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May 31, 2016

Ms. Jeanine Townsend
Clerk to the Board
State Water Resources Control Board
1001 I Street, 24th Floor [95814]
P.O. Box 100
Sacramento, CA 95812-0100

VIA (email) commentletters@waterboards.ca.gov

SUBJECT: Comments on File 2239 (a)-(c) (Eastern San Joaquin Ag Petitions)

Ladies and Gentlemen:

Please consider the enclosed comments from the Water Programs at Fresno State on the subject draft Order.

Sincerely,

David Zoldoske

David Zoldoske
Executive Director

Attachment: Testimony and references

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Testimony of David Zoldoske*

At the

May 17, 2016 Public Workshop

On the

Review of a Proposed State Water Resources Control Board Order

For

Growers within the Eastern San Joaquin Water Quality Coalition

SWRCB/OCC Files A 2239(a)-(c)

Ladies and Gentlemen;

We offer the following testimony on the proposed Order.

Background

California State University, Fresno operates several water management entities and programs including the Center for Irrigation Technology (CIT) and the California Water Institute (CWI). Our entities and programs all have the same goal; supporting the proper use and management of water and better understanding its impacts. We assist in achieving that goal through targeted education, research and implementation strategies. The Center for Irrigation Technology, which has been active for over 35 years, is focused on agricultural water use efficiency and use impacts while the California Water Institute adds analysis and support on water policy and water quality issues. We believe we have significant experience in the matters before you today and appreciate the opportunity to offer our thoughts on both the technical and policy aspects of the proposed General Order (Order) for the Eastern San Joaquin Water Quality Coalition third-party group members.

Review of the Proposed Order

Our review is based on answering two critical questions. The first is, does implementation of the proposed Order additions/changes to the Central Valley Region (CVR) version substantially improve the process of attaining the regulatory goal of either protecting or improving surface or groundwater quality? The second is whether the proposal is consistent with implementation strategies of other equivalent water quality control programs? Our answer to both questions is NO. The following comments include both the technical and policy issues that would make it difficult for us to assist agriculture in meeting the goals the Order was designed to accomplish.

As to the first question of "improving regulatory goals" we offer the following.

The principal critical issue not addressed adequately by the proposal is that ***water*** is the core element for success or failure of any irrigated lands water quality control implementation strategy. Water management is, or should be, the goal of the program as well as the physical driver and source of impacts. While the language in the reasoning for the proposed Order acknowledges advice from an agricultural expert panel that water use and management is part and parcel of the impact assessment process, the narrative fails to recognize that managing the water cycle on irrigated lands is the predominant mechanism for success or failure of the program. Our findings are based on that premise and further analyzed below.

1. Technical issues.

    a. *Water is the solvent, nitrogen is a potential solute, one of several of potential concern, such as salts or pesticides*. Understanding water management and water pathways will provide a more efficient process of understanding the threat of any materials of concern, including nitrogen. The proposed Order amendments go into substantial detail to justify using a nitrogen budget approach as the analog for an assessment and/or compliance tool. The Order does add *irrigation* as a component of the assessment process but the relative importance of this irrigation is not adequately articulated or sufficiently emphasized. Without understanding the relationship with water movement, the information gathering additions (A/R and certified INMP) in the proposed Order have potential for failure. The INMP includes irrigation but does not address it further. The impact of irrigation uniformity, soil health and scheduling is key to nutrient management success. Regardless of the materials of concern, the location of an irrigated area or the management practices of the land operators, the driver for potential impact from water use to other water bodies is water itself. That consideration has to be the focus of any program designed to control the impacts of irrigated agriculture on the water quality of receiving waters.

    b. *A/R*. The proposal uses the "applied minus removed" (A/R) nitrogen budget as a potential reporting mechanism and threat evaluation for farm compliance in the draft Order. A/R is much more complicated than the proposed Order portrays. The R portion in particular has many complications. R is not only what the crop removes but also includes denitrification, gasification and complex sequestration and release components (Rosenstock et al, UCANR 2013).

        Denitrification involves microbial conversion of soluble nitrogen species in the soil/water complex to nitrogen gas. Ammonia gas (gasification) can be directly released to the atmosphere in unsaturated soil zones. These two loss rates are soil physical condition-specific but common in varying degrees in all irrigated soils.

        Also, carbon condition and sequestration were hinted at in the narrative for the proposal but not sufficiently explained as to the importance and impacts on annual nitrogen budgets and availability of soluble nitrogen forms for runoff or deep percolation. The technical issue is the ratio of carbon to nitrogen. When the carbon to nitrogen (C/N) ratio is higher than approximately 25:1, the nitrogen is substantially held in the carbon matrix; when lower than 25:1 the nitrogen is released slowly to more rapidly as the ratio decreases. If more carbon is added (crop stubble, stems and pieces from woody material, etc.) nitrogen again becomes sequestered and while measurable in laboratory testing, not mobile.

Carbon in the agricultural environment is microbially oxidized quickly in high temperatures. Microbial activity is an indicator of soil health. One of the most effective methods of improving microbial activity is through a consistent program of organic matter additions to elevate the carbon content of the soil. Thus soil health must be a consideration for nitrogen management. High summer temperatures combined with moist soil and a source of carbon provide the perfect environment for microbial activity and nitrogen accelerates the oxidation process. Proper soil carbon levels will serve to maintain soil nitrogen in a sequestered state. The process of nitrogen release from sequestration is known as the "decay series process" and has been developed into a computer model (NLEAP, Shaffer et al, USDA, 2001). The annual accounting or measurement of these complicated conditions is difficult, making the A/R process an academic or scientific endeavor beyond the scope of most land operators. This is acutely true with the 21,000 growers farming on 60 acres or less.

The availability of nitrogen as a threat is different for surface water and groundwater. Current fertilizer formulations are designed to be fairly soluble making land slope, infiltration rates and runoff key factors impacting surface waters. In the case of the groundwater, the nitrogen discharge begins when nitrogen gets below the active root zone of plants, but as stated previously, the *water flow and transport conditions* are paramount in determining the actual impacts. Nitrogen below the root zone may still have an opportunity to be reduced (denitrified) and mitigated as a matter of the rate of transport (vertical permeability) and additional microbial activity in the vadose zone or next zone of saturation which may or may not be usable groundwater. In contrast, salts are the most conservative of the solutes in deep percolation and are the more consistent analog for potential impacts to the receiving groundwater. Interestingly, <u>CV SALTS participants, the salt and nutrient transport, management and policy development program of the Central Valley Region, apparently had not been consulted in this proposed Order</u>. CV Salts is developing the strategies that could assist with understanding fate and transport of materials in the Region, including the area of the proposed General Order. Once again, water is the driver, not the materials themselves. Transport and fate are the determining factors for truly regulating the threat. In areas of low vertical permeability, the rate of transport is so slow that it would likely take thousands of years for the most conservative materials to reach usable groundwater. What use is the A/R reporting in such areas? This point brings our analysis to an additional goal of the original CVR order, vulnerability assessment.

c. *Vulnerability assessment is still an important control program tool.* Vulnerability may be a poor choice of words because as noted above, <u>any</u> land area under irrigation may alter the conditions of receiving water bodies. No one wants to have their land and the associated natural resources labeled as “vulnerable”. However, once again, discharges and water quality impacts from irrigated lands have significant differences in time scale. Irrigated land discharges to surface water may have immediate consequences. Discharges to groundwater have differences of impacts from months to thousands of years with complex interactions along the way (e.g. denitrification). The point is there are opportunities to regulate the activities in a way that emphasizes the highest water quality protection value for the regulatory investment. The program implementation strategy would benefit by describing a “prioritization” process rather than “vulnerability”. The Order reports that the agricultural expert panel rejected risk categorization for groundwater requirements and that all irrigated lands should have groundwater protection requirements. While this has validity, we believe the intent was that all areas should have some reporting of the activities on irrigated areas, but not necessarily the level suggested by the proposed Order. Since the expert panel left open the concept of prioritization we believe there is sufficient evidence that prioritization should be used.

First and foremost, most of the CVR Coalitions, including the ESJ Coalition, have already performed groundwater assessment reports (GAR) that describe the conditions that assist with understanding irrigation return flow fate and transport to groundwater. When coupled with water use information, we believe a fair priority system of regulatory reporting could be developed. Once prioritization of regulatory action is in place, the monitoring and compliance programs can be appropriately scaled to the conditions related to the priority. In addition to the existing GAR there are other existing tools that can assist with prioritization. For example was the Department of Pesticide Regulation consulted on how they developed their groundwater protection strategy (Troiano et al, Final Report to US EPA)? Also, consideration should be given to the recent presentation by UCANR called SAGBI (O’Geen et al, UCANR California Agriculture, 2015). SAGBI is a groundwater recharge rating index based on soils, subsurface geology and crops. The index rates the potential for targeted recharge of water to improve groundwater conditions, potentially including quality. The index could be used equally as a prioritization process where recharge is considered for protection or restoration of groundwater quality. Prioritization needs to be developed in an open process with the regulated community and interested parties so meaningful improvements in water quality can be envisioned by all concerned.

d. *Water sampling at each farm well location.* The proposal to require well sampling of every on-farm well supplying drinking water does not appear to be of value. Groundwater moves both laterally and vertically, therefore the sampling of an on-site farm well may not reflect the overlying surface activities. There are other programs that are charged with systematically sampling and characterizing such groundwater conditions including the USGS GAMA program of which the Board system is affiliated, the Board’s own Division of Drinking Water and SGMA. SGMA in particular will likely provide a much more relevant program of representative monitoring that can be used to characterize groundwater conditions. Putting such a sampling burden on farms that have no impact or control over confined groundwater conditions lacks foundation. The Order discharge compliance point should be below the root zone and as described above in many instances may involve extremely long time frames to alter deep groundwater quality. Additionally, this NEW data may bring the unintentional consequences of legal actions which will divert limited resources and not help achieve stated goals.

Well testing and the provision of safe water supplies must be addressed holistically (including other contaminants) if the problem of providing safe water to disadvantaged communities is to be resolved. The Governor's Stakeholder Drinking Water Group successfully addressed a number of statewide drinking water issues but did not address either the institutional or financial issues associated with providing safe drinking water to disadvantaged <u>rural</u> communities. Elsewhere in the United States collective regional and centrally managed rural water systems have been successfully established. To the best of our knowledge we have not investigated this approach for providing safe water to disadvantaged rural communities and, instead, we invest considerable amounts of funds into small communities that cannot support the drinking water systems that are provided. A good example of this is Lanare, a small community in Fresno County. A number of years ago Lanare received a considerable sum of funds to construct a water treatment plant to remove arsenic from their groundwater source but the treatment plant was out of operation in a few months because of the inability of the community to financially support the plant operation . We need to seriously work towards developing a holistic strategy for solving the drinking water problems these small rural communities face.

e. *Integration opportunities abound.* A singular focus on any component involved in the multiple activities of crop production precludes the opportunity for maximum benefits. For example, a strategic combination of crop, nutrient, salt and water management actions can result in significant energy and greenhouse gas savings. Nutrient management using less fertilizer results in less gasification (ammonia release) or deep percolation. Water management can decrease the amount of energy demands for pumping and/or pressurization. Minimization of deep percolation can reduce the energy costs of treatment of drinking water for nitrates, salts or other soluble materials. Ultimately these activities decrease production costs and result in better margins for operators.

2. Policy Issues

   a. The proposed Order would benefit from a combined approach. As previously noted there are a number of programs in place or anticipated that propose to accomplish many of the same goals of the Order in nitrogen management or groundwater protection. These efforts need to be integrated to avoid duplication, conflict and costs. Programs include the DPR groundwater protection program, CDFA FREP, DDW drinking water system monitoring, SGMA "undesirable results" avoidance, IRWMP and CASGEM.

A coordinated working group with the irrigated lands program would be an appropriate method to make sure programs are not asking for the same things from the same people in agricultural settings.

b. The Order recognized that an economic evaluation under W.C. Section 13141 was done for the ESJ Coalition and other Central Valley Coalitions. However, based on the findings and conclusions in the Order for the Central Coast irrigated lands program that no such additional evaluation was needed since it was a permit, not a basin plan element. This seems to contradict language in the document where the narrative proposes that the Order is a "precedent" (pg. 8 of the Order) for all succeeding orders including for all Regions that do not currently have an irrigated lands program. We believe that Section 13141 does need compliance for the <u>difference</u> between the costs of the ESJ CVR Order and the new proposal, including a full economic analysis of the costs for the overall program. This should apply for any Region that does not have an irrigated lands Order, which means additional information is required in their basin plan.

   We believe the State Board staff's recommendation to not conduct the economic analyses misses the legislative intent of this section of code. One of the original purposes of the cost analysis and inclusion of the report in the California Water Plan was to assist the agricultural industry with the opportunity to utilize the loan capability of the California Pollution Control Financing Authority (CPCFA). Without the costs quantified and Water Plan inclusion, the Authority would not have sufficient information to develop the bond expenditure findings needed to authorize bond sales. Funding the agricultural industry's water quality control investments using the Financing Authority's low-interest loans is important. Other industries, from energy companies to food processors and dairies, have had access to capital through that Authority (see attached recent CPCFA expenditure report) to make the necessary improvements to meet water quality control program goals. Public entities have access to loans <u>and grants</u> as well. Irrigated agriculture should have the same opportunity. The State Water Board must direct the necessary economic analysis to capture the impact of the costs for compliance that can then be utilized for authorizing bond sales by the Authority. Failure to do so could be seen as discriminatory, put an undue burden on irrigated agriculture and not in the State's best interest. The loans are another tool to accelerate compliance and are paid back to the State so there is no cost to the taxpayer.

As to the second question, what effect will this proposal have on comparative water quality control programs?

We all have to be mindful of precedents and impacts on other activities of a similar nature and whether the precedent meets the test of reasonableness when applied elsewhere. Several activities come to mind in the realm of water quality control programs. One is septic tanks and allied water wells on rural properties. Will the proposed Order create the need to ask all septic tank owners to monitor their releases and sample their own wells? The second is storm water control. Will storm water collection, storage and associated groundwater recharge facilities that potentially impact groundwater quality need to sample private water supply wells at or near the storage site? Third, should all petroleum product storage and delivery systems be required to test private water supply wells at or near their location? The point is that intelligent representative monitoring at or near the actual likely release of materials of concern is relied upon and a common thread among many water quality control programs, not strictly on- or near-site water supply wells. It should remain so for this proposed Order as well.

Our Contribution Going Forward

We propose to assist irrigated agriculture to further improve practices and to demonstrate responsible stewardship of our water resources. The water quality problem the Order proposes to address is 60 or more years in the making, so any notion that it can be resolved immediately does not reflect reality. As stated earlier, the proposed Order needs to take a holistic approach to problem solving by integrating all the varying and sometimes conflicting regulatory programs and to focus on agricultural water use efficiency. We believe that estimating crop nitrogen requirements and improving on-farm water use efficiency are simply two halves of the same coin. Done properly, this should continue to reverse the historical negative impacts on surface and groundwater quality. We don't believe the investments and costs of collecting nitrogen conditions in soil/water data that ends up in the public domain will achieve any of the stated water quality goals.

The below activities support our emphasis on a more integrated approach by including a significant investment in basic water management tools and conditions that we believe can assist in appropriately managing potential discharges to surface and groundwater:

1. Promote the California Healthy Soils Program – healthy soil with proper carbon sequestration improves water holding capacity and improves nutrient uptake.
2. Water management activities (with verification) including but not limited to:
    a. Water measurement is critical to monitoring the health of irrigation systems and documenting good water management practices
    b. Proper timing and amount of applied water
    c. High distribution uniformity (DU) of the irrigation system
    d. Knowledge of root zone depth and water movement
    e. Soil moisture and where possible, nutrient measurement
3. Monitoring representative soil nitrogen below the root zone may be a viable addition to the A/R process. Real-time environmental monitoring technology is getting better and cheaper all the time. Getting feedback on actual water/nutrient movement will provide a valuable tool for farm managers to adjust management practices.
4. Educate, educate and educate some more. On-line and E-learning strategies provide for easy and powerful tools to advance and demonstrate mastery of complex irrigation system management. Programs which provide basic understanding of water and nutrient management would provide an important resource in achieving Order goals. Knowledge can be quantified by on-line certification. Demonstrating agriculture's commitment and professionalism in water management would send a strong message to the Legislature and all Californians that agriculture is a responsible steward of our finite water resources.

Conclusions

Given the focus of this hearing on methods to mitigate nitrates found in the groundwater and the new SGMA legislation, I believe recognizing that we have to contend with both the irrigated lands program and SGMA, leads us to a common path forward. Demonstrating proper nitrogen budgets with high water use efficiency will address both issues.

1) Water measurement is “key” to improved water management, and should be used as a common practice in irrigated agriculture.

2) A demonstrated knowledge of maintaining irrigation system performance and determining the proper timing and amounts of irrigation events is critical to protecting groundwater quality.

Step 1 activities and funding

1) The State of California should be strategic in providing funds for improving water/energy use efficiency. Given the impending SGMA regulations, targeted funding for groundwater measurement, evaluating distribution uniformity and a good working knowledge of the science behind the timing and amount of applied water will improve groundwater and runoff quality. This will also potentially lead to greenhouse gas reductions.

2) A proposed on-line “E-learning” program that will provide for training and demonstration of basic technical knowledge through a qualifying exam.

3) Providing basic water measurement and educational programs to operate irrigation systems efficiently will assist in meeting both SGMA goals and water quality objectives.

References attached:

1. Rosenstock et al - Nitrogen Fertilizer use in Calfornia: Assessing the data, trends and a way forward, California Agriculture, Volume 67, Number 1, 2013.
2. Troiano et al – Profiling Areas Vulnerable to Ground Water Contamination by Pesticides in California, CALEPA – DPR.
3. Shaffer et al – Simulation Processes for the Nitrogen Loss and Environmental Assessment Package, USDA ARS, 2001.
4. O’Geen et al – Soil suitability index identifies potential areas for groundwater banking on agricultural lands, California Agriculture, April-June 2015.
5. California Pollution Control Financing Authority, 2014 Annual Report to the California State Legislature.

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RESEARCH ARTICLE

Nitrogen fertilizer use in California: Assessing the data, trends and a way forward

by Todd S. Rosenstock, Daniel Liptzin, Johan Six *and* Thomas P. Tomich

Jack Kelly Clark, UC Statewide IPM Program

Tractor operator applies fertilizer to cole crop plants near Pigeon Point Lighthouse, San Mateo County. Nitrogen fertilizer is an essential resource for agriculture, but its overuse can threaten human health and the environment.

Nitrogen fertilizer is an indispensable input to modern agriculture, but it also has been linked to environmental degradation and human health concerns. Recognition of these trade-offs has spurred debate over its use. However, data limitations and misinformation often constrain discussion, cooperative action and the development of solutions. To help inform the dialogue, we (1) evaluate existing data on nitrogen use, (2) estimate typical nitrogen fertilization rates for common crops, (3) analyze historical trends in nitrogen use, (4) compare typical nitrogen use to research-established guidelines and (5) identify cropping systems that have significant influence on the state's nitrogen cycle. We conclude that a comprehensive grower self-monitoring system for nitrogen applications is required to improve nitrogen-use information and to better support evidence-based decision making. The discussion here presents a primer on the debate over nitrogen fertilizer use in California agriculture.

Nitrogen fertilizer is an essential resource for agriculture, and its use has undoubtedly benefited California and its citizens. However, overuse of nitrogen fertilizer threatens the health of the state's agricultural, human and natural resources. On the one hand, nitrogen is necessary for crop growth and development, and thus nitrogen fertilizer use supports California's robust agricultural economy and rural society. On the other hand, applying nitrogen in excess has been linked to water and air pollution, depletion of the ozone layer, climate change and numerous human health concerns (Galloway et al. 2003; Millennium Ecosystem Assessment 2005).

The trade-offs that nitrogen fertilizer use present to society have been documented in California for more than 50 years (Harding et al. 1963; Proebsting 1948). It is worth noting that fertilizer is just one way humans add reactive nitrogen into the environment, and other activities such as fossil fuel combustion and waste discharge contribute to the aforementioned concerns. However, a forthcoming report indicates that inorganic nitrogen fertilizer use is responsible for the largest fraction, by far, of new nitrogen introduced into California's environment each year (Liptzin and Dahlgren, unpublished data).

