper, only one clipping scheme tested (early season clip to 4 inches) in this project achieved the 6-inch standard, while four of the schemes tested achieved a 4-inch standard. Using Clover Valley as a case study, the manager has only two options to achieve a 6-inch stubble height standard. One, the manager could prevent livestock from grazing below 6 inches during the mid- to late season, only grazing the pasture in the mid- to late season. Two, the manager could graze to 4 inches in the early season, remove livestock for the remainder of the summer and rely on within-season regrowth to achieve a 6-inch end-of-season stubble height. Under either option, the forage below 6 or 4 inches must be considered unavailable and the livestock carrying capacity of the pasture (available annual forage) recalculated accordingly. The majority of above ground herbaceous plant biomass (forage) is located in the lower 50% of plant height, so stubble

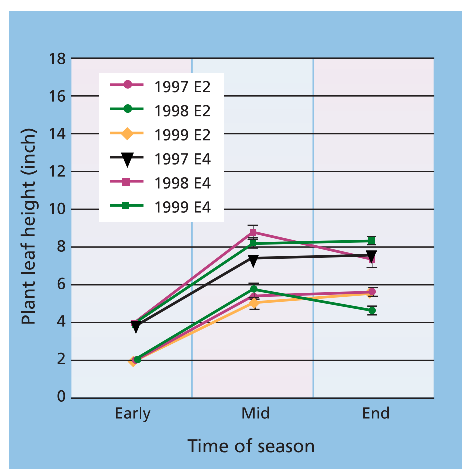

Fig. 3. Mean plant height recovery following early-season clipping treatments to 2 inches (E2) and 4 inches (E4) applied annually to plots in Clover Valley from 1997 to 1999. Sample size for each treatment per year is four. These data illustrate the minimal recovery of plant height that occurs following mid-season. Error bars represent one standard error of the mean.

STUBBLE HEIGHT — continued from page 63

height standards that exclude this forage significantly reduce available annual forage.

While early season grazing appears to provide the best chance of achieving stubble height standards while using the most available forage, this grazing scheme could have negative effects on soils and stream banks because of wet conditions and the composition of plant species in the early growth stage of the plant at defoliation. Potentially, the negative impacts of early season grazing designed to achieve a set stubble height standard might exceed the negative effects of other grazing schemes that do not achieve the stubble height standard. Where early season grazing is the only option to achieve standards, restrictions on early season grazing (such as a grazing permit start date of mid-July) would essentially make little or no forage available to the grazing manager, and almost assure noncompliance with grazing permit requirements.

Given the limitations that stubble height standards impose on the grazing options available to managers, it is important to note that stubble height standards are an annual grazing management tool designed to achieve general riparian resource protection, not a long-term management goal (Clary and Leininger 2000). If one of the intentions of stubble height standards is to allow grazing to continue in an economically and ecologically sustainable manner, significant research and revision of these standards seems warranted. The direct links between herbaceous stubble height and specific riparian resource goals are not clearly illustrated in the published scientific literature, indicating the need for long-term research on the relationship between annual stubble height standards and the condition and trend of riparian systems. The significant effect of annual weather patterns on plant leaf height in the absence of defoliation should also be factored into the annual application of stubble height standards on these dynamic meadow systems.

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COMINGUP

Wine and cheese

California's wine drinkers and cheese lovers are going upscale: In the last 10 years wine drinkers have increasingly favored premium wines by reaching for bottles priced $7 and over rather than the $3-a-bottle jug wines. At the same time, diners in fine restaurants are being treated to dishes prepared with specialty cheeses and courses featuring simply cheese — artisan and handmade. In the next issue of *California Agriculture*, UC scientists examine trends in the state's wine consumption and the factors that prompt Californians to purchase artisan cheese.

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