The amount of inorganic (chemical) nitrogen fertilizer sold in California has risen dramatically over the past 70 years (fig. 1). By the 1970s, nitrogen fertilizer sales — and presumably use — exceeded 400,000 tons of nitrogen contained in inorganic fertilizer per year, and in the subsequent decade sales grew more than 25% to more than 500,000 tons of nitrogen per year. Between 1980 and 2001, the average amount of nitrogen sold per year was no longer increasing significantly, but annual sales have surpassed 600,000 tons of nitrogen in some years. Large upward trends in fertilizer sales in the last half of the twentieth century are not

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.E.v067n01p68&fulltext=yes

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unique to California; similar increases are evident throughout the developed world (Millennium Ecosystem Assessment 2005). As nitrogen fertilizer use has expanded, so has the evidence documenting the negative consequences of reactive nitrogen on human health and the environment (Davidson et al. 2012; Townsend et al. 2003).

Today, nitrogen in general and nitrogen fertilizer use specifically both figure prominently in regulatory discourse. Federal and state agencies tasked with protecting air and water quality as well as with mitigating climate change are evaluating the causes, consequences and costs of agricultural nitrogen use. Examples of this concern in California include the UC Center for Watershed Sciences' report to the California Legislature on nitrate in drinking water, the Central Coast Regional Water Quality Control Board's (RWQCB) renewal process for the Irrigated Agricultural Lands Waiver, the Climate Action Reserve's nitrogen fertilizer reduction protocol, the Central Valley RWQCB's Irrigated Lands Regulatory Program, the Central Valley SALTS program and the Central Valley RWQCB's General Order for Dairy Waste Dischargers. The latter, for instance, regulates nitrogen fertilizer application on croplands associated with dairies, constraining its use.

It is important that credible and comprehensive scientific information on nitrogen use be available to support evidence-based policy-making. Without information based on sound science, nitrogen policies may be poorly prescribed, ineffective, cause unintended consequences or even be counterproductive. Stakeholders recognize this and have identified the need for more information

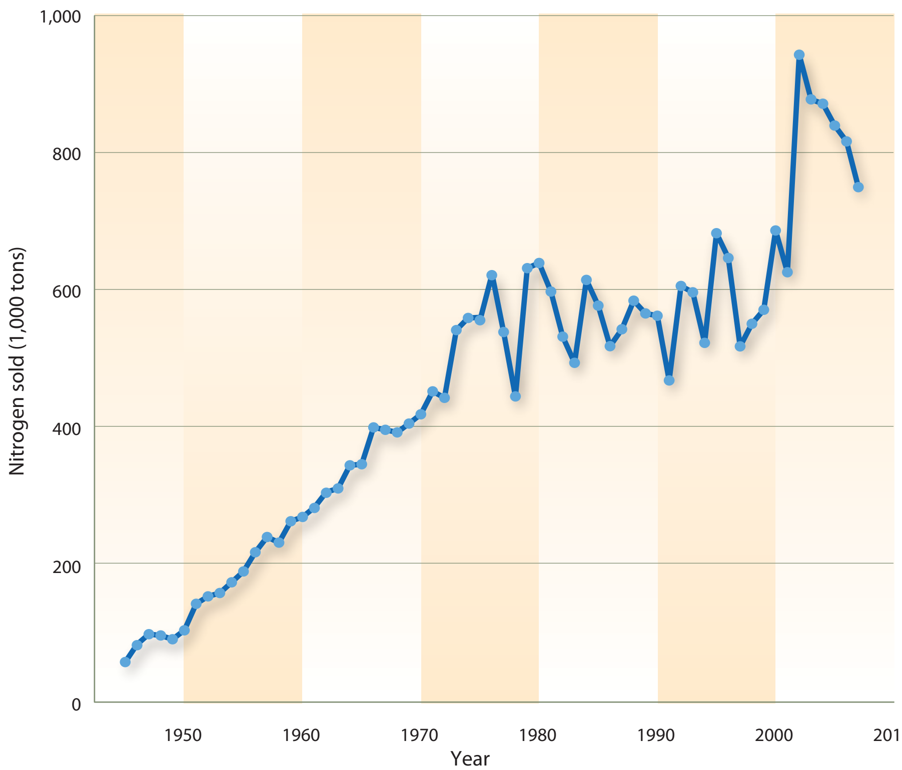


Fig. 1. Statewide sales of nitrogen fertilizer, 1945–2008. Because there is no explanation for the 50% rise in sales from 2001 to 2002, the largest 1-year change since estimates began, there is reason to question the accuracy of data since 2001. Source: California Department of Food and Agriculture.

Background and scope of this article

This article reports research from one part of the California Nitrogen Assessment (see sidebar page 70). Assessments are an increasingly common method scientists use to analyze existing data sets and gain a big-picture view of what is known and what is scientifically uncertain.

The best example of an assessment is the global effort that led to reports by the Intergovernmental Panel on Climate Change (Ash et al. 2010; IPCC 2007; MA 2005). Recently, the Integrated Nitrogen Committee published an assessment of nitrogen in the United States (Integrated Nitrogen Committee 2011).

Here the authors assess existing knowledge on inorganic nitrogen fertilizer flows, practice and policy in California agriculture — knowledge that has only now been integrated and analyzed as a whole. They examine how statistics are generated, identify sources of uncertainty and compare and interpret data.

Scope. The research scope is limited to inorganic nitrogen fertilizer. Dairy manure, for instance, is not considered, although it is a high priority for attention by scientists and policymakers — and is included in the larger California Nitrogen Assessment (http://nitrogen.ucdavis.edu). Dairy manure application adds about 200,000 tons of nitrogen to California soil per year, an amount equivalent to more than one-third of the annual inorganic nitrogen sold in recent years, and it is applied to a relatively small number of forage crops.

Limits. The authors examine soil nitrogen cycling processes, which include exchanges of nitrogen between the soil and either air or water. However, the discussion is intentionally general; it does not capture nitrogen transformation or emissions under various soil, crop and water management conditions. Further analysis and experiments are needed to draw conclusions regarding the fate of nitrogen in specific fertilized and irrigated systems.

Stakeholder questions addressed. This article addresses stakeholder questions about nitrogen management practices in cropping systems. It presents the best available information that applies to these questions: How is nitrogen fertilizer currently being used? What are the current nitrogen rate recommendations? Are those recommendations adequate for present-day cropping conditions?

More information on the stakeholder process can be found at http://nitrogen.ucdavis.edu. — *Editor* on inorganic nitrogen fertilizer use as a high priority task (http://nitrogen.ucdavis.edu).

Accurate data on nitrogen fertilizer use are difficult to come by, however. Either nitrogen fertilizer use is simply not tracked at relevant scales, as is most often the case, or the data sources are inconsistent (see discussion of grower and expert surveys below). Despite the fact that this data scarcity makes current estimates of nitrogen fertilizer use uncertain, the estimates still serve as an input to policy discussions. For example, the Intergovernmental Panel on Climate Change (IPCC) suggests that estimated application of nitrogen fertilizer to cropland is a key parameter to use in approximating cropland emissions of nitrous oxide, a potent greenhouse gas.

Because of the relationships among fertilizer use, crop yields, resource degradation and the current policy environment in California, information on nitrogen use is in high demand now and will become of even greater importance as policies are developed in the future. The objective of this research is to assess the available information on nitrogen use in California by (1) identifying data sources and their limitations, (2) establishing average nitrogen application rates by crop, (3) determining historical trends in nitrogen use (within the context of changes in crop yield) and (4) comparing how average nitrogen application rates articulate with nitrogen rate guidelines. We go on to show that these results identify crops that have significant influence on nitrogen use, and we suggest this information can then be used to set priorities for research, outreach or policy. This evaluation of the current state of knowledge on nitrogen fertilizer use is part of a broader assessment of nitrogen in California, the California Nitrogen Assessment (see box below).

Without information based on sound science, nitrogen policies may be poorly prescribed, ineffective, cause unintended consequences or even be counterproductive.

Scientific assessments, such as the California Nitrogen Assessment, have become a common method scientists use to inform policymakers on complex social and environmental issues. Instead of generating new research, these assessments analyze existing bodies of research, data and models. Assessments generate insights through the synthesis and integration of available information from multiple scientific disciplines to distinguish that which is known and well established from that which is unknown and scientifically uncertain. Assessments piece together the best available information to inform discussions, systematically calling out uncertainty. The assessment of nitrogen fertilizer use reported here relied on standard assessment methods, such as engaging stakeholders to frame the scientific question, aggregating available information and identifying sources of uncertainty (Ash et al. 2010).

The nitrogen cycle

There are no easy solutions to managing the trade-offs associated with agricultural nitrogen; this is due to (1) the complexity of the nitrogen cycle in general (fig. 2) and (2) the mobility and diversity of soil nitrogen compounds in particular. The vast majority of nitrogen in soils is in soil organic matter and hence does not pose an immediate threat to the environment or humans. This soil organic matter serves as a nitrogen reservoir, and each year a fraction of this nitrogen is mineralized to ammonium. Soil microbes can then turn ammonium into nitrate via

What is the California Nitrogen Assessment?

The California Nitrogen Assessment (CNA) is a comprehensive effort to examine existing knowledge on nitrogen science, policy and practice in California. Researchers have collected and synthesized a large body of data to analyze patterns and trends in nitrogen inputs, outputs and storage throughout the state. The aim is to more effectively link science with action, and inform policy and field-level practice.

The CNA includes:

- Identification of underlying drivers (e.g., regulations, population growth) and direct drivers (e.g., fertilizer use, soil management and fuel combustion) that affect stocks and flows of nitrogen in California agriculture.
- Calculation of a mass balance to examine how nitrogen moves through California agroecosystems and the state as a whole (including agriculture, sewage, industry and transportation).
- Evaluation of the state of knowledge about nitrogen's impacts on ecosystem health and human well-being.
- A suite of practices and policy options and the potential effects each would have on agriculture, the environment and human health.
- Communications to help the public understand the nitrogen cycle and to help decision makers at the farm and public policy levels.

The CNA is a project of the Agricultural Sustainability Institute at UC Davis and the UC Sustainable Agriculture Research and Education Program.

For more information:

General information on California Nitrogen Assessment (CNA)
http://nitrogen.ucdavis.edu

Basics of nitrogen biogeochemistry and the CNA's mass balance
http://nitrogen.ucdavis.edu/research/nitrogen/n-science/n-biogeochemistry

Information on stakeholder involvement, review and questions
http://nitrogen.ucdavis.edu/research/nitrogen/n-stakeholders/nitrogen-stakeholders

Major funding for the California Nitrogen Assessment is provided by a grant from the David and Lucile Packard Foundation. Work on the assessment began in January 2009 and will continue through 2013. Institutional partners are the UC Agricultural Issues Center and the Kearney Foundation of Soil Science. — *Editors*

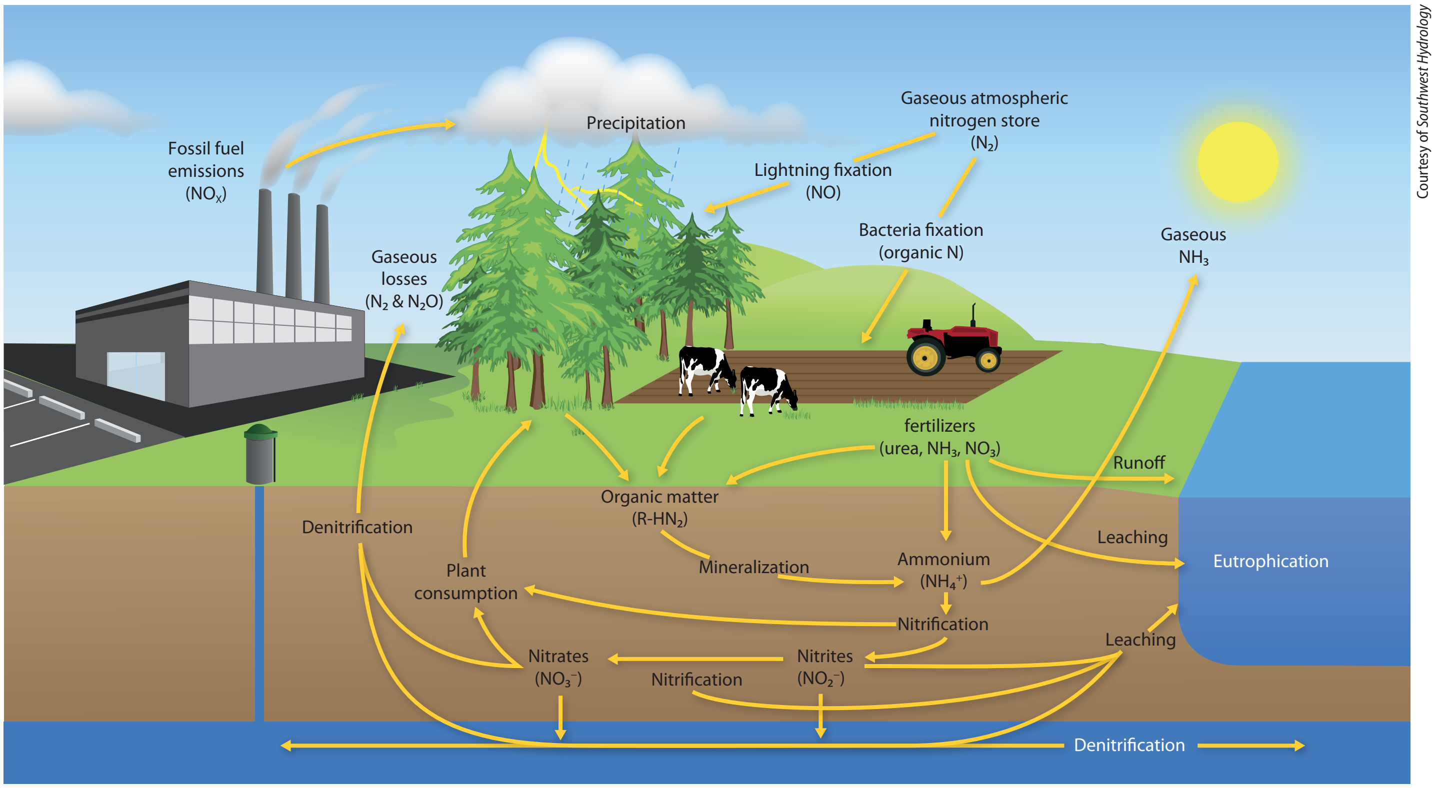


Fig. 2. The nitrogen cycle. Nitrogen in the environment is mobile and readily transformed into various compounds by physical, chemical and biological processes. Arrows indicate major nitrogen-cycling processes, which continuously produce diverse nitrogen compounds in the environment.

Glossary: Nitrogen in soils

Nitrogen may enter the soil through rainfall, lightning, nitrogen fixation by soil organisms, plant and animal decomposition, or manures and commercial fertilizers. It may be lost by plant removal, volatilization, leaching or erosion. It transforms continuously in soil, air and water.

Ammonification (mineralization): During decomposition of plant or animal material, specialized soil bacteria transform nitrogen to ammonia (NH_3) or ammonium (NH_4^+); the latter is useful to plants.

Ammonium (NH_4^+): This form of nitrogen can be used by plants, or converted to nitrate by bacteria (and then taken up by plants). It is a positively charged ion (cation), attracted to negatively charged soil clay. For this reason, it is not leached to a great extent.

Denitrification: In this anaerobic process, other specialized bacteria change nitrate back to nitrogen gas, reducing pollution of groundwater but increasing nitrogen oxides in the air. Denitrification occurs only when oxygen is low, such as during flooding and in clay soils. Because most California soils are coarse and weldrained, denitrification occurs less often, and soils are more vulnerable to nitrate contamination of water supplies by leaching.

Nitrification, nitrite (NO_2^-) and nitrate (NO_3^-): Specialized bacteria change ammonia to nitrite, and still others change nitrite to nitrate. Both processes are nitrification, and they are aerobic, occuring only when oxygen is present. Nitrate is the principal form of nitrogen used by plants. Because it is negatively charged (an anion) and is not attracted to soil clay, it leaches easily and is a water pollutant. Nitrate-enriched groundwater can also contribute to algal blooms in streams, although most such blooms result from nitrogen- and phosphorus-enriched surface runoff.

Nitrogen gas (N_2): Dinitrogen gas occurs when two nitrogen atoms form a very strong trivalent chemical bond; it comprises 78% of the atmosphere. Although largely inert, nitrogen gas can be "fixed" into biologically useful forms in the soil (see first paragraph).

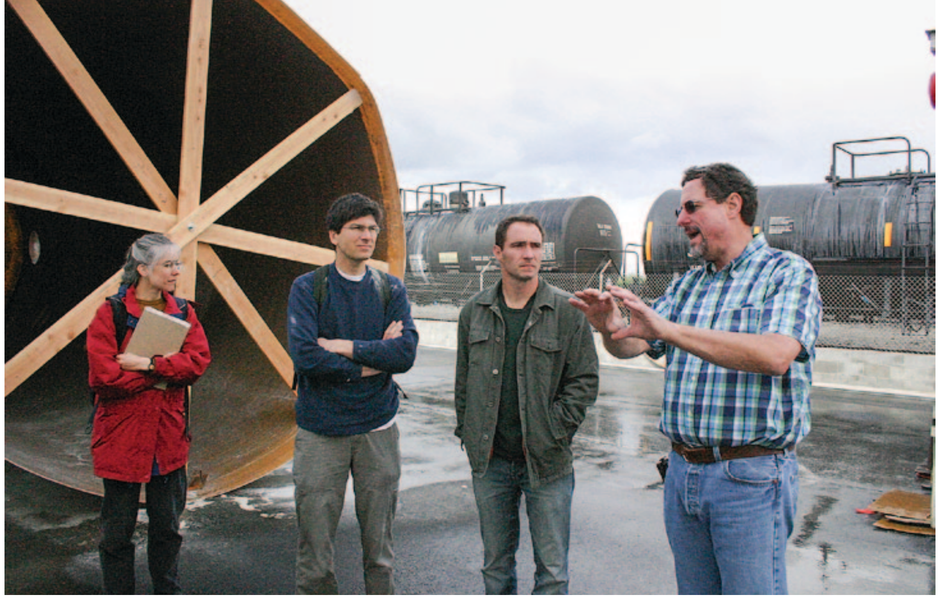
Nitrogen loss (leaching, erosion): Nitrogen losses from the soil system occur by plant removal, denitrification, leaching, volatilization and erosion. Plant removal by crops is fertilization. Erosion and leaching can contribute to ground and surface water pollution.

Nitrogen, organic (nitrogen in living or once-living things): "Organic nitrogen" originated in living material and is still part of a carbon-chain complex. It can enter soil as decomposed plant or animal tissue. It is not available to plants until microorganisms transform it to ammonium (NH_4^+).

Nitrogen, reactive: Reactive nitrogen is all nitrogen other than dinitrogen gas (N_2).

Volatilization: Soil microorganisms convert ammonium nitrogen to ammonia gas in soils with a high pH, that is a pH greater than 7.5. Such soils are not common in California.

Glossary sources include an article by Thomas Harter in the July/August 2009 Southwest Hydrology.— Janet White



Colin Bishop

Sonja Brodt, Daniel Liptzin and Todd Rosenstock learn about fertilizer production from Ken Johnson of TSI Fertilizer Manufacturing in Dixon. Large upward trends in fertilizer sales in the last half of the twentieth century are evident throughout the developed world.

the process of nitrification. Both forms of nitrogen, ammonium and nitrate, are available for plant uptake. Mineralization supplies as much as half or more of the nitrogen to crops (Gardner and Drinkwater 2009). The reverse process (immobilization) entails the integration of the inorganic nitrogen produced by mineralization into the living biomass of plants and microbes.

Nitrogen compounds can also be released from the crop root zone through multiple processes. Leaching relates to the physical movement of nitrate downward through the soil profile. Volatilization is a physiochemical process that emits gaseous ammonia. Denitrification is a microbial-mediated release of inert dinitrogen gas and potentially nitrogen oxides including nitrous oxide. It is the emission of these nitrogen compounds that threatens the health of California's environment and human population.

The rate at which nitrogen cycling occurs in soils is a function of a multitude of abiotic (precipitation and temperature), biotic (microbial communities) and human-mediated (such as tillage and nitrogen fertilizer application rate) factors.

Fertilizer and excess nitrogen

Adding inorganic nitrogen fertilizer to soil promotes high plant productivity and long-term soil fertility (Ladha et al. 2011), but this can also cause large surpluses of nitrogen in the environment. This excess nitrogen can lead to environmental degradation by percolation (leaching) through the root zone and into groundwater, through surface runoff into waterways, or via emissions of nitrogen gases such as ammonia, nitric oxide or nitrous oxide into the atmosphere. Gaseous and waterborne nitrogen may be related to nitrogen fertilizer application rates in linear and nonlinear ways, which means application rates alone are not always enough to determine how much is lost to the environment (Broadbent and Rauschkolb 1977; Hoben et al. 2011; Linquist et al. 2012). Recent evidence suggests that the best indicator of potential nitrogen loss into the environment is the "surplus" nitrogen, which is the difference between the nitrogen applied as fertilizer and the nitrogen taken up by the crop (Van Groenigen et al. 2010). Therefore, both nitrogen application rate and nitrogen surplus, which is calculated after the crops are harvested, are important factors for predicting where nitrogen loss should be highest.

Nitrogen-fertilizer-use data

Data on nitrogen fertilizer use in California are scarce and fragmented. Typically, data are less available and more variable at finer spatial resolutions. The following identifies the primary sources of data available for statewide and county nitrogen use and nitrogen application rates by crop, and discusses some of the inherent limitations of these data sources.

Statewide nitrogen fertilizer use. Fertilizer sales data are collected by the California Department of Food and Agriculture (CDFA) and reported at the state and county levels. Since fertilizer sales are only recorded when a licensed fertilizer dealer sells to an unlicensed buyer, these data provide a rough approximation of the total inorganic nitrogen applied statewide, assuming no stockpiling or interstate transfer of fertilizing materials (fig. 1). Annual data are available dating back to 1945. However, there are additional reasons to question the accuracy of these data. Perhaps the most obvious is the unexplainable 50% jump

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Fertilizer trucks transport liquid ammonia throughout the state. Adding inorganic nitrogen fertilizer to soil promotes high plant productivity and long-term soil fertility but can also lead to excess nitrogen in the environment and environmental degradation.

in sales between 2001 and 2002, the largest 1-year change since annual estimates began. And the reported sales remained abnormally high in the following 5 years (2003 to 2007). Because there is no explanation for this large jump in reported fertilizer sales statewide — neither its root cause nor an apparent accounting error — we have little confidence in the data reported since 2001.

County nitrogen fertilizer use. While fertilizer sales data are reported to CDFA at the county level, the precision of these data is problematic. County fertilizer data portray a geographic distribution of sales unlikely to match actual use for most counties. This is due to the method of data collection, which neglects fertilizer transported from one county to another. For example, more than 20% of total statewide nitrogen sales were reported to have taken place in San Joaquin County. It is entirely possible that this value can be attributed to the large quantity of ammonia delivered to the Port of Stockton and redistributed from there. County-level sales data may be an appropriate proxy for nitrogen applications in counties where one does not suspect significant transport of nitrogen into or out of the county, but it is not possible to be certain with the current data collection system.

Nitrogen fertilizer use by crop. There is neither a comprehensive source of information nor current estimates of average nitrogen applications by crop in California. The most complete source of data in California is a 1973 survey of approximately 120 UC experts and affiliates about nitrogen application rates on 45 commodities (Rauschkolb and Mikkelsen 1978). (The term "expert" in this article refers to UC employees — faculty, farm advisors and facility managers — but we acknowledge there are many other sources of expertise.) However, these rates are unlikely to be the same today due to changes in irrigation technology, tillage, cultivars and countless other management practices since the 1970s. While a few other expert estimates are available, they generally cover fewer crops than the 1973 survey (Miller and Smith 1976; Zhang et al. 2009).

Data direct from growers are largely unavailable. In a few instances, surveys have been conducted (Hartley and van Kessel 2003), though they sometimes omit asking for (Lopus et al. 2010) or reporting (Dillon et al. 1999) nitrogen application rates. The only systematic source of nitrogen application data based on grower surveys is the USDA Agricultural Chemical Use Program reports (USDA NASS 2010). The USDA surveys growers for nitrogen fertilizer application rates for major crops on a rotating schedule, with an emphasis on field crops. As a result, surveys on nutrient use for each crop only occur intermittently — sometimes with significant time elapsing between information being gathered for certain crops. For example, almond was surveyed in 1999 and 2009. Though long-term trends may be detectable from such data, there is the distinct possibility that they may be obscured by year-to-year variability in data that is not quantified and therefore cannot be taken into account. Furthermore, some crops that contribute significantly to California's agricultural economy are not customarily surveyed in any state (such as fresh-market tomatoes), not surveyed in California (such as corn) or not surveyed for nutrient use (such as nursery and greenhouse plants).

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A farmworker applies fertilizer to nursery crops in Winters in the Central Valley. At present, there is neither a comprehensive source of information nor current estimates of average nitrogen applications by crop in California.

Assessing crop nitrogen use

Developing new estimates of nitrogen use by crop is critical to informing the research, outreach and policy agenda on nitrogen fertilizer use. Surveys are resource intensive, and their design and scale may make it difficult to achieve a representative sample, especially in the diverse California agricultural landscape. In addition, the California Nitrogen Assessment had little success in an effort to survey UCCE employees about nitrogen use, and commodity boards about nitrogen research; the response rate was less than 7% and less than 15%, respectively. In place of a new survey, we developed and utilized a new approach to estimate an average nitrogen application rate by crop based on available data. The premise underlying this assessment was to smooth out some of the uncertainties and variation in these data by aggregating across sources. We compiled the available information from expert and grower sources into a database according to the methods described below.

For each crop, we first averaged the available expert data since 2000 and then averaged the grower data since 1999. Utilizing nitrogen estimates that date from 1999 or 2000 was necessary to increase the sample sizes, as a result of the limited number of expert responses available over the time period for each crop.

Expert data. Expert opinions of nitrogen fertilizer use were taken from UC Agricultural and Resource Economics (ARE) Cost and Return Studies that have been conducted from 2000 to the present (UCD 2010). Studies of each crop

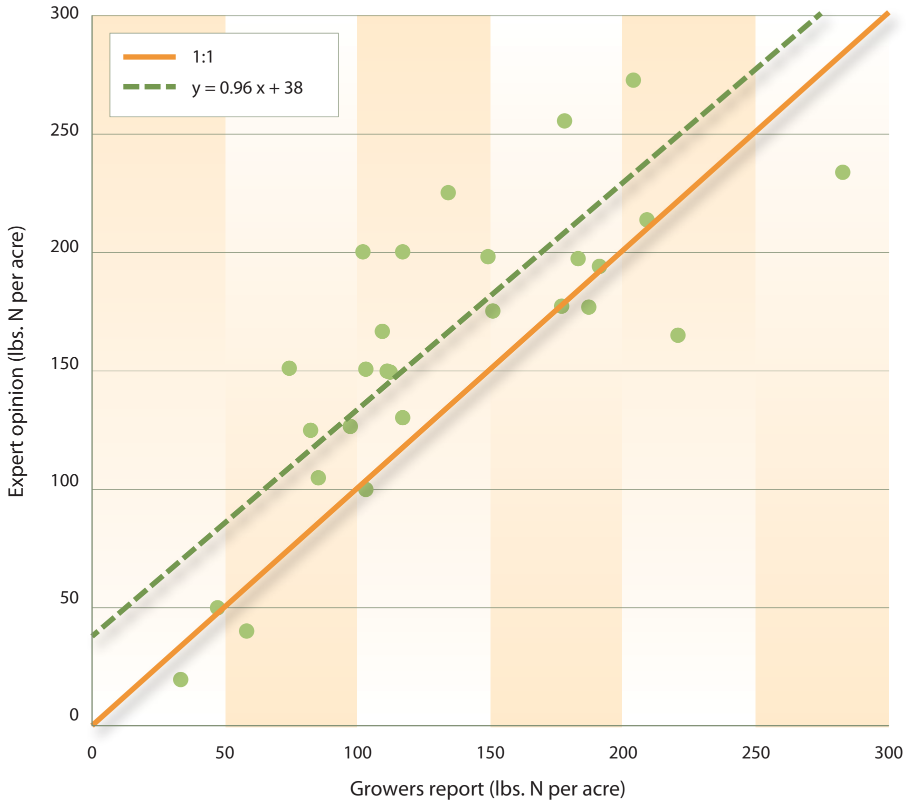

Fig. 3. Relationship between the experts' opinions and growers' reports of nitrogen application rates. Data were available from both sources for only 23 of the 33 commodities. The solid line represents 1:1 agreement, representing the theoretical point (in each case) where expert opinion and grower reports would have been in complete agreement; the dashed line is the best linear fit to the actual data (y = 0.96x + 38).

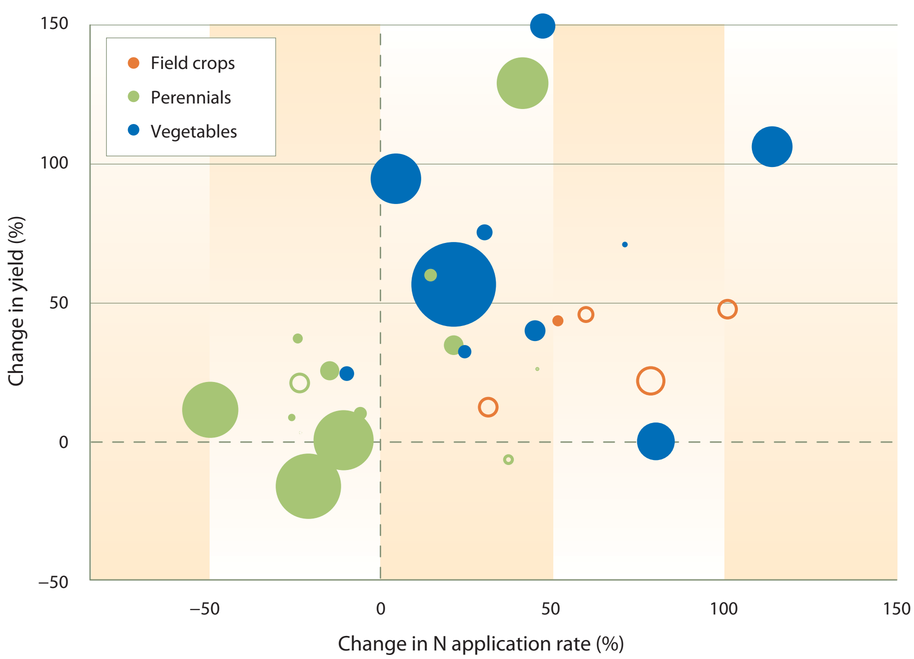

Fig. 4. Changes in nitrogen application rates, yields and cropped area. The size of circle represents the percentage change in the area cultivated for that particular crop between 1973 and 2005; closed circles represent increases in area and open circles represent declines in area.

were selected to represent variations in California's agricultural regions (such as the Imperial Valley versus the Salinas Valley) as well as the breadth of management practices (such as furrow versus drip irrigation). Compiling studies that span the geographic and production continuum was important because of the potential differences in nitrogen application with the various environmental conditions and production techniques.

Not all of the available studies were included in the database. Some studies were omitted because studies of the same crop often recycle the descriptions and estimates of nitrogen use until management practices change significantly, and thus inclusion of every study would have skewed the estimate. An average of two studies were included for each crop, but the number of studies included ranged from one to five. Data were averaged to provide a representative value of nitrogen fertilizer use for each crop based on expert opinion.

Grower data. Estimates from grower reports included all nitrogen fertilizer application rates for the respective crops from the USDA Agricultural Chemical Use Program reports between 1999 and 2009 (USDA NASS 2010). We extended the starting date to 1999 to accommodate the USDA's variable schedule for these surveys. By adding 1999, we were able to obtain an additional year of data — in some cases doubling the available data — in particular for fruit and nut crops, such as almond, which are key crops in California. These data were averaged by crop to determine a typical nitrogen application rate reported by growers.

Discrepancy between expert and grower data. Our results show that experts believe growers apply more nitrogen – in fertilizer — than the amount that growers report applying (fig. 3). Both expert and grower data were available for 23 crops, and experts suggest that the average nitrogen fertilizer use per acre for all of these crops is 38 pounds higher than growers report. One possible explanation for this discrepancy is that the expert opinion reflects the application rates for a "well-managed" farm with good soil and favorable environmental conditions, and therefore high yield. However, producers with lower management intensity or more marginal land may apply less than experts expect. Another possible explanation is that the data reflect asymmetry in the scales of focus and methods of data collection. The USDA grower surveys are statewide, while the expert UC Cost and Return Studies have a regional focus. Thus, the latter may be sampling regions where the productivity and fertilizer demands are greater. The difference between expert and grower values for nitrogen fertilizer use highlights both the variation in the available information and the need to reconcile estimates more generally.

Because of the difference between expert and grower accounts and the uncertainty regarding the real relationship of the two, we calculated the simple average of the two values to determine the representative rate. Our representative rate approximates nitrogen use by crop for 2005 (table 1). The 33 crops were selected based on their current contribution to California's agricultural industry; each represents more than 1% of the annual value of agricultural products or the agricultural acreage, excluding animal products and alfalfa.

Nitrogen use and crop trends

While nitrogen fertilizer use on a crop-by-crop basis has risen over the last three decades, this increase has been more modest than fertilizer sales suggest. Between 1973 and 2005, fertilizer sales increased 31%, but nitrogen application rates increased only 25% across the 33 crops (fig. 1, table 1). (While both sets of data were available for 23 crops, we used the data that were available — expert or grower — for the other 10.) Across crops, an average of 161 pounds of nitrogen was applied per acre in 2005 versus 130 pounds of nitrogen in 1973. Over the time period examined, application rates increased less than 10% for 13 of the 33 crops (39%), and decreased for 11 of these crops (33%). Since the amount of irrigated cropland remained relatively stable over this time period, the calculated average rate of increase is nearly 33% less than the fertilizer sales data suggest.

Shifting toward nitrogen-intensive crops. What then accounts for the rise in nitrogen fertilizer sales between the 1973 survey and the present? While the average increase in nitrogen application rates was modest, the rates used on some commodities increased significantly. In addition, some of these commodities simultaneously increased in area (fig. 4). For example, the area of almonds and carrots increased by 174% and 124%, respectively, while their respective nitrogen application rates increased 41% and 80% to 179 and 216 pounds of nitrogen per acre (table 1). We hypothesize that the increased nitrogen sales seem to be partly a consequence of the shift to commodities with higher nitrogen demands. Increased nitrogen fertilizer sales are not solely a result of an increase in application rate but are also due to an interaction between changes in application rates and

TABLE 1. Crop area and nitrogen application rates in California, 1973 and 2005

	Area*		Nitrogen rate†			Nitrogen use§	
Crop	1973	2005	1973	2005	% change‡	1973	2005
	acres		pounds nitrogen per acre			% of total	
Almond	216,154	592,000	127	179	41	6	15
Avocado	20,360	61,820	125	112	−11	1	1
Beans, dry	169,400	64,000	51	91	79	2	1
Broccoli	43,580	117,500	182	190	4	2	3
Carrots	31,480	70,620	120	216	80	1	2
Cauliflower	23,160	34,060	183	238	30	1	1
Celery	18,050	25,740	287	259	−10	1	1
Corn, sweet	14,200	25,560	145	213	47	0	1
Cotton	932,100	626,000	109	174	60	24	16
Grapes, raisin	240,200	240,000	57	44	−23	3	2
Grapes, table	66,080	83,200	57	43	−24	1	1
Grapes, wine	164,980	477,800	53	27	−49	2	2
Lemons	41,520	48,400	166	123	−26	2	1
Lettuce	145,120	232,400	159	193	21	5	6
Melons, cantaloupe	47,540	44,600	95	163	71	1	1
Melons, watermelon	11,200	11,920	159	151	−5	0	0
Nectarines	10,460	33,700	131	104	−21	0	1
Onions	28,500	46,860	146	212	45	1	1
Oranges	186,040	192,400	65	95	46	3	3
Peaches, cling	50,500	29,380	133	102	−23	2	0
Peaches, free	21,100	33,400	133	113	−15	1	1
Peppers, bell	8,800	20,700	162	346	114	0	1
Peppers, chili	4,718	5,460	162	300	85	0	0
Pistachio		102,600	148	159	7		2
Plums, dried	82,800	67,600	95	130	37	2	1
Plums, fresh	23,540	32,200	110	104	−6	1	0
Potato	70,060	40,820	189	248	31	3	1
Rice	413,000	535,800	86	130	52	8	10
Strawberry	8,620	33,680	159	193	21	0	1
Tomatoes, fresh market	28,180	38,800	142	177	24	1	1
Tomatoes, processing	221,940	279,400	142	182	28	7	7
Walnut	159,040	215,200	120	138	15	4	4
Wheat	675,600	394,800	88	177	101	14	10
Average			**130**	**161**	**25**		

* Area is based on a 5-year average centered on 1973 and 2005 for the 1970s and 2000s, respectively.

† Nitrogen rates are estimated from Rauschkolb and Mikklesen (1978), UC ARE Cost and Return Studies and USDA Agricultural Chemical Use Program reports.

‡ Percentage change is between nitrogen use in 1973 and nitrogen use in 2000s. When 1973 data were unavailable, percentage change is between 1971 data cited in Miller and Smith (1976) and 2005, except for pistachio, where percentage change is between 1998 (Zhang et al. 1998) and 2005.

§ Crop yields (lbs. per acre) and cropped area (acres) were calculated as 5-year averages to minimize year-to-year variation. The median year was the same year for which historical and current fertilizer use was estimated (i.e., 1973 and 2005). Data were collected from USDA (2010b).

shifts toward a more nitrogen-intensive crop mix.

Using nitrogen more efficiently. Simply applying a greater amount of nitrogen fertilizer in and of itself is not necessarily harmful. It is the fraction of excess nitrogen applied that poses a threat to the environment. For almost every crop examined, yields and nitrogen uptake increase with greater nitrogen supply (fig. 4). These data clearly show the positive effect increased nitrogen use has had on California's ability to produce food. Because the rate of change of yields is often greater than that of nitrogen use, these findings further suggest that growers of the 33 commodities examined have, on average, become more agronomically nitrogen-efficient (in the technical, not the economic, sense) than in 1973. For most crops, less nitrogen is applied per unit of product.

TABLE 2. Published UC nitrogen fertilizer rate guidelines for select crops*

Crop	Nitrogen guidelines: Minimum	Nitrogen guidelines: Maximum	Source
	pounds per acre		
Alfalfa	0	50	Meyer et al. 2007. Pub. 3512
Almond	100	200	Weinbaum 1996. Pub. 3364
Avocado	67	100	Faber 2005. CE Ventura Avocado Handbook and Pub. 3436
Bean, dry	86	116	Long et al. 2010. Pub. 8402
Broccoli	100	200	LeStrange et al. 2010. Pub. 7211
Carrot	100	250	Nunez et al. 2008. Pub. 7226
Celery	200	275	Daugovish et al. 2008. Pub. 7220
Corn	150	275	http://agri.ucdavis.edu
Corn, sweet	100	200	Smith et al. 1997. Pub. 7223
Cotton	100	200	Hake et al. 1996. Pub. 3352
Grape, raisin	20	60	Christensen et al. 2000. Pub. 3393
Lawn (heavy soil)	174	261	Harivandi and Gibeault 1997. Pub. 7227
Lawn (shade)	87	130	Harivandi and Gibeault 1996. Pub. 7214
Lettuce	170	220	Jackson et al. 1996. Pubs. 7215 and 7216
Melon, cantaloupe	80	150	Hartz et al. 2008. Pub. 7218
Melon, watermelon	†	160	Baameur et al. 2009. Pub. 7213
Melons (mixed)	100	150	Mayberry et al. 1996. Pub. 7209
Nectarine	100	150	Pub. 3389
Oats	50	120	Munier et al. Pub. 8167
Onion	100	400	Voss et al. 1999. Pub. 7242
Peach, cling	50	100	Norton et al. 2007. Pub. 8276
Peach, free	50	100	Norton et al. 2009. Pub. 9358
Pepper, bell	180	240	Hartz et al. 2008. Pub. 7217
Pepper, chili	150	200	Smith et al. 1998. Pub. 7244
Pistachios	100	225	Beede et al. 2005. In Ferguson et al. 2009
Plums, dried (prunes)	†	100	Norton et al. 2007. Pub. 8264
Plums, fresh	110	150	Johnson and Uriu 1989. Pub. 3331
Rice	110	145	Mutters et al. 2009. Pub. 3514
Safflower	100	150	Kafka and Kearney 1998. Pub. 21565
Strawberry	150	300	Strand et al. 2008. Pub. 3351
Tomatoes, fresh market	125	350	Le Strange et al. 2000. Pub. 8017
Tomatoes, processing	100	150	Hartz et al. 2008. Pub. 7228
Walnuts	150	200	Anderson et al. 2006. Pub. 21623. Weinbaum et al. 1998. Pub. 3373
Wheat	100	240	Munier et al. 2006. Pub. 8167

* Publications can be found in the ANR catalog at http://anrcatalog.ucdavis.edu.
† No minimum specified.

Judicious nitrogen use?

UC researchers have historically established nitrogen rate guidelines through replicated research trials. These guidelines are not recommendations. Whereas recommendations prescribe nitrogen rates appropriate under specific production conditions, guidelines are ranges of nitrogen rates that are usually sufficient to obtain maximum production. Ranges are often large to account for the diversity of production conditions encountered. Guidelines are widely available in bulletins and reports published by UC Agriculture and Natural Resources (ANR). We assembled a database of the most recent nitrogen rate guidelines to evaluate (1) if they reflect current cropping conditions and (2) if the estimates of current nitrogen application rates fall within the published guidelines (table 2).

Nitrogen guidelines. We located periodic ANR publications with nitrogen guidelines that have been published within the last 25 years for 28 of the 33 crops. Guidelines for 16, 18 and 24 of the 28 crops were published within the last 5, 10 and 15 years, respectively. In most cases, more recent publications were revisions of previously published guidelines to incorporate findings from new research, changes in management practices, and crop genetics. We were unable to find recent print publications listing nitrogen application guidelines specific to California for five crops (potato, wine grapes, table grapes, lemons and oranges). Information to guide nitrogen fertilizer use for these crops was available, however, either online (Peacock et al. 1998) or in other forms used to support nitrogen management in some systems (that is, critical values for tissue tests) (Flint 1991; Ingels 1994) or more generally for the western United States (Strand 2006).

Beyond these 33 crops though, information on appropriate nitrogen fertilizer management is less readily available. Yet, we conclude that ANR nitrogen rate guidelines are generally up to date with the needs of current cropping conditions for two reasons: (1) the 33 crops studied are grown on more than 70% of the non-alfalfa California cropland (alfalfa does not need nitrogen fertilizer because it fixes its own nitrogen) and (2) most guidelines were published within a reasonably recent period. This is not to suggest that there is no longer a need to perform nitrogen rate trials. Replicated research trials to refine current practices and to account for any future changes in various management practices are still required.

Nitrogen use. Do growers apply nitrogen in accordance with research results? We compared our 2005 estimates, which can be said to represent typical applications by growers for a particular crop, to the published UC nitrogen rate guidelines (table 3). We found that the maximum values of the guideline ranges were nearly double the minimum values, a range that should be sufficient to account for heterogeneous cropping conditions. Our representative application rates were within the guidelines for 17 crops (61%), indicating that nitrogen is generally applied in line with research guidelines and, in that sense, can be considered "best management" practice. For nine of the crops (32%), typical application rates exceeded the maximum value in the guidelines. Vegetables and annual fruits accounted for the largest percentage of crops that fell within that category, with 42% of the crops receiving more nitrogen than suggested by guidelines. Whereas the majority of crops appear to be fertilized appropriately, the latter results suggest that in nearly one-third of California cropping systems, either the research underestimates nitrogen requirements for on-farm cropping conditions or the producers, on average, overapply nitrogen fertilizer.

TABLE 3. Relevance of current nitrogen rate guidelines

Crop type	N	Range of guideline*	Within†	Over‡	Average excess§
		%, average ± SD	·········· %	··········	*lbs. nitrogen per acre ± SD*
Field crops	4	73 ± 46	100	–	–
Perennials	12	88 ± 54	50	33	14 ± 12
Vegetables and annual fruits	12	101 ± 83	58	42	53 ± 47
All crops	**28**	**90 ± 65**	**57**	**36**	**36 ± 39**

* Calculated as the percentage difference between the maximum and minimum rate in the guideline. Average and standard deviation are among the crops in the crop type.

† The percentage of crops with an average nitrogen application rate that falls within the range outlined by the UC guideline.

‡ The percentage of crops with an average nitrogen application rate exceeding the maximum listed in the UC guideline.

§ Excess refers to the amount of nitrogen applied above the maximum rate in the guideline.

Nitrogen management

The need to balance the benefits of nitrogen fertilizer use (such as increased food supply) with the costs (such as water and air pollution) is clear. However, uncertainty about basic questions on nitrogen use obstructs substantive discourse and cooperation among stakeholders toward workable solutions. While still not devoid of uncertainty, the typical nitrogen application rates established in this research can be used to identify priorities for nitrogen research, outreach and policy.

High-nitrogen-use crops. Fertilizer use is not distributed equally among crops. Of the 345,900 tons of nitrogen fertilizer accounted for in the application rates of the 33 commodities considered in this study, approximately 34% is applied to perennials, 27% to vegetables and 42% to field crops. Notably, our estimates show that relatively few crops account for much of the nitrogen use. Multiplying the average-nitrogen-use estimates for each crop by the average harvested acreage for 2002 to 2007 indicates cotton received the largest fraction of the total nitrogen applied, 16%, while almond received 15%, rice and wheat each received 10%, processing tomatoes received 7% and lettuce received 6%. Altogether these six crops account for 64% of the total nitrogen use (fig. 5). Moreover, these estimates may be conservative for the perennials and field crops in this small group because only bearing and harvested areas, respectively, were used in these calculations. Even with the uncertainty surrounding the precision of our estimates and with the relative changes in cropped area that occur year to year, it is difficult to imagine a scenario

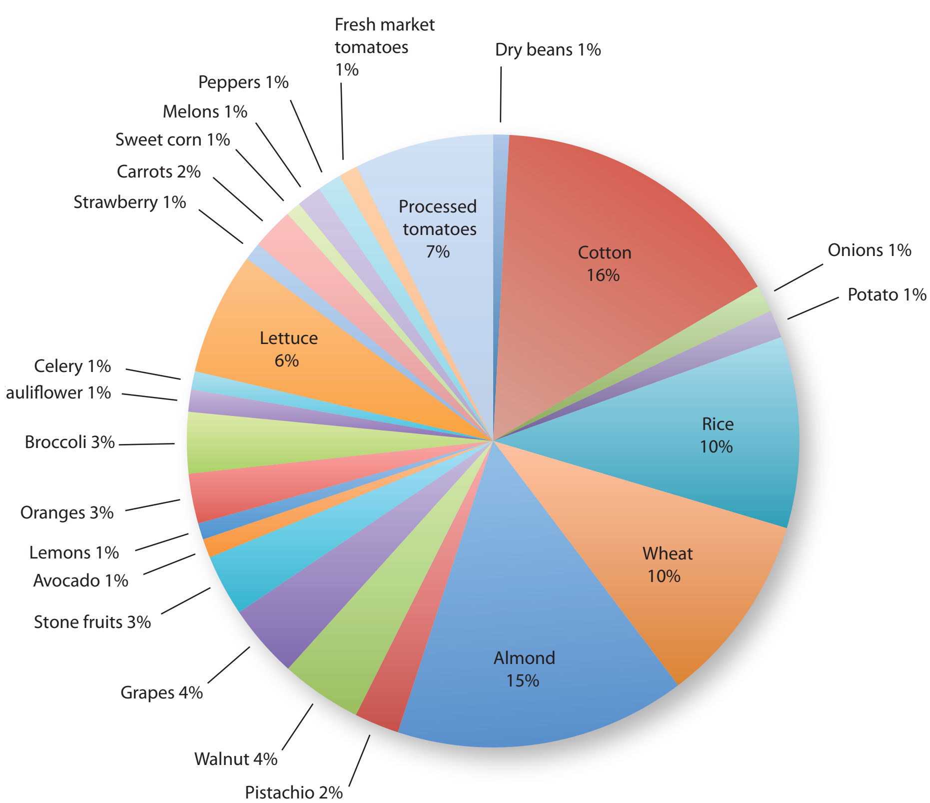

Fig. 5. Relative proportion of nitrogen fertilizer use of the 33 commodities included in the analysis. Stone fruits include peaches, nectarines and dried and fresh plums. Grapes include wine, table and raisin grapes.

where other crops could account for as much total inorganic nitrogen fertilizer use in the state, at least in the short term.

Thus, the highest priority becomes understanding nitrogen management (and the fate of applied nitrogen) in these cropping systems, which include a representative range of crop types and are commonly grown with an array of soil, irrigation and fertility management practices. Indeed, nitrogen research activities have focused attention on these crops as of late. Evidence of that are the ongoing experiments to quantify nitrous oxide emissions in cotton, almond, lettuce, wheat and tomatoes, as well as using the Salinas Valley, the epicenter of lettuce production, as one of the two pilot areas in the report on nitrate to the California Legislature.

Richard Smith, UC Cooperative Extension farm advisor in Monterey County, tests for nitrogen. Salinas Valley is one of two pilot areas studied in a report on nitrate to the California Legislature.

Excess nitrogen. What these data do not allow for is predicting the fraction of nitrogen fertilizer that is applied in excess of crop uptake. There are clearly some crops not identified by this analysis that may receive excess nitrogen application per unit of area. Given the significance of surplus nitrogen applications to environmental pollution, it is probable that even though such crops may account for relatively small cultivated areas, they may still become hot spots of potential nitrogen emissions. In addition to considering total nitrogen use, which will be weighted by crop area and application rate, it is important to calculate surplus nitrogen when setting priorities. Calculating this surplus, however, requires data on yield, nitrogen and moisture content of harvested products, and nitrogen application, much of which is not available in a comprehensive way. Better information on these four parameters would go far toward increasing our knowledge of the nitrogen pollution hot spots, as well as of leverage points to balance economic and food production benefits of nitrogen fertilizer use with threats to California's human and natural capital.

A way forward

Agricultural nitrogen fertilizer use sits at the nexus of multiple social and environmental debates in California. Policymakers appear ready to act, but finding solutions workable to the diverse constituencies is severely constrained by a lack of credible, comprehensive information. The ability to target any remedial action — incentives, regulations, education, research, and so on — requires better information on the location and severity of the concern. As shown, available data lack reliability and coverage, presenting significant barriers to scientifically sound efforts to address this issue, which therefore suggests the need for a new approach.

One option would be the development of a grower self-reporting system for total nitrogen applications to serve as a warning sign of excess nitrogen use. Pesticide-use reporting provides a positive example that can inform design of nutrient reporting. Information derived from the pesticide-use reporting system serves as the foundation for better information, science and management (see Zhang, unpublished, an online bibliography of research and trade publications that rely heavily on the pesticide-use database to understand the extent of agricultural, environmental and human health effects of pesticide use). Establishing a reporting system would require careful consideration of its fundamentals, however. Concerns over

Water treatment facilities at San Joaquin Valley farms. Irrigation water high in nitrogen can contribute to growth of algal blooms, especially blue-green algae.

costs and institutional barriers will likely be among the most cited reasons for resistance to the idea and may challenge the efficacy of the system.

California, however, is at an opportune juncture for developing such a reporting system, which could help farmers save on fertilizer costs while, at the same time, reinforcing the good practice of many producers and reducing agriculture's impact on the environment. So, we recommend establishing a multistakeholder process to ensure a workable and useful solution for growers, regulators and scientists alike. Funding to develop a practical, cost-effective fertilizer application reporting system would seem to be compatible with the mandate of the California Department of Agriculture's Fertilizer Research and Education Program.

When facing an issue of such fundamental importance to our state — involving trade-offs between the basic needs of food production versus clean water and air — it seems reasonable to invest effort to develop data necessary to make fully informed decisions. Decisions based on currently available data, which are unreliable and inadequate, risk unintended negative consequences and reduce chances that objectives will be balanced in an efficient and effective way.

Lettuce, a major Salinas Valley crop, uses significant nitrogen fertilizer. However, the quantity used cannot predict the fraction applied in excess of crop uptake, or where nitrogen hot spots may arise.

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PROFILING AREAS VULNERABLE TO GROUND WATER CONTAMINATION BY PESTICIDES IN CALIFORNIA

FINAL REPORT TO THE U.S. ENVIRONMENTAL PROTECTION AGENCY
FOR CONTRACT # E-009565-01-0

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ABSTRACT

Identifying areas vulnerable to ground water contamination by pesticides is desirable because pollution prevention policies could be developed for specific locations. Previous attempts to correlate predicted levels of vulnerability with measures of the absence and/or presence of pesticide residues in well water have not been entirely satisfactory. Poor correlation between predicted level of vulnerability and occurrence of pesticide residues in well water may have been caused by assuming that only the leaching pathway was involved or by uncertainties in the use of well sampling data as an indication of vulnerability. An alternative approach was devised that produced classification algorithms based on climatic and soil data from known vulnerable (KV) sections. KV sections in California are defined as 1 square mile areas of land where pesticide residue has been detected in well water samples and the detection attributed to nonpoint source agricultural applications. Clustering procedures were used to group similar KV sections first with respect to climate data and then with respect to soil data. Principal Components Analysis was used to construct soil profiles of the clusters. The profiles were used as the basis for a classification procedure to determine if soil properties of candidate sections with unknown vulnerability were similar to profiles developed for KV sections. Since this scheme is based only on data from KV sections, candidate sections with dissimilar profiles cannot be considered as non-vulnerable; they receive a status of non-classifiable. However, the process is flexible and it can revised to incorporate updated well sampling information.

INTRODUCTION

Identification of areas vulnerable to ground water contamination by pesticides is desirable because pollution prevention policies could be developed for specific locations. One approach to identifying vulnerability has been to: 1) devise a vulnerability index based on variables thought important in facilitating pesticide movement to ground water, usually assuming the leaching pathway; 2) stratify land areas based on the vulnerability index; 3) obtain data on the detection of pesticide residue in well water; and 4) use percentage of detections as a discriminator variable in analyses conducted to test correspondence with the vulnerability index.

Tests conducted with indices derived from the DRASTIC model are an example of this approach. In DRASTIC, indices of vulnerability are derived from a series of weights and ratings of seven hydrogeologic variables which experts agreed were important determinants in leaching of pesticides to ground water (Aller et. al., 1985). The correspondence between the detection of pesticide residue in well water and DRASTIC indices, generated for county-wide areas, have been statistically tested in three studies (EPA, 1992; Balu and Paulsen, 1991; Holden et. al., 1992). None of the studies found a good correspondence between occurrence of residues and the DRASTIC scores.

Problems related to well sampling may have caused unfavorable results with this approach. First, presence of pesticide residue in well water may not solely result from leaching through soil via the normal route of water percolation. Observations of construction and quality of a well are usually made during a study to ensure that local streaming from the surface to ground water had not occurred, but movement to ground water may occur through other pathways that are difficult to investigate. For example, collection of runoff water from rainfall or irrigation may be shunted to special drainage wells or to fast draining areas of soil. Contamination could then result from an unexpected route of water movement through the soil. Second, the probability of detecting pesticides in well water is complicated by the location of the well in relation to depth and direction of ground water flow from contaminated areas. For example, a domestic well situated near and downstream (in terms of ground water flow) of an agricultural field would appear to be a good candidate sampling site because it should reflect local conditions. However, residue that has leached from the nearby field may encounter ground water at a stratum above that tapped by the well causing the residue to bypass the well. Determining specifics of ground water flow and well location for each sampled well is usually not feasible when conducting large-scale field studies.

Wilkersen et. al., (1985) used an empirical discriminant analysis approach to produce a classification equation for vulnerability. Their approach was to: 1) identify land use, geographic, and well construction variables for 1-square-mile areas designated as sections in the Public Land Survey System (PLSS) (Davis and Foote, 1966); 2) derive a classification variable for vulnerable and non-vulnerable areas which was the presence or absence of pesticide residues in well water sampled in a section; and 3) use discriminant analysis to a produce classification equation for vulnerability. A discriminant classification model was developed from data for 10 sections that were selected from 3 adjacent townships in an agricultural region of Fresno County. DBCP had been detected in 7 sections which were classified as vulnerable. The remaining 3 sections were identified as non-vulnerable.

The discriminant model which contained 4 variables correctly classified the original 10 sections. However, when tested against an independent data set, sections with DBCP detections were correctly classified as vulnerable whereas non-vulnerable sections without DBCP detections were misclassified as vulnerable. Well sampling data available after that study indicated that nearly all sections in the test townships now contain positive DBCP detections. If the study had been conducted at a later date, the entire area would have been classified as vulnerable (Brown et. al., 1986) and a discriminant analysis would not have been possible. As illustrated by this example, the dynamic nature of well sampling evidence should be considered when ratios of the presence or absence of residues in well water are used as classification variables for vulnerability.

In a similar discriminant procedure employed by Teso et. al. (1988), soil data were used to develop a discriminant function for the occurrence of either DBCP contaminated or uncontaminated sections in Fresno county. When tested against an independent data set describing DBCP contamination in Merced county, a 40% misclassification rate was measured.

Since the attempts to devise classification systems that predict levels of vulnerability have not been entirely satisfactory, an approach was devised that profiled known vulnerable (KV) sections in California. Cluster analysis was first used to identify groups of KV sections with similar climate and soil conditions. Then, a classification algorithm was derived to determine whether soil conditions of new candidate sections of unknown vulnerability matched KV section profiles. This type of approach has been described as a Hydrogeologic Setting Comparison (HSC) where areas are judged similar based on hydrogeologic character (Marshall, 1991). Previous HSC efforts utilized a restricted set of hydrogeologic variables that were interpreted with respect to the leaching pathway (Kisel et. al., 1982; Fisher and Reid, 1986; Sacha et. al., 1987). This current work expanded upon the HSC approach in six ways: 1) the number of climatic and soil variables considered as identification variables was increased; 2) data were obtained that could be resolved at the section level, a 1 square-mile area; 3) no assumptions were made about the causes of ground water contamination because, according to our experience, leaching is only one of several possible causes of ground water contamination from nonpoint source pollution; 4) clustering techniques were used to chose combinations of climate and soil variables that formed unique clusters of vulnerable sections; 5) classification algorithms were developed from the clustering results; and 6) the entire process could be revised to accommodate new information on vulnerable areas when a greater amount of sampling data become available. As much descriptor information as possible with respect to climatic, soil, and other variables was collected for 1 square-mile vulnerable sections in California. Multivariate clustering techniques were then used to determine whether the descriptor information could be used to identify unique groups of vulnerable sections.

MATERIALS AND METHODS

Determination of Vulnerable Sections

A vulnerable section was defined as a 1 square-mile area of land where pesticide residues had been found in ground water due to agricultural use. By definition, all sections designated as Pesticide Management Zones (PMZs) in California were included, but other sections not regulated as PMZs were also included. Sections with bentazon and aldicarb detections were not designated as PMZs because their regulations apply statewide. Also, sections with detections of active ingredients that are no longer registered in California were not designated as PMZs (Maes, et. al., 1991). DBCP detections, though numerous, were omitted from the study. Use of DBCP was banned in 1979. Since then, a large number of detections in well water have been reported, primarily from a sampling conducted by the California Department of Health Services (Brown et al., 1986). Detections could have resulted from movement of contaminated ground water between sections during the time span between cessation of use and sampling of well water. This problem may be amplified for DBCP because of a long half-life in ground water, estimated at greater than 100 years (Burlinson et. al., 1982), and because large quantities were applied to soil.

Data for pesticide detections in well water, excluding DBCP detections, were obtained from the Well Inventory Data Base maintained since 1985 by the Department of Pesticide Regulation (DPR) (Cardozo et al.,1985). The Pesticide Prevention Contamination Act (Connelly, 1986) requires the DPR to determine whether or not reported detections are due to agricultural use. Therefore, detections determined to be due to agricultural use were used as indicators of areas that are vulnerable to contamination of ground water as a result of nonpoint agricultural use of pesticides. A total of 258 sections were identified as KV sections.

Data Sources

Climatic data for temperature and precipitation were obtained from a weather station database maintained by the California Department of Water Resources (CDWR). Data were obtained from 127 weather stations. Mean values for cumulative and monthly rainfall and for mean yearly and monthly temperature were derived from daily values averaged over 30 years at each station for 1961-1990 (Table 1). The weather station closest to the center of each KV section was determined from latitude-longitude coordinates.

Data for physical and chemical properties of soil were obtained at the level of soil mapping unit as delineated in soil survey maps for individual counties in California. The type of mapping unit used in this study was primarily surface texture phases of consociations of soil series (Soil Conservation Service, 1983). Two data sets were required. One data set identified the occurrence of soil mapping units in KV sections (personnel communication, Bob Teso, DPR, University of Riverside, Riverside, Ca). This data set was used to extract information from a second data, the Map Unit Interpretations Record (MUIR) data base provided by the Soil Conservation Service (SCS), USDA. The MUIR data base contains chemical, textural, and observational data by soil layer to the 5 foot depth for each soil mapping unit. Variables for soil texture in the MUIR database were presented in descriptive terms such as 'sandy loam'. These descriptions were transformed to a numeric scale by assigning values for sand and clay determined from the centroid of corresponding textural classes in the Soil Triangle (Soil Conservation Service, 1975) (Table 2). Other categorical variables whose categories were ordinal were transformed to a numeric scale. High and low values were reported for numeric variables so mid-points were calculated. The amount of data present for each variable varied between soil layers. Data for certain variables were partitioned to represent surface and subsurface conditions. The variable representative of the surface soil was derived by averaging data over the first soil layer for all soil mapping

Table 1. Description of climatic and soil variables.

Acronym	Description
Climate variables[a]	
MIYR	Yearly minimum temperature
MXYR	Yearly maximum temperature
MNYR	Average Yearly temperature
M1T-M12T	Mean monthly January-December temperature
PYR	Mean annual precipitation
M1P-M12P	Mean monthly January-December temperature
Soil variables[b]	
Textsand, Textclay	Derived percent sand and clay for Overall USDA Textural class of the soil
Txt1sand, Txt1clay	Derived percent sand and clay for USDA textural class for surface soil
Subtxsnd, Subtxcly	Derived percent sand and clay for USDA textural class for subsurface soil
Lay1clay, Subclay	Measured % clay content of surface and subsurface soil reported in the MUIR data base.
Lay1no4[c], Subno4[c]	Percent by weight of soil material smaller than 76 mm in diameter that passes a no. 4 (5 mm) sieve
Lay1no10[c], Subno10[c]	Percent by weight of soil material smaller than 76 mm in diameter that passes a no. 10 (2 mm) sieve
Lay1n200[c], Subn200[c]	Percent by weight of soil material smaller than 76 mm in diameter that passes a no. 200 (75 µm) sieve
Textind	Indicator for cobbles or stoniness in overall USDA textural class
Text1ind, Subtxind	Cobble or stoniness indicator for surface and subsurface soil
Lay1shsw, Subshsw	Shrink-swell of the surface and subsurface soil
Lay1perm, Subperm	Permeability of the surface and subsurface soil
Lay1deph, Subdeph	Average depth of the derived surface and subsurface soil layers
Lay1awc[c], Subawc[c]	Average water holding capacity of surface and subsurface soil
Lay1om[c]	Average percentage of organic matter in the surface
Hyd[c]	Hydrologic group
Pan[c]	Indicator for hard pan
Drain[c]	Drainage group
Wattab[c]	Indicator for presence of a water table above 1.5 m
Flood[c]	Indicator for presence of annual flooding
Slope[c]	Surface slope of soil
DGW[a,c]	Depth from surface to ground water

a Data obtained from California Department of Water Resources.
b Data obtained from Soil Conservation Service.
c Variables used in the classification algorithm.

Table 2. Scale transformations used for soil variables.

Variable	Initial Scale	Transformed Scale
Texture	Sand	92% sand, 4% clay
	Loamy Sand	83% sand, 6% clay
	Sandy Loam	65% sand, 11% clay
	Loam	42% sand, 20% clay
	Silt Loam	20% sand, 15% clay
	Silt	8% sand, 6% clay
	Clay Loam	33% sand 34% clay
	Sandy Clay Loam	59% sand, 28% clay
	Silty Clay Loam	10% sand, 33% clay
	Sandy Clay	52% sand, 40% clay
	Silty Clay	7% sand, 46% clay
	Clay	20% sand, 60% clay
Water Table	No indication	0
	APPAR or PERCH	1
Annual Flooding	NONE	0
	RARE	1
	COMM or FREQ or OCCAS	2
Drainage Class	VP	0
	P	1
	SP	2
	MW	3
	W,MW	3.5
	W	4
	W,SE	4.5
	SE	5
	E	6
Hard Pan	No indication	0
	THICK or THIN	1
Shrink-Swell	LOW	0
	MODERATE	1
	HIGH	2
Hydrologic Group	A	0
	B	1
	C	2
	D	3

units within a section. The variable representative of the subsurface soil was derived by averaging data for all soil layers below the first layer within a mapping unit and then averaging across all mapping units within a section. Missing data for Del Norte, Humbolt, Kern and Tulare counties were obtained manually from published soil surveys or through personal contact with local SCS personnel. Soil data could not be obtained for KV sections in Los Angeles, Orange, and San Bernardino counties. This reduced the number of KV sections used in the statistical analysis from 258 to 180.

One other variable, depth to ground water, was obtained from a 1985 CDWR report that contained information for specific wells with PLSS Township-Range identifications. Since only a portion of vulnerable sections contained data, a gridding procedure, available in the SAS® statistical package was used to produce estimated values (SAS Inc, 1988). Del Norte, Humbolt, and Santa Clara Counties lacked enough information to conduct the gridding. Values for vulnerable sections in these areas were estimated from well log information. Depth to ground water could not be determined for 9 other KV sections. In the discussion that follows, depth to ground water will be grouped with soil data.

Each data set was initially processed using the ORACLE® database management system on a SUN® computer. The processed data were output to a single file in American Standard Code For Information Interchange (ASCII) format with each record representing a vulnerable section and containing all climate and soil data for that section. Twenty-eight climatic and thirty-three soil variables were identified (Table 1). The ASCII data file was analyzed with SAS® software on a DOS based personal computer (SAS Institute, 1988).

Cluster Analysis

Initially, the plan was to conduct a cluster analysis using all climate and soil variables. Climate variables, however, dominated results of the first analysis. This was caused by a difference in the variance structure between climate and soil variables for KV sections. Since weather stations were less numerous than KV sections, identical rainfall and temperature data were assigned to some KV sections. When means were obtained for each county, the variance for climate variables was zero. In order to retain climate information for KV sections, a two-stage process was developed where in the first, cluster analysis was conducted on climate variables from 32 weather stations nearest KV vulnerable sections. In the second stage, cluster analysis was conducted on soil variables from KV sections within climate clusters.

When the number of variables is large, one common clustering procedure is to first conduct a Principal Components Analysis (PCA) analysis on all variables to determine if a subset of principal components (PCs) could be used to describe the raw data set. Clustering procedures are then conducted on the reduced number of principal components (Gnanadesikan and Kettenring, 1989). This procedure has two disadvantages. First, description of the clusters could be unclear because assignment of meaning to the principal components could be difficult. Second, use of principal components could produce indistinct clustering results and obscure the actual number of clusters that exist in a data set (Fowlkes, et. al., 1988). The latter was observed with the soils data.

An alternative procedure was developed based on a forward selection technique suggested by Fowlkes et. al. (1988). Prior to analysis, variables were standardized to mean 0 and standard deviation ± 1 to remove effects of scale. In the first step, the single best clustering variable was identified. In the second step, the single best variable was tested in combination with the rest of the variables and the best clustering pair of variables identified. Variables that were highly correlated with chosen variables were not included in subsequent steps because correlation between variables tends to inflate statistical measures used to test the performance of the cluster analysis (Aldenderfer and Blashfield, 1984). A correlation coefficient value < 0.75 was selected as the cut-off point for inclusion. This process was repeated until there was no clear clustering from the higher-order combinations of variables.

Three statistical measures were used to determine the number of clusters; the Cubic Clustering Criterion (CCC), the Pseudo-F and Pseudo-t statistics (SAS Institute Inc., 1983; SAS Institute Inc., 1988). Three clustering methods were used: Ward, Average linkage, and Centroid. In the Ward method, distance between two clusters is computed as the Analysis of Variance sum of squares between the two clusters added up over all the variables. In the Average method, distance between two clusters is computed as the average distance between pairs of observations, one in each cluster. In the Centroid method, distance between two clusters is computed as the squared Euclidean distance between their centroids. The appropriate number of clusters at each step was determined as the best level of agreement between criteria and between methods.

Classification of Candidate Vulnerable Sections

Vulnerability classification was based on measuring the similarity of soil data from candidate sections to profiles developed from the clustering analysis. Climate data would be used as a screen to determine the appropriate soil profile test. Soil profiles were developed by conducting a PCA analysis on the standardized soil variables within identified clusters, and then computing the mean and standard deviation of each principal component (PC) score. Corresponding PCs for each cluster would be calculated for soil data from candidate sections. Inclusion of a candidate section into one of the vulnerable clusters would occur only if every PC score from the candidate section fell within a specified distance of the corresponding cluster's PC mean. The distance for each PC was determined as a constant 'K' multiplied by the cluster standard deviation of the PC. The value of K was chosen by examining the proportion of correct and incorrect classifications of KV sections as a function of K.

RESULTS

Climate Variables

Prior to clustering, correlation analysis was conducted on climatic variables from 32 weather stations nearest KV sections. In general, temperature variables were uncorrelated with precipitation variables (Table 3). Minimum yearly temperature was highly correlated with September through May mean monthly temperatures and less correlated with June, July, and August values. In contrast, maximum yearly temperature was highly correlated with March through October mean monthly temperatures and less correlated with November through February values. Total annual precipitation was highly correlated with September through May monthly

Table 3. Correlation matrix for climate variables. Correlation coefficients of 0.75 or greater are underlined to illustrate trends in the data. Acronyms are defined in Table 2.

Pearson Correlation Coefficients/N=32

Temperature Variables

	MIYR	MXYR	MNYR	M1T	M2T	M3T	M4T	M5T	M6T	M7T	M8T	M9T	M10T	M11T	M12T
MIYR	1.00	0.68	0.90	0.88	0.95	0.96	0.89	0.76	0.64	0.56	0.64	0.78	0.92	0.94	0.85
MXYR		1.00	0.93	0.49	0.66	0.81	0.92	0.95	0.94	0.93	0.96	0.97	0.90	0.64	0.45
MNYR			1.00	0.73	0.86	0.98	0.99	0.94	0.87	0.82	0.88	0.96	0.99	0.85	0.69
M1T				1.00	0.97	0.87	0.70	0.47	0.31	0.23	0.34	0.53	0.78	0.98	1.00
M2T					1.00	0.96	0.85	0.67	0.52	0.43	0.53	0.70	0.90	1.00	0.95
M3T						1.00	0.96	0.83	0.72	0.63	0.71	0.85	0.97	0.95	0.84
M4T							1.00	0.95	0.88	0.82	0.87	0.95	0.98	0.83	0.66
M5T								1.00	0.98	0.94	0.96	0.98	0.91	0.63	0.42
M6T									1.00	0.99	0.98	0.97	0.83	0.49	0.26
M7T										1.00	0.99	0.94	0.77	0.41	0.18
M8T											1.00	0.97	0.83	0.51	0.30
M9T												1.00	0.93	0.68	0.48
M10T													1.00	0.89	0.75
M11T														1.00	0.97
M12T															1.00
PYR															
M1P															
M2P															
M3P															
M4P															
M5P															
M6P															
M7P															
M8P															
M9P															
M10P															
M11P															
M12P															

Precipitation Variables

	PYR	M1P	M2P	M3P	M4P	M5P	M6P	M7P	M8P	M9P	M10P	M11P	M12P
MIYR	-0.13	-0.03	-0.01	-0.03	-0.07	-0.35	-0.71	-0.74	-0.27	-0.22	-0.23	-0.13	-0.14
MXYR	-0.60	-0.48	-0.50	-0.57	-0.59	-0.72	-0.78	-0.71	-0.33	-0.62	-0.64	-0.63	-0.59
MNYR	-0.42	-0.30	-0.30	-0.35	-0.38	-0.60	-0.81	-0.79	-0.33	-0.47	-0.49	-0.43	-0.41
M1T	0.02	0.13	0.14	0.16	0.08	-0.24	-0.63	-0.60	-0.17	-0.05	-0.14	0.00	0.01
M2T	-0.11	0.02	0.02	0.01	-0.05	-0.39	-0.75	-0.72	-0.28	-0.21	-0.25	-0.13	-0.11
M3T	-0.27	-0.15	-0.14	-0.18	-0.21	-0.52	-0.83	-0.79	-0.34	-0.37	-0.38	-0.29	-0.27
M4T	-0.42	-0.30	-0.31	-0.36	-0.37	-0.61	-0.84	-0.80	-0.36	-0.50	-0.49	-0.44	-0.41
M5T	-0.52	-0.42	-0.42	-0.50	-0.49	-0.64	-0.76	-0.74	-0.35	-0.57	-0.54	-0.53	-0.50
M6T	-0.57	-0.48	-0.49	-0.58	-0.56	-0.64	-0.67	-0.67	-0.32	-0.59	-0.55	-0.57	-0.55
M7T	-0.63	-0.56	-0.57	-0.64	-0.63	-0.64	-0.61	-0.60	-0.28	-0.60	-0.60	-0.63	-0.62
M8T	-0.62	-0.53	-0.54	-0.61	-0.61	-0.65	-0.67	-0.65	-0.29	-0.59	-0.61	-0.62	-0.61
M9T	-0.54	-0.44	-0.44	-0.51	-0.53	-0.66	-0.76	-0.74	-0.33	-0.57	-0.58	-0.55	-0.53
M10T	-0.39	-0.26	-0.26	-0.31	-0.35	-0.60	-0.83	-0.80	-0.36	-0.46	-0.48	-0.41	-0.38
M11T	-0.11	0.02	0.02	0.01	-0.06	-0.38	-0.73	-0.71	-0.26	-0.20	-0.26	-0.14	-0.12
M12T	0.06	0.16	0.17	0.19	0.10	-0.21	-0.59	-0.57	-0.15	-0.02	-0.11	0.03	0.04
PYR	1.00	0.97	0.98	0.98	0.97	0.87	0.59	0.47	0.44	0.88	0.97	0.99	0.99
M1P		1.00	0.99	0.95	0.93	0.73	0.43	0.32	0.29	0.75	0.89	0.94	0.98
M2P			1.00	0.97	0.96	0.77	0.45	0.33	0.30	0.80	0.91	0.96	0.98
M3P				1.00	0.98	0.85	0.49	0.39	0.39	0.88	0.93	0.97	0.98
M4P					1.00	0.84	0.50	0.37	0.32	0.84	0.93	0.96	0.96
M5P						1.00	0.83	0.71	0.64	0.96	0.93	0.90	0.83
M6P							1.00	0.90	0.69	0.74	0.70	0.61	0.55
M7P								1.00	0.76	0.68	0.60	0.49	0.45
M8P									1.00	0.72	0.56	0.46	0.39
M9P										1.00	0.92	0.90	0.84
M10P											1.00	0.98	0.96
M11P												1.00	0.98
M12P													1.00

average precipitation and less correlated with June, July, and August values. The forward clustering technique identified 5 distinct clusters formed from 3 variables. The clustering variables, given in order of selection, were average January temperature, average March precipitation, and average July precipitation. Means for each variable in each cluster are given for the solution derived from the Ward method (Table 4). Clusters 3 and 5 had high precipitation values: cluster 5 had the highest March precipitation and cluster 3 the highest July precipitation. Clusters 1, 2, and 4 had low precipitation vales, differing mainly in January temperatures: cluster 2 had the highest and cluster 4 the lowest January temperatures. The following geographic patterns were observed when weather station membership in each cluster was identified by county location of the weather station (Table 5). Cluster 1 was dominated by counties in the the Central Valley. Counties in cluster 2 were located in the central and south coasts and in inland portions of southern California. Counties in clusters 3 and 5 were Humbolt and Del Norte, northern coastal counties. Siskiyou comprised cluster 4, reflecting the weather of a higher mountainous locale.

Soil Variables

Theoretically, clustering of soil variables would have occurred within each of the climate clusters to identify unique soil clusters within climate clusters. There were insufficient numbers of sections in most of the climate clusters to perform this analysis. However, the results of the climate clustering were highly indicative that KV sections in clusters 1, 2, and 4 could be grouped because they represented a low rainfall condition when compared to much higher rainfall values for those in clusters 3 and 5. Thus, the eleven sections in Del Norte and Humbolt counties were excluded from the soil clustering analysis. An additional 9 sections were excluded

Table 4. Means by cluster for weather variables produced by the 5 cluster solution for the Ward clustering method.

Cluster	Weather Stations	Nearest KV Sect	January Temperature	Precipitation March	Precipitation July
	---------#---------		---°F---	-------inches-------	
1	20	153	45	1.8	0.03
2	7	16	52	2.0	0.04
3	2	2	47	4.5	0.71
4	2	2	29	1.0	0.29
5	1	7	47	8.6	0.31

Table 5. Cluster association given by county location for 32 weather stations nearest KV sections.

Cluster	County Location of Weather Station
1	Contra Costa, Colusa, Fresno, Glenn, Kern, Merced, Sacramento, San Joaquin, Stanislaus, Tehama, Tulare, Yolo, Yuba
2	Santa Cruz, Orange, Riverside, Santa Clara, San Diego
3	Humbolt
4	Siskiyou
5	Del Norte

because of a lack of depth to ground water data. A total of 160 KV sections located in dry weather clusters were used in the soil clustering analysis.

Correlation analysis was first conducted on the 33 soil variables (Table 6). One group consisted of 15 highly correlated variables which was comprised of 10 variables that indicated texture in terms of sand and clay content of either the surface or subsurface soil, 4 variables that measured the permeability and shrink-swell potential of the surface and subsurface soil, and a variable that indicated the hydrologic category of the soil. A second group of seven correlated variables consisted of indicators of cobbly or stony soil and measures of the percentage by weight of soil particles passing through coarse sieve sizes Nos. 4 and 10. The 11 remaining variables were uncorrelated.

The best clustering variable in the first step of the forward selection technique was a texture variable that measured the percent by weight of soil particles that pass through a No. 200 soil sieve. Soil texture is reflected by this variable in the following way: the lower the number of soil particles passing through the No. 200 sieve, the greater the sand content of the soil and conversely, the greater the number, the greater the clay content of the soil. Two clusters were indicated with this single variable. The best combinations of variables that indicated clustering in subsequent steps are given in Table 7. The final solution occurred with a combination of four variables: 1) the texture variable measuring soil particles passing a No. 200 soil sieve; 2) a variable that indicated presence of a water table above 5 feet some time during the year;

Table 6. Correlation matrix for soil variables. Correlation coefficients of 0.75 or greater are underlined to illustrate trends in the data. Acronyms are defined in Table 2.

Pearson Correlation Coefficients/N=160

Variables Correlated with Soil Texture

	TEXTSAND	TEXTCLAY	TXT1SND	TXT1CLY	LAY1SHSW	HYD	LAY1CLAY	LAY1PERM	LAY1N200	SUBTXSND	SUBTXCLY	SUBSHSW	SUBCLAY	SUBPERM	SUBN200
TEXTSAND	1.00	-0.87	0.98	-0.87	-0.82	-0.80	-0.89	0.89	-0.95	0.90	-0.85	-0.86	-0.87	0.79	-0.88
TEXTCLAY		1.00	-0.87	0.99	0.97	0.85	0.98	-0.78	0.91	-0.88	0.92	0.92	0.92	-0.73	0.89
TXT1SND			1.00	-0.88	-0.84	-0.80	-0.91	0.89	-0.96	0.92	-0.86	-0.87	-0.89	0.79	-0.90
TXT1CLY				1.00	0.97	0.84	0.99	-0.78	0.92	-0.88	0.92	0.92	0.92	-0.72	0.90
LAY1SHSW					1.00	0.76	0.97	-0.68	0.90	-0.86	0.89	0.91	0.89	-0.63	0.89
HYD						1.00	0.85	-0.84	0.83	-0.84	0.90	0.88	0.89	-0.87	0.82
LAY1CLAY							1.00	-0.82	0.94	-0.92	0.94	0.94	0.95	-0.76	0.93
LAY1PERM								1.00	-0.85	0.86	-0.82	-0.79	-0.84	0.89	-0.80
LAY1N200									1.00	-0.96	0.92	0.93	0.94	-0.79	0.96
SUBTXSND										1.00	-0.96	-0.95	-0.97	0.86	-0.98
SUBTXCLY											1.00	0.99	0.99	-0.82	0.95
SUBSHSW												1.00	0.99	-0.79	0.95
SUBCLAY													1.00	-0.84	0.97
SUBPERM														1.00	-0.81
SUBN200															1.00
TEXTIND															
TXT1IND															
LAY1NO4															
LAY1NO10															
SUBTXIND															
SUBNO4															
SUBNO10															
LAY1DEPH															
PAN															
SUBDEPH															
DRAIN															
WATTAB															
FLOOD															
SLOPE															
LAY1OM															
LAY1AWC															
SUBAWC															

Table 6. Continued.

Pearson Correlation Coefficients/N=160

	Variables Correlated with Coarse Soil Variables							Uncorrelated Variables											
	TEXTIND	TXT1IND	LAY1NO4	LAY1NO10	SUBTXIND	SUBNO4	SUBNO10	LAY1DEPH	PAN	SUBDEPH	DRAIN	WATTAB	FLOOD	SLOPE	LAY1OM	LAY1AWC	SUBAWC	DGW
TEXTSAND	-0.04	-0.03	-0.26	-0.41	-0.02	-0.22	-0.34	-0.45	-0.05	-0.28	0.64	-0.57	-0.11	0.08	-0.69	-0.69	-0.58	0.45
TEXTCLAY	0.01	-0.01	0.28	0.43	-0.07	0.29	0.41	0.61	-0.03	0.35	-0.62	0.58	0.10	0.00	0.65	0.53	0.55	-0.41
TXT1SND	-0.05	-0.03	-0.27	-0.42	-0.02	-0.24	-0.36	-0.47	-0.01	-0.29	0.69	-0.63	-0.16	0.09	-0.72	-0.69	-0.61	0.44
TXT1CLY	0.02	0.00	0.27	0.42	-0.06	0.29	0.42	0.62	-0.05	0.36	-0.61	0.58	0.07	0.00	0.64	0.53	0.54	-0.41
LAY1SHSW	-0.05	-0.07	0.34	0.49	-0.12	0.36	0.48	0.59	-0.15	0.36	-0.59	0.59	0.12	-0.04	0.64	0.48	0.55	-0.39
HYD	0.04	0.04	0.22	0.34	-0.04	0.23	0.33	0.58	0.23	0.28	-0.63	0.44	-0.08	0.10	0.49	0.57	0.44	-0.47
LAY1CLAY	0.03	0.01	0.27	0.43	-0.05	0.28	0.41	0.61	-0.07	0.37	-0.65	0.61	0.12	-0.03	0.66	0.55	0.58	-0.38
LAY1PERM	-0.14	-0.13	-0.08	-0.20	-0.13	-0.04	-0.14	-0.51	-0.14	-0.29	0.61	-0.44	-0.06	0.00	-0.55	-0.70	-0.60	0.29
LAY1N200	-0.02	-0.03	0.35	0.51	-0.05	0.31	0.43	0.55	-0.05	0.33	-0.67	0.62	0.11	-0.11	0.70	0.68	0.64	-0.48
SUBTXSND	-0.02	-0.01	-0.28	-0.44	0.05	-0.26	-0.39	-0.54	0.08	-0.28	0.68	-0.59	-0.13	0.09	-0.64	-0.65	-0.66	0.43
SUBTXCLY	0.04	0.03	0.25	0.41	-0.07	0.27	0.40	0.59	-0.04	0.31	-0.64	0.52	0.05	-0.01	0.58	0.56	0.55	-0.43
SUBSHSW	-0.01	-0.02	0.30	0.46	-0.13	0.33	0.46	0.58	-0.05	0.31	-0.63	0.53	0.08	-0.02	0.60	0.56	0.54	-0.43
SUBCLAY	0.03	0.02	0.27	0.43	-0.08	0.29	0.43	0.59	-0.05	0.29	-0.67	0.55	0.08	-0.03	0.62	0.58	0.58	-0.42
SUBPERM	-0.04	-0.03	-0.15	-0.26	0.00	-0.15	-0.24	-0.51	-0.19	-0.26	0.62	-0.39	-0.01	-0.03	-0.49	-0.63	-0.62	0.29
SUBN200	-0.07	-0.09	0.38	0.54	-0.15	0.38	0.51	0.56	-0.13	0.29	-0.67	0.60	0.12	-0.09	0.65	0.61	0.67	-0.43
TEXTIND	1.00	0.99	-0.86	-0.76	0.86	-0.80	-0.72	0.01	-0.10	-0.12	0.11	-0.04	-0.10	0.07	0.00	0.00	-0.07	-0.03
TXT1IND		1.00	-0.85	-0.76	0.85	-0.80	-0.72	0.00	-0.09	-0.13	0.12	-0.05	-0.10	0.07	0.00	-0.01	-0.09	-0.02
LAY1NO4			1.00	0.95	-0.78	0.91	0.87	0.13	0.09	0.10	-0.34	0.30	0.08	-0.09	0.29	0.25	0.23	-0.31
LAY1NO10				1.00	-0.73	0.89	0.91	0.21	0.01	0.14	-0.46	0.42	0.15	-0.18	0.42	0.32	0.32	-0.33
SUBTXIND					1.00	-0.89	-0.84	-0.03	-0.02	0.02	0.15	-0.06	-0.14	0.01	-0.09	0.02	-0.04	-0.02
SUBNO4						1.00	0.98	0.14	0.01	0.01	-0.33	0.26	0.06	0.00	0.29	0.13	0.19	-0.22
SUBNO10							1.00	0.22	-0.06	0.04	-0.41	0.35	0.09	-0.02	0.38	0.18	0.27	-0.25
LAY1DEPH								1.00	-0.12	0.66	-0.29	0.24	-0.13	0.04	0.33	0.33	0.38	-0.24
PAN									1.00	-0.11	-0.09	-0.13	-0.15	0.10	0.00	0.17	-0.07	-0.13
SUBDEPH										1.00	-0.18	0.17	0.06	-0.24	0.16	0.12	0.13	-0.04
DRAIN											1.00	-0.85	-0.43	0.19	-0.67	-0.36	-0.35	0.33
WATTAB												1.00	0.57	-0.28	0.65	0.29	0.33	-0.34
FLOOD													1.00	-0.36	0.35	0.07	0.05	0.21
SLOPE														1.00	-0.08	-0.07	0.05	-0.04
LAY1OM															1.00	0.58	0.52	-0.44
LAY1AWC																1.00	0.66	-0.46
SUBAWC																	1.00	-0.23
DGW																		1.00

Table 7. Comparison between clustering methods and between criteria for the number of clusters found from stepwise addition of soil variables. Acronyms are defined in Table 2.

Variables and Clustering Method	Number of Clusters According to these Criteria: CCC	Pseudo-F	Pseudo-t
Step 1: Lay1n200[a]			
Ward	2	2	5
Average	2	2	2
Centroid	2	2	2
Step 2: Lay1n200 and Wattab			
Ward	3	3	3
Average	3	3	3
Centroid	5	5	4
Step 3: Lay1n200, Wattab, and Slope			
Ward	4	4	4
Average	5	5	5
Centroid	5	5	5
Step 4: Lay1n200, Wattab, Slope, and Lay1no4			
Ward	6	5	5
Average	7	7	7
Centroid	7	7	7

3) a variable that indicated the average slope of the section; and 4) a variable that measured the number of soil particles that pass through a No. 4 soil sieve (the lower the number, the more volume of soil taken up by large soil constituents). Although the number of clusters differed between the Ward and the other 2 clustering methods at the four variable solution, the variables selected by the methods were identical. The Average and Centroid methods indicated a 7 cluster solution but 2 extra clusters, enclosed in the boxes in Figure 1, were produced from an early split of the same parent clusters identified in the Ward procedure.

The 5 cluster solution from the Ward method was determined as the final solution. Each cluster from this solution had a unique combination of variables as indicated by the means for variables in each cluster (Table 8). Soils in clusters 1 and 3 were clayey, as indicated by the higher % values for the Lay1n200 variable and had shallow slopes. Cluster 3 was split from cluster 1 because those sections also had a high incidence of soils with a water table above 5 feet. In contrast, soil in cluster 2 was sandy with shallow slope and with practically no presence of a shallow water table. Clusters 4 and 5 were intermediate in terms of surface soil texture but each was unique in that sections in cluster 4 had greater values for slope and those in cluster 5 had a greater incidence of large soil particles such as cobbles or stones as indicated by the lower % values for the Lay1no4 variable.

Assessment of the clustering results was conducted by mapping the location of sections as identified by cluster association. There was good geographic

Figure 1. Heirarachical clustering results for the Ward and Average methods using 4 soil variables. Underlined numbers represent the final cluster solution for each method and numbers inside boxes for Average method are splits of clusters 11 and 15 in Ward method.

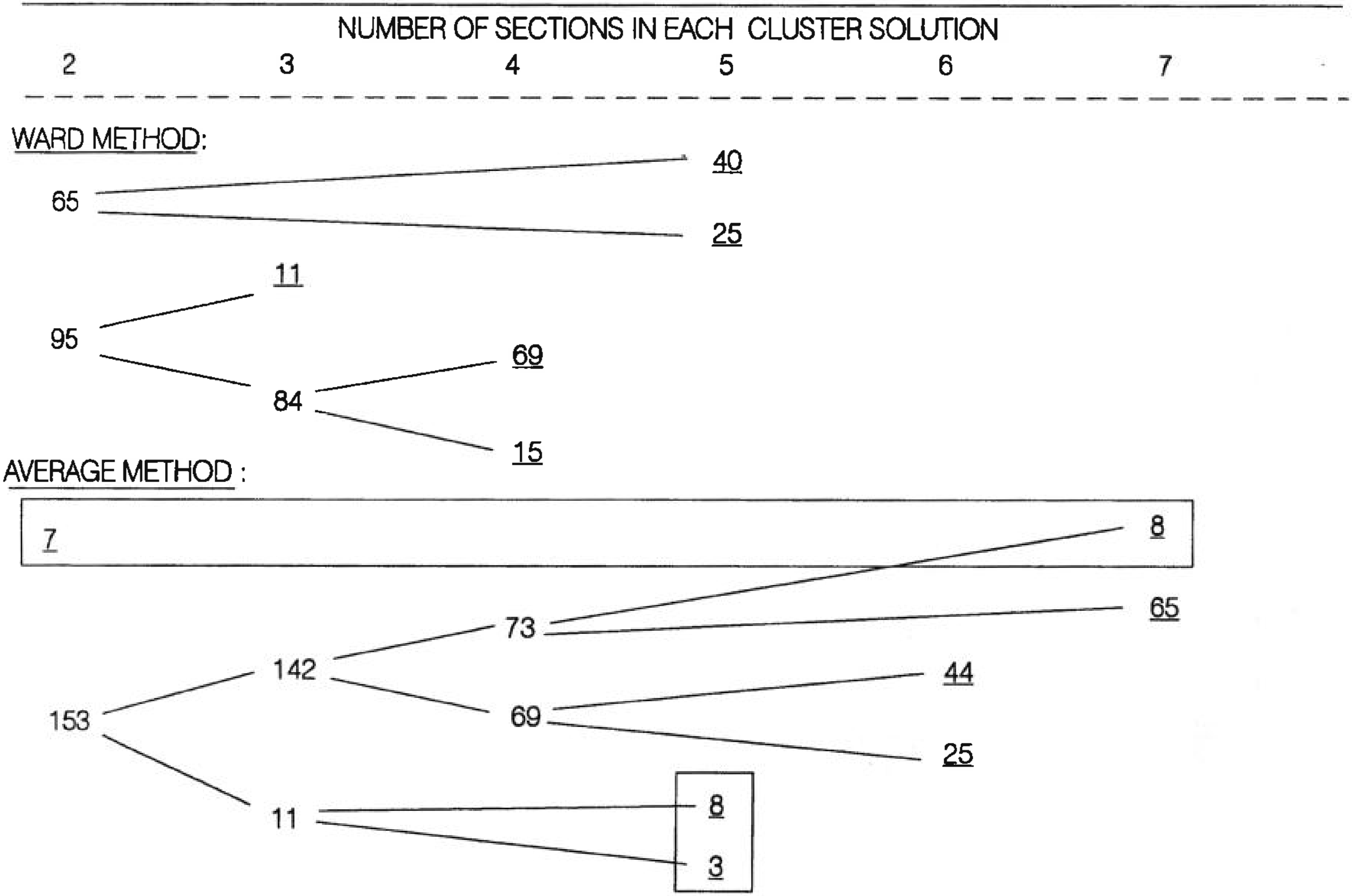


Table 8. Means by cluster for soil variables produced by the 5 cluster solution for the Ward clustering method.

Cluster	N	Lay1n200	Wattab[a]	Slope	Lay1no4
		---%----		--------%-----------	
1	40	79	0.22	1.4	99
2	69	40	0.04	1.6	96
3	25	81	0.76	0.8	98
4	11	57	0	12.7	96
5	15	56	0.15	2.6	86

a Scale from 0-1 with a 0 value representing no soils in a section with a shallow water table above 5 feet and a value of 1 representing all soils in a section with a shallow water table.

separation between clusters. Sandy sections in cluster 2 were predominately located in the southern portion of the Central Valley and in the Southern Desert areas whereas clayey sections in clusters 1 and 3 were predominately located in the northern portion of the Central Valley (Figure 2). Within the clayey clusters, those with a greater incidence of shallow water table were located in a band sandwiched between groups of sections in cluster 1 (Figure 3). Sandy sections of cluster 2 in the southern Central Valley were located along the valley floor with some sections in cluster 4 located along the foothills (Figure 4). Thus, the clustering appeared effective in providing a regional description of the location of vulnerable sections. If pathways of contamination are related to variables associated with each cluster, then it may be possible to devise and specify cluster-based management strategies. This approach could facilitate management decisions on a regional basis.

Procedure for Identifying Vulnerable Sections

A two-stage procedure for identifying candidate sections as vulnerable was developed. The first stage would be a climate screen to determine if the candidate section's rainfall was either high or low. If the candidate section had high rainfall, then it would be subject to a soil profile test derived from soil data for KV sections in Humbolt and Del Norte counties. If the candidate section had low rainfall, then it would be subjected to further classification based on the soil profiles developed from KV sections in each of the 5 low-rainfall soil clusters.

Figure 2. Spatial location of sections in clusters 1 and 3 with predominantly clayey soil contrasted to locations of sections in cluster 2 with predominantly sandy soil.

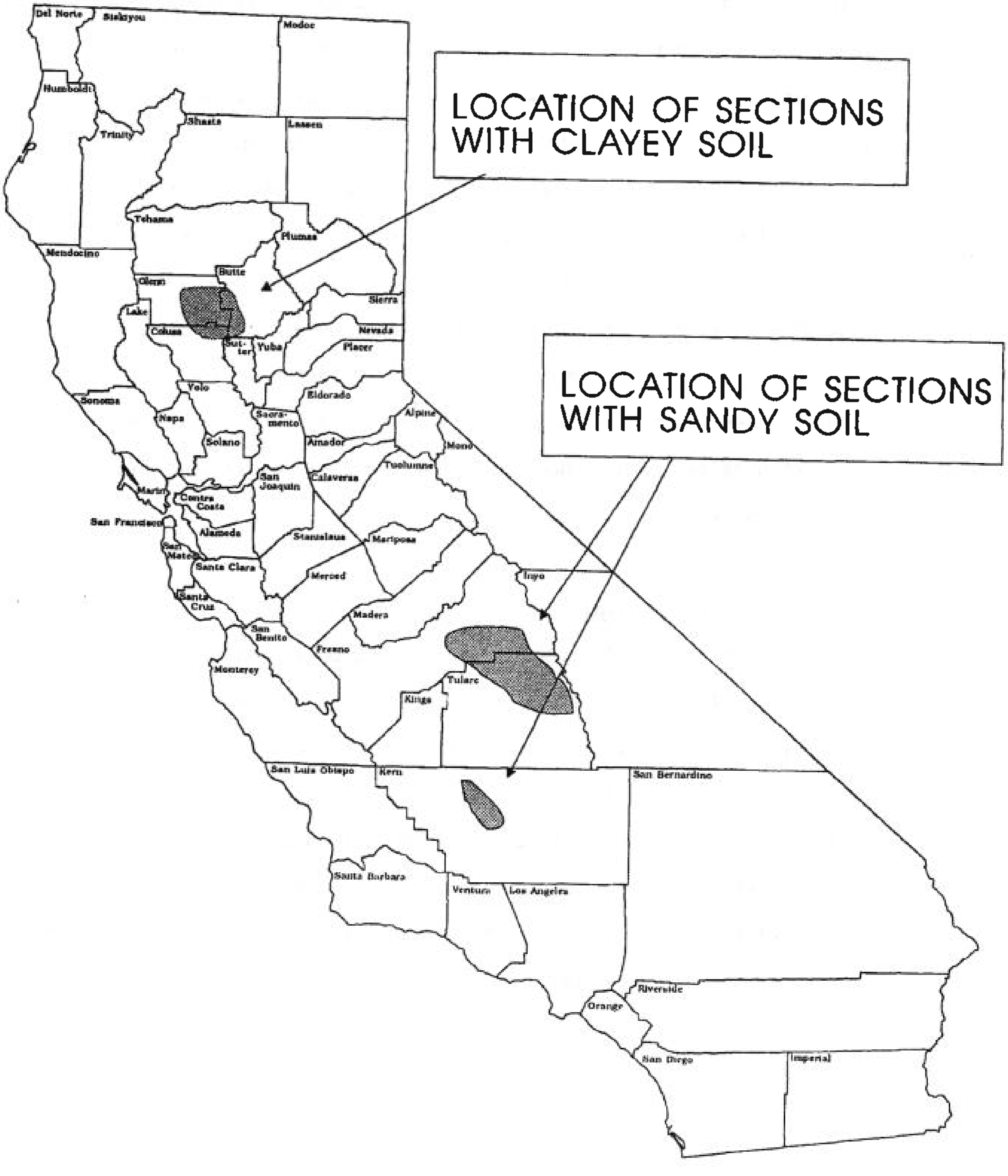


Figure 3. Cluster membership for known vulnerable sections in the northern Central Valley.

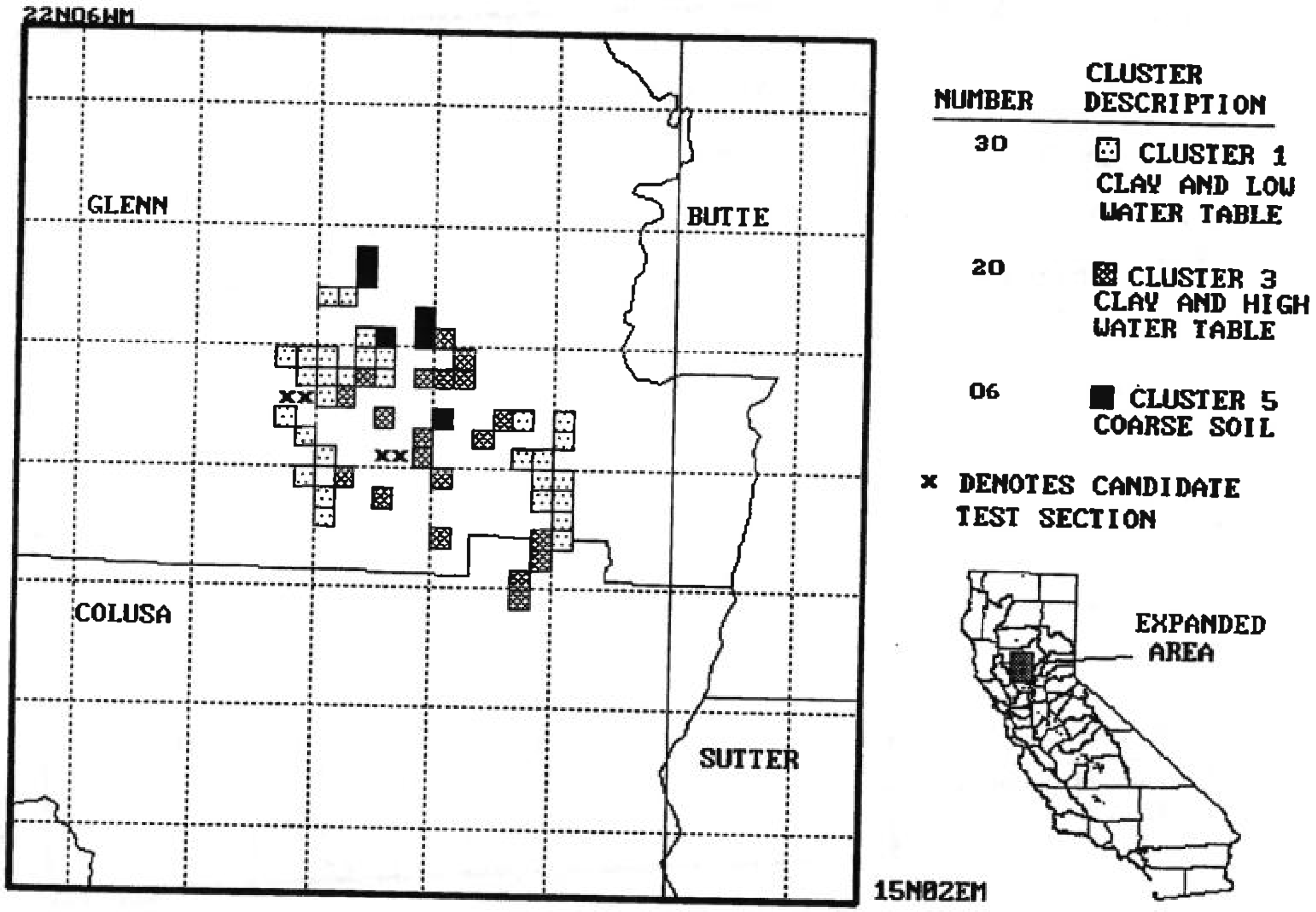
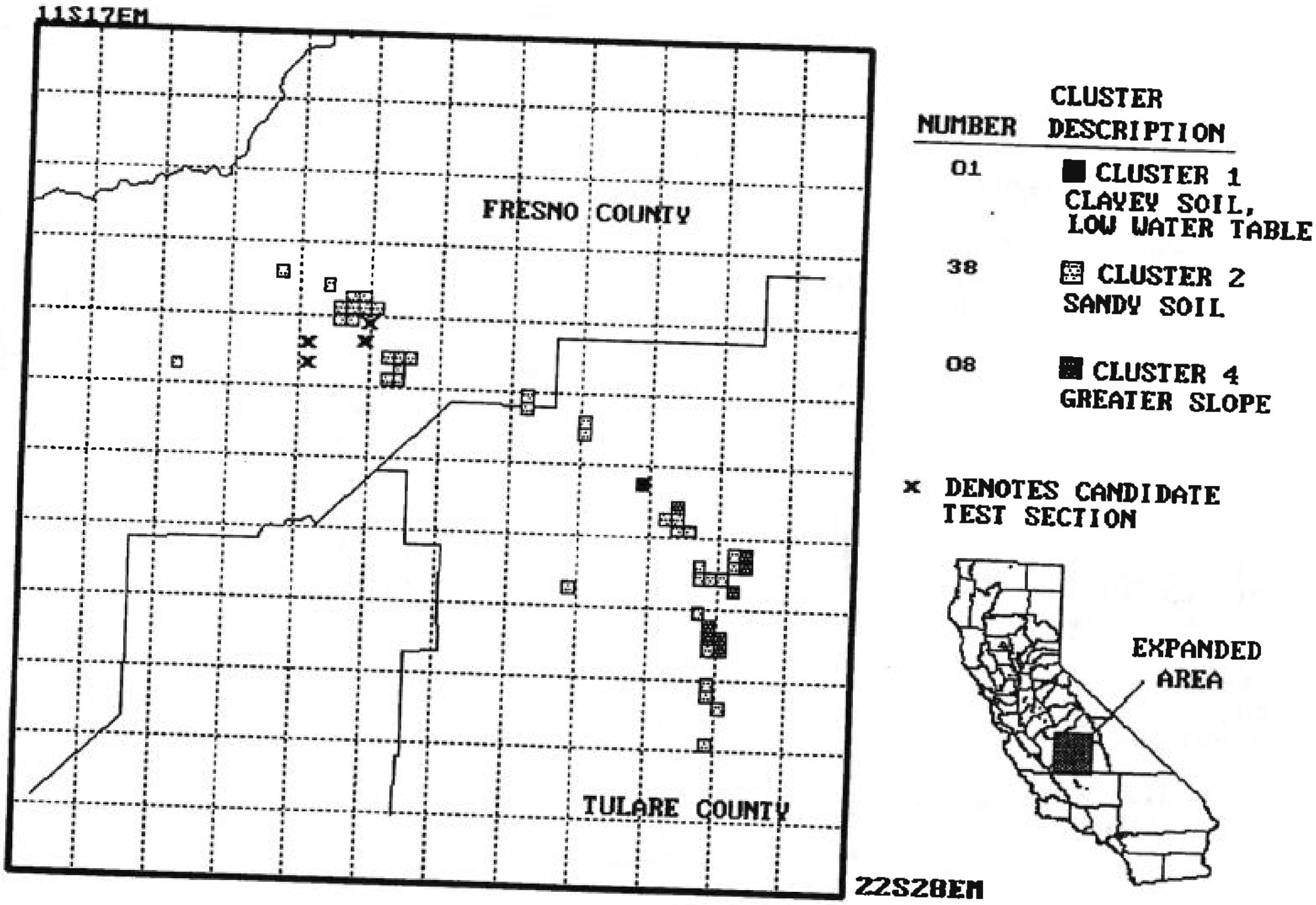
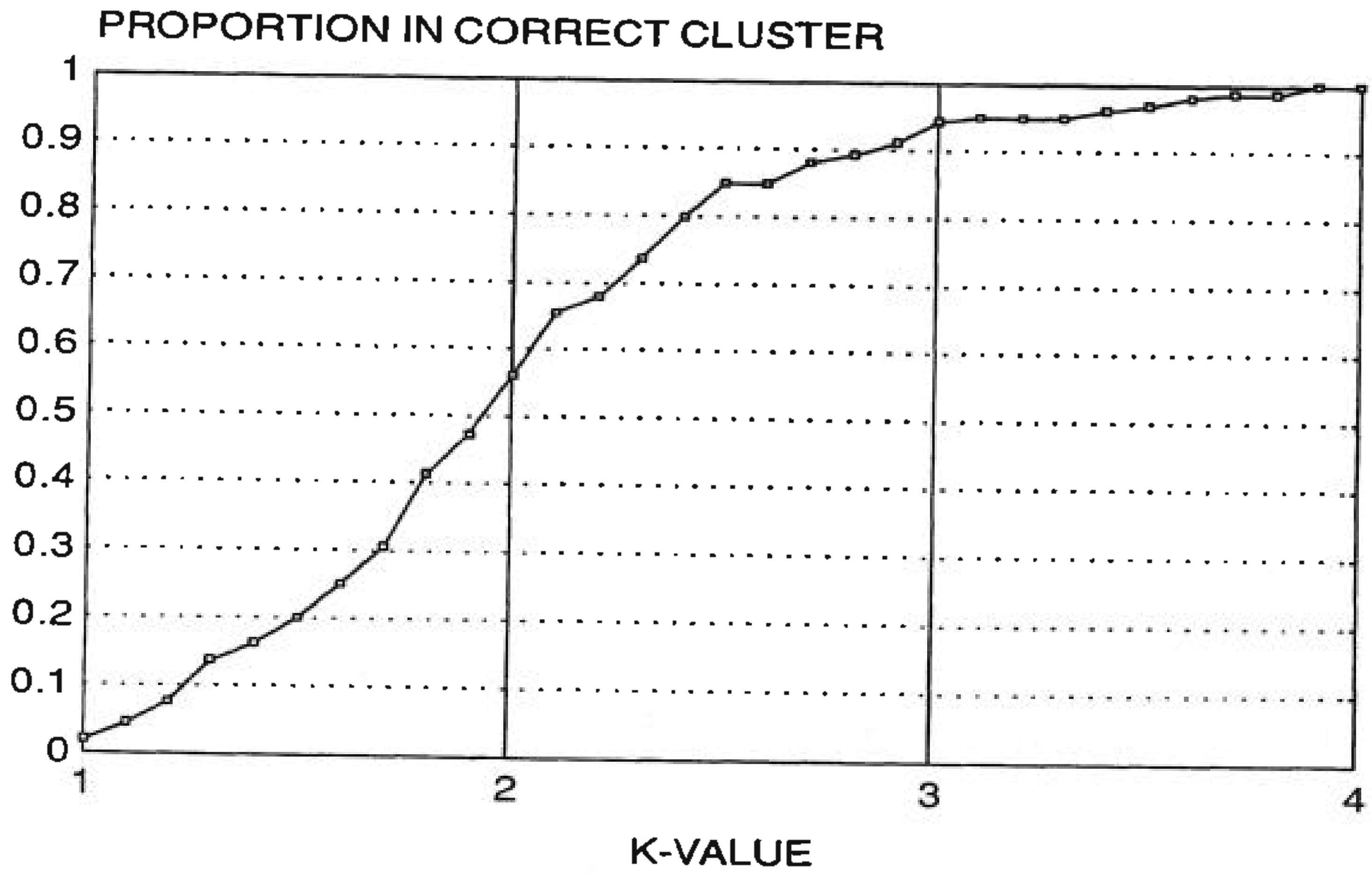


Figure 4. Cluster membership for known vulnerable sections in the southern Central Valley in Fresno and Tulare counties.



Soil profiles were developed using 15 of the 33 soil variables. Redundant variables were excluded from the algorithm. For example, the number of soil particles passing sieve No. 200 was highly correlated with all derived texture variables so the derived texture variables were omitted. Classification into surface and subsurface layers was retained because this could be an informative division in future investigations. The variables denoted with the superscript 'c' in Table 1 were used to develop the classification algorithm. For a candidate section, data for the 15 soil variables first would be standardized to the mean and standard deviation of corresponding variables in each of the KV soil clusters. PC scores would be calculated for the candidate section based on the 15 standardized variables and the values compared to a specified range for each corresponding PC in a soil cluster. Inclusion into a cluster would occur only if <u>all</u> PC scores were within 3 standard deviations of the mean (zero). The multiplier 3 was determined from a plot of the number of KV sections correctly classified as a function of the value of K. When the value was 3, 95% of the KV sections were correctly classified into their respective soil clusters (Figure 5). Although a larger value of K would achieve 100% correct classifications, it could also result in the classification of more dissimilar sections as vulnerable. A candidate section would be classified as vulnerable if it could be considered a member of one of the soil clusters, otherwise it would be considered as not classifiable. There is no implication that sections not classified are invulnerable.

Figure 5. Proportion of sections classified into the correct cluster as a function of K, a multiplier of the standard deviation of PC scores.



An example of the classification procedure is given for eight candidate sections, 4 in Glenn county and 4 in Fresno county. The sections were chosen from areas near 3 of the low-rainfall KV clusters (Figures 3 and 4). Since these sections are near low rainfall weather stations, their soil data were compared to the 5 clusters identified from the cluster analysis of the low rainfall KV sections. The occurrence of soil mapping units in each of the candidate sections was manually determined from SCS soil maps in published soil surveys for Glenn and Fresno counties. Data for the 15 soil variables for each of the soil mapping units were extracted from the MUIR database and average values calculated for each section. The average sectional values were standardized to the corresponding mean and standard deviation of each of the 5 soil clusters. Next, PC scores for the standardized values were calculated by multiplying the standardized values with the PC coefficients for each of the 5 clusters. The membership test was then conducted by determining if each sectional PC score was within 3 standard deviations of the mean of that cluster. Results in Table 9 are expressed in terms of the number of tests for that cluster where the PC score for the standardized section was outside the range. A value of zero indicates cluster membership. All 4 sections in Fresno county were classified as belonging to Cluster 2, the predominately sandy cluster. Two of the sections in Glenn county were geographically near and subsequently, classified into Cluster 3, clayey sections with high incidence of a water table above 5 feet. Two other section in Glenn county were geographically near Cluster 1, clayey sections with low incidence of a shallow water table, but only one of those sections was identified as a member of that cluster.

Table 9. Test of the classification of candidate sections for membership in one of the low rainfall soil clusters.

Section Location	Number of PC Tests Out of The Range for Cluster: 1	2	3	4	5
Fresno County					
15S21E01	6	0	12	2	6
15S21E06	6	0	12	6	7
15S21E07	6	0	10	6	6
15S21E12	5	0	10	3	6
Glenn County					
19N03W34	3	6	0	9	7
19N03W35	1	7	0	7	8
19N04W13	2	4	7	3	5
19N04W14	0	3	11	6	4

These results have two implications with respect to implementation of management strategies. First, the choice of a section as a basic geographic unit appears to give good results: averaging all mapping units within a section produced logical patterns with respect to geographic association of soil mapping units. Second, regional management strategies may be possible based on the clusters. For example, division of sections based on soil texture suggested that different management strategies may be required for clayey vs sandy soils: special properties of clay soil such as the appearance of cracks or a shallow water table could require a different set of management conditions than those generated for sandy soils. However, more information is needed on the processes important in pesticide movement in each cluster in order to provide a link between management practices and cluster identification.

In summary, the present study has endeavored to create profiles of groups of known contaminated sections in California with respect to a series of climatic and physical soil properties. The following question has been answered: what are some of the vulnerable sections in California like? The profile analysis of this study differed from a typical discriminant analysis in two ways. First, profiles were devised only for vulnerable sections: no non-vulnerable sections were studied or defined. We, therefore, have no way of evaluating the usefulness of the climatic and soil variables as discriminators for vulnerability. It is possible that variables were used which are not effective in discrimination. Second, profiles were created for five clusters comprising a total of only 160 sections. There may be other vulnerable cluster profiles with characteristics not included in our description of vulnerability. Therefore, new candidate sections which are not classified as similar to one of the known vulnerability clusters are not necessarily invulnerable. They retain a status of unknown vulnerability which could be changed when the clustering and classification procedures are updated to reflect new positive well sampling data.

SUMMARY

1. Clustering methods were successful in grouping vulnerable sections based on climate and soil variables. However, due to differences in the variance structure two separate procedures were used.
2. Clustering of data from weather stations resulted in 5 distinct groups that were related to geographic location of the weather station. With respect to pesticide movement to ground water, two of the clusters had high rainfall and contained 11 of the 180 vulnerable sections, 7 in Del Norte and 4 in Humbolt counties. The remaining KV sections were in the other 3 clusters that had low rainfall.
3. Clustering analyses were conducted on soil data from 160 KV sections that were members of the low rainfall clusters. Using a forward selection technique, four soil variables were identified that clustered 160 vulnerable sections into 5 groups. The variables were: 1) soil texture as measured by the percentage by weight of soil material smaller than 76 mm that passes a No. 200 (75 µm) soil sieve; 2) indication of the presence of a water table above 5 feet during the year; 3) the average slope of mapping units in a section; and 4) an indication of the presence of coarse soil particles such as cobbles or stones as measured by the percentage by weight of soil material smaller than 76 mm that passes a No. 4 (5 mm) soil sieve.

4. Due to differences noted in the variance of the climate and soils data sets, a two-stage approach was developed to identify candidate sections as vulnerable. A candidate section would be screened to determine whether if it had low or high rainfall. If the candidate section had low rainfall, then it would be subjected to a classification algorithm developed from the results of the clustering of soil variables for 160 vulnerable sections in low-rainfall areas. If the section passed the soil algorithm then it would be identified as a vulnerable section. If the section had high rainfall, then it would be considered vulnerable if data from soil variables passed an algorithm developed from properties of soils that occur in vulnerable sections in Del Norte and Humbolt counties.

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Chapter 13

Simulation Processes for the Nitrogen Loss and Environmental Assessment Package

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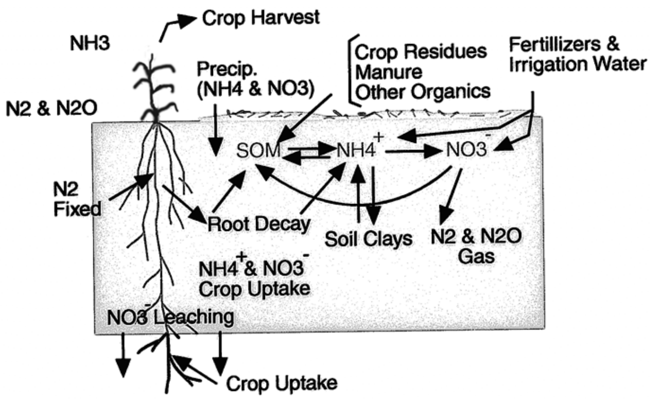
NLEAP SIMULATION OF CARBON AND NITROGEN CYCLING

NLEAP simulates soil carbon and nitrogen ratio (C/N) processes for upland soils in one dimension starting with residue cover on the soil surface and continuing down through the crop root zone to the bottom of the soil profile (Figure 1). Processes include infiltration and transport of soil water and nitrates; carbon and nitrogen cycling and transformations on the soil surface and within the soil profile; surface runoff of water, nitrate, and ammonium; nitrate leaching from the root zone; crop uptake of nitrate and ammonium; denitrification losses (including N_2 and N_2O); and ammonia volatilization.

As with the previous version, NLEAP DOS the user supplies the expected crop yields, and the information is used to distribute crop uptake of water and nitrogen over the growing season. The current NLEAP can handle a wide range of agricultural crops (over 50), and additional crops can be easily configured for inclusion. The model allows for the flexibility to add crop varieties that are used at site-specific regions of the country.



Nitrogen Cycle (upland soils)

Figure 1. The NLEAP modeling approach provides a fast and efficient means of integrating management effects with soil and climate information to calculate nitrogen (N) losses from agricultural fields. These losses include NO_3-N leaching from the crop root zone, gaseous emissions of N_2O and N_2, NH_3 volatilization, and surface wash-off of N (Shaffer and Ma, 2001).

SUBMODELS FOR C/N CYCLING PROCESSES ON THE SOIL SURFACE AND WITHIN THE SOIL PROFILE

A submodel has been added for C/N cycling on the soil surface. This simulation accounts for decomposition of crop residues, manure, other organics, and inorganic nitrogen fertilizers that are applied to the soil surface. Decay of standing, dead crop residues is handled separately from flat-lying residue decay, and an algorithm is included to convert values of standing to flat-lying residues. The surface submodel also accounts for denitrification and gaseous losses of NH_3 plus surface runoff of NH_4-N and NO_3-N.

A similar, related submodel for residue decomposition and cycling within the soil profile uses most of the base rate equations and computer code but includes different process rate coefficients and stress functions. With both submodels, individual applications of organic materials are tracked from the time they enter the soil surface or soil profile until they become soil organic matter (SOM). SOM formed on the soil surface is assumed to be part of the upper-most (Ap) soil horizon. Tillage incorporates surface materials into the soil and infiltration of water moves NO_3-N into the soil.

Mineralization of Soil Organic Matter

Mineralization of SOM is simulated using a two-pool model, containing a fast, readily decomposable pool and a slower humus pool (Figure 2). Decomposition within each pool is simulated using a first order rate equation of the form shown in the following equation:

$$NOMR = k_{om\ r} * SOM * TFAC * WFAC * ITIME * 0.58/10 , \quad (1)$$

where NOMR = the ammonium-N mineralized (kg/ha/time step); k_{omr} = the first order rate coefficient (fast or slow pool); SOM = soil organic matter (kg/ha); and ITIME = the size of the time step (days).

The fraction of carbon in the SOM is 0.58 and the C/N ratio is 10. Factors for temperature stress (TFAC) and water stress (WFAC) are calculated using the relationships described below. Transfer from the fast to slow organic matter pools is accomplished using a transfer coefficient, which is controllable by the user.

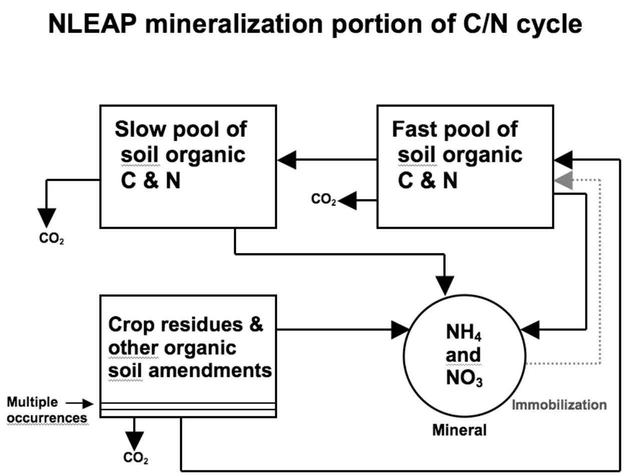


Figure 2. Mineralization of soil organic matter is simulated using a 2-pool model containing a fast, readily-decomposable pool and a slower humus pool.

Crop Residue and Other Organic Matter Mineralization

Mineralization of crop residues and other organic materials, such as manure, are computed using the following equations:

$$CRES = fr * RES \ , \tag{2}$$

where CRES = the carbon content of the residues (kg/ha); RES = the dry residues (kg/ha); fr = the carbon fraction of the residues;

constrained by

$$CRESR = k_{res} * RADJST * CRES * TFAC * WFAC * ITIME \ , \tag{3}$$

where CRESR = the residue carbon metabolized (kg/ha/time step); k_{resr} = the first order rate coefficient (day^{-1}); RADJST = the rate adjustment factor depending on the current C/N ratio.

RADJST is set to 0.29 at a C/N of 100; 0.57 at a C/N of 40;1.0 at a base C/N of 25; and 2.6 at a C/N of 9. Linear interpolation is used between these points. Transfer of decayed residue material to the fast N_0 pool occurs at a C/N ratio of 6.5 for manure and other organics, at a C/N ratio of 10 for crop residues starting at less than 25, and at a C:N ratio of 12 for crop residues starting at ≧25.

The residue carbon is updated after each time step using the following equation:

$$CRES = CRES - CRESR \ , \tag{4}$$

constrained by CRESR $\leq$ CRES.

Net mineralization-immobilization is determined using the following:

$$NRESR = CRESR * (1/CN - 0.0333) \ , \tag{5}$$

constrained by

$$- NRESR \leq NAF + NIT1, \text{ when } NRESR < 0.0 \ ,$$

where NRESR = the net residue-N mineralized (kg/ha/time step); CN = the current carbon to nitrogen ratio of the residues used in equation 5; NAF = the ammonium-N content; NIT1 = the nitrate-N content of the top 30 cm (kg/ha).

The N content of the decaying residues is updated after each time step using the following:

$$NRES = NRES - NRESR \ , \tag{6}$$

constrained by

$$NRESR \leq NRES \ .$$

A new value for CN is computed for the next time step using equation 7:

$$CN = CRES/NRES \ , \qquad (7)$$

where NRES = N content of the crop residues, manure, or other organic wastes (kg/ha).

The mineralization of manure and other organic wastes is calculated using the same basic equation set for crop residues given above, with manure or organic wastes substituted for crop residues.

Equations 2 through 7 assume (1) that crop residues contain a user-supplied percent carbon (manure and other organic wastes are assigned percentages based on separate user-supplied analysis), (2) that net mineralization/immobilization equals zero at a C/N value of 30, and (3) that the C/N value for soil microbes is 6.0. The values of corresponding first order rate coefficients (k_{resr}, k_{manr}, and k_{othr}) depend on the material being decomposed and the current C/N values. In general, fresh materials are assigned a higher rate coefficient until a C/N value is reached, where most of the faster pool has been decomposed and a lower rate coefficient is required.

In the case of surface standing dead crop residues, a conversion function is used to estimate when standing residues break off and become flat-lying on the ground. This function is driven by decay of the residue base, wind run, and tillage and can be expressed as follows:

$$RESMOV = k_{till} * (1 - RES/SSORIG) * WINDRUN/250000 \ , \qquad (8)$$

where RESMOV = the daily fraction of the standing residue converted to flat-lying; k_{till} = a tillage coefficient (0.045 with tillage, 0.035 without tillage); RES (kg/ha) = the mass of residue contacting the soil; SSORIG (kg/ha) = the mass of original fresh residue contacting the soil; WINDRUN (km) = total wind since the residue was fresh.

Nitrification and N_2O Emissions

The nitrification of ammonium-N is calculated using the following equation:

$$N_n = k_n * TFAC * WFAC * ITIME \ , \qquad (9)$$

constrained by

$$N_n \leq NAF \ ,$$

where k_n = the zero order rate coefficient for nitrification (kg/ha/time step); TFAC = the temperature stress factor (0-1); WFAC = the soil water stress factor (0-1); ITIME = the length of the time step (days); NAF = the ammonium-N content of the top 30 cm (kg/ha).

The use of nitrification inhibitors is simulated by reducing the magnitude of the rate coefficient, k_n. N_2O emissions (NN_{N2O}) from the nitrification process are computed using the equation:

$$NN_{N2O} = N_n * alpha * TFAC * WFAC \; , \quad (10)$$

where alpha = the maximum fraction of N_2O leakage from the nitrification process when temperature and water content are not constraining factors.

Losses to Denitrification (N_2 plus N_2O)

Nitrogen lost to denitrification (N_{det}) during the time spans ending with precipitation and irrigation events is computed using the equation:

$$N_{det} = k_{det} * NIT1 * TFAC * [NWET + WFAC * (ITIME - NWET)] \; , \quad (11)$$

constrained by

$$N_{det} \leq NIT1 \; ,$$

where N_{det} = nitrate-N denitrified (kg/ha/time step); k_{det} = the rate constant for denitrification; NIT1 = the nitrate-N content of the top 30 cm (kg/ha); NWET = the number of days with precipitation or irrigation during the time step (for daily time steps NWET is either 1 or 0).

The value assigned to k_{det} is a function of percent SOM, soil drainage class, type of tillage, presence of manure, tile drainage, type of climate, and occurrence of pans (Meisinger and Randall, 1991). Equation 11 offers the ability to calculate maximal denitrification occurring on the wet days, while calculating a separate estimate of denitrification under dryer soil water conditions for other days.

N_2O emissions from denitrification are calculated based on extensions to equation 11 (Xu et al., 1998). Emissions for wet conditions are calculated using the following equation:

$$NW_{N2O} = N_w * alpha_w \; , \quad (12)$$

where N_w = total nitrogen denitrified under wet conditions; $alpha_w$ = the fraction of total N denitrified as N_2O under wet conditions.

For dry soil conditions, N_2O emissions are estimated using the following equation:

$$ND_{N2O} = N_d * alpha_d * (1 - WFAC) \; , \quad (13)$$

where N_d = total nitrogen denitrified under dry conditions; $alpha_d$ = the maximum fraction of total N denitrified as N_2O at 50 percent water-filled pore space.

Total N_2O emissions (N_{N2O}) are then calculated as a sum of the components:

$$N_{N2O} = NN_{N2O} + NW_{N2O} + ND_{N2O} . \tag{14}$$

N_2 gas emissions are calculated by subtracting N_{N2O} from N_d.

Temperature Stress Factor

The soil temperature stress factor, TFAC, is computed using an Arrhenius equation of the form:

$$TFAC = 1.68E9 * EXP (-13.0/(1.99E-3 * (TMOD+273))) , \tag{15}$$

where TMOD = (T - 32)/1.8 when T $\leq$ 86°F; TMOD = 60 - (T - 32)/1.8 when T > 86°F (T is soil temperature in °F).

TFAC has a range of 0.0 to 1.0. This equation was developed using data reported by Gilmour (1984) and Marion and Black (1987). Equation 15 approximately doubles the rate for each 18°F increase in soil temperature below a maximum of 86°F and halves the rate for equivalent increases above 86°F.

The above equations for TFAC apply to the soil simulation model only. TFAC for use on the soil surface is calculated using a modified version of the soil equations.

Soil Water Stress Factor

The soil water factor, WFAC (also range 0.0 to 1.0), is computed as a function of percent water-filled pore space (WFP) by using curves fitted to data developed by Linn and Doran (1984) and Nommik (1956) for aerobic and anaerobic processes. For aerobic processes such as mineralization and nitrification, the following equations are used:

$$WFAC = 0.0075 * WFP , \tag{16}$$

where WFP $\leq$ 20 ;

$$WFAC = -0.253 + 0.0203 * WFP , \tag{17}$$

where 20 $\leq$ WFP < 59 ;

$$WFAC = 41.1 * EXP(-0.0625 * WFP) , \tag{18}$$

where WFP $\geq$ 59; and

$$WFAC = 0.000304 * EXP(0.0815 * WFP) , \tag{19}$$

for anaerobic processes such as denitrification.

The above equations for WFAC apply to the soil simulation model only. WFAC for use on the soil surface is calculated using a modified version of the soil equations.

Crop N Uptake

Nitrogen taken up by the crop (N_{plt}) is calculated using the following equations:

$$N_{dmd} = YG * TNU * fNU * ITIME \, , \tag{20}$$

where N_{dmd} = N uptake demand (kg/ha/time step); YG = yield goal or maximum yield in appropriate units; TNU = total N uptake (kg/harvest unit); fNU = fractional N uptake demand at the midpoint of the time step.

A normalized curve relating fNU to relative crop growth stage is used to proportion N uptake demand (Shaffer et al., 1991). The N uptake demand is proportioned between the upper and lower soil horizons according to the relative water uptake. N available for uptake in each horizon is computed as follows for the upper horizons:

$$Navail_1 = NAF + NIT1 \, , \tag{21}$$

and as follows for the second and third horizons:

$$Navail_{2or3} = NIT2 \text{ or } NIT3 \, , \tag{22}$$

where NIT2 or NIT3 = the nitrate-N contents in the lower horizons (kg/ha). Note that a third horizon has been added as follows:

$$Navail_3 = NIT3 \tag{23}$$

This three-horizon configuration provides the same capability as that provided by NLEAP version 1.2, reported by Delgado et al. (1998).

In each case, the uptake demand for each layer is constrained by the nitrogen availability. Therefore, N_{plt} is set equal to the smaller of N_{dmd} or ($Navail_1$ + $Navail_2$ + $Navail_3$). Plant uptake of ammonium-N (NPLTA) is calculated from total N uptake in the upper 30 cm according to the fraction of nitrate-N plus ammonium-N that is ammonium-N.

Soil N Uptake by Legumes

Soil nitrogen uptake by legumes is considered to be the lesser of either the nitrogen demand by the crop or the sum of $Navail_1$ + $Navail_2$ + $Navail_3$. If the nitrogen demand is greater than the nitrogen available in the soil, it is assumed that the plant obtains the difference from nitrogen fixation.

N Loss to Ammonia Volatilization

Nitrogen lost to ammonia volatilization (N_{NH3}) during the same time steps discussed above is calculated using the following equation:

$$N_{NH3} = k_{af} * NAF * TFAC * ITIME \,, \tag{24}$$

constrained by

$$N_{NH3} \leq NAF \,,$$

where N_{NH3} = ammonia-N volatilized (kg/ha/time step); k_{af} = the rate constant for ammonia volatilization; NAF = the ammonium-N content of the top 30 cm (kg/ha).

The particular value used for k_{af} is a function of fertilizer application method, occurrence of precipitation, cation exchange capacity of surface soil, and percent residue cover (Meisinger and Randall, 1991). In the case of manure, k_{af} is a function of the type of manure and application method (Meisinger and Randall, 1991).

Water Available for Leaching

Water available for leaching (WAL) is calculated after each precipitation and irrigation event using the three-horizon soil model and the following equations:

$$WAL1 = P_e - ET1 - (AWHC1 - S_{t1}) \,, \tag{25}$$

constrained by

$$WAL1 \geq 0.0, \text{ and}$$

$$WAL2 = WAL1 - ET2 - (AWHC2 - S_{t2}) \,, \tag{26}$$

$$WAL3 = WAL2 - ET3 - (AWHC3 - S_{t3}) \,, \tag{27}$$

constrained by

$$WAL \geq 0.0 \,,$$

where WAL1 = water available for leaching from the top 30 cm; WAL2 and WAL3 = water available for leaching from the second and third horizons (cm); ET1 and ET2 = potential evapotranspiration associated with the top two horizons (cm/time step); AWHC1 and AWHC2 = the available water holding capacities of the upper two horizons (cm); WAL = water available for leaching from the bottom of the soil profile (cm); P_e = effective precipitation (inches); ET2 and ET3 = potential evapotranspiration from the lower two horizons (cm); S_{t1} = available water in the top 30 cm at the end of the previous time step (cm); AWHC2 and AWHC3 = available water holding capacities of the second and third horizons (cm); S_{t2} and S_{t3} = available water in the lower two horizons at the end of the previous time step.

Potential Evapotranspiration

Potential evapotranspiration is computed using pan evaporation data and appropriate coefficients as follows:

$$ET_p = EV_p * k_{pan} * k_{crop} * ITIME \,, \tag{28}$$

where ET_p = potential evapotranspiration (cm/time step); EV_p = average daily pan evaporation during the time step (cm/day); k_{pan} = pan coefficient; k_{crop} = crop coefficient.

ET_p is proportioned between potential evaporation at the soil surface (ET_{ps}) and potential transpiration (ET_{pt}), using normalized curves for each crop. ET_{pt} is then proportioned between the upper and lower soil horizons according to the relative root distributions. Actual surface evaporation for any time step is considered to be the lesser of either ET_{ps} or the soil water available for evaporation. Actual transpiration for each time step and soil horizon is considered to be the lesser of either the potential transpiration for that layer or the remaining soil water above the permanent wilting point. If one horizon is depleted of water, an attempt is made to extract the water from the next horizon.

Nitrate-N Leached

Nitrate-N leached (NL (kg/ha)), during a time step is computed using an exponential relationship (Shaffer et al., 1991), expressed as follows:

$$NL1 = NAL1*(1 - \exp(-1.2*WAL1/POR1)) \,, \tag{29}$$

$$NAL2 = NAL2 + NL1 \,, \tag{30}$$

$$NL2 = NAL2*(1 - \exp(-1.2*WAL2/POR2)) \,, \tag{31}$$

$$NAL = NAL3 + NL2 \,, \tag{32}$$

$$NL = NAL*(1 - \exp(-1.2*WAL/POR3)) \,, \tag{33}$$

where NL1 and NL2 = nitrate-N leached from the top two horizons (kg/ha); POR1 = the porosity of the top 30 cm (cm); POR2 = the porosity of the second horizon (cm); NAL1, NAL2, and NAL3 = the nitrate-N available for leaching at the start of the time step for each horizon (kg/ha); NAL = nitrate-N available for leaching from the root zone (kg/ha); NL = nitrate-N leached from the bottom of the root zone (kg/ha); POR3 = the porosity of the lower horizon (cm).

Total nitrate-N leached for any month or year is computed by summing the leaching values obtained from each time step during the period of interest.

SUMMARY

The identification of potential problems with N losses quickly leads to a list of potential solutions in terms of BMPs. Local Extension and USDA Natural Resources Conservation Service have identified practices shown to be of value in each local region. This list should be used as a starting place and potential BMPs evaluated for the site-specific conditions. Some common practices for control of NO_3-N leaching include multiple fertilizer applications, the use of fall cover crops to recover residual soil NO_3-N, adjustment of fertilizer and manure rates to account for other sources of N, precision application of fertilizers across a field, use of management zones, crop rotations with deeper rooted crops and legumes, and avoidance of off-season fertilizer applications. The relative effectiveness of each method will depend on site-specific conditions and can be evaluated by comparing simulated N loss results with corresponding results using the historical data. NLEAP has been used to evaluate BMPs across several different regions, agroecosystems, and climates.

There is potential to use NLEAP as a management tool to assess the effect of BMPs. The NLEAP model uses national database resources from soils, climate, and management, which allows for the potential application of the model without any ground-truthing. We caution the users to be aware that application of the model without a previous evaluation of local conditions and management are often wrong, leading to a poor application of the model and questionable results.

We emphasize that the users and staff should visit the site; talk to local producers, USDA Natural Resources Conservation Service, and Extension; and take some samples if possible. Users need to remember that N losses (especially their magnitudes) are often determined by local effects, as opposed to regional or national generalizations. Users need to review Shaffer and Delgado (2001) and Delgado and Shaffer (2008) and their recommendation for a Tier approach to management. If more detailed and accurate results are needed, users should move to a tier 3 approach, supported by research at the local site. The model will use adequate databases, accurate information, and realistic management scenarios that have been calibrated and evaluated only when examples can be reported by multiple national and international users across hundreds of simulations.

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Soil suitability index identifies potential areas for groundwater banking on agricultural lands

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Groundwater pumping chronically exceeds natural recharge in many agricultural regions in California. A common method of recharging groundwater — when surface water is available — is to deliberately flood an open area, allowing water to percolate into an aquifer. However, open land suitable for this type of recharge is scarce. Flooding agricultural land during fallow or dormant periods has the potential to increase groundwater recharge substantially, but this approach has not been well studied. Using data on soils, topography and crop type, we developed a spatially explicit index of the suitability for groundwater recharge of land in all agricultural regions in California. We identified 3.6 million acres of agricultural land statewide as having Excellent or Good potential for groundwater recharge. The index provides preliminary guidance about the locations where groundwater recharge on agricultural land is likely to be feasible. A variety of institutional, infrastructure and other issues must also be addressed before this practice can be implemented widely.

California is experiencing its third major drought since the 1970s, and projections suggest that such episodes will become longer and more frequent in the second half of the 21st century (Barnett et al. 2008; Cayan et al. 2010). Droughts place more demand on groundwater resources to buffer surface water shortfalls. Ordinarily, about 30% of the water applied to crops in California (roughly 34 million acre-feet per year) is supplied by groundwater sources, but in times of drought the proportion can increase to as much as 60% (Megdal 2009). As a result, groundwater levels fall during droughts (Ruud et al. 2004). If groundwater is not replenished during wet years, long-term overdraft occurs. From 2005 through 2010, average annual overdraft in the Central Valley was estimated to be between 1.1 and 2.6 million acre-feet (Department of Water Resources 2015).

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Two recent trends in California have tended to increase the rate of groundwater overdraft in agricultural regions.

First, over the past two decades, irrigation technologies have significantly improved water use efficiencies (Canessa et al. 2011; Howell 2001; Orang et al. 2008; Tindula et al. 2013; Ward and Pulido-Velazquez 2008). Where surface water is used for irrigation, a consequence of applying less water is that groundwater recharge is diminished because of a reduction in deep percolation of excess water.

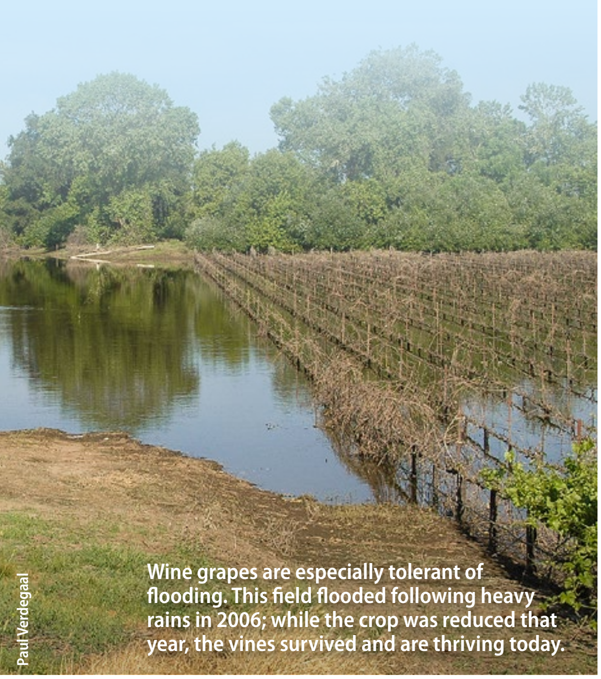
Second, expanding worldwide markets have driven significant expansions of nut and wine grape acreage. For example, the almond acreage in California has doubled, to roughly 1 million acres, since 1994 (NASS 2014). Much of this expansion has occurred in the San Joaquin Valley where rates of rainfall and natural groundwater recharge are low. This shift in cropping systems to high value perennial crops reduces the flexibility of agricultural water demand because the economic costs of not irrigating are severe. Inflexible demand has made agriculture even more reliant on groundwater during dry periods when surface water resources are curtailed.

During fallow or dormant periods, agricultural lands have the potential to serve as percolation basins for groundwater recharge.

David Doll

Five factors that determine the feasibility of groundwater recharge on agricultural land

1. **Deep percolation:** Soils must be readily able to transmit water beyond the root zone (1.5 m, 5 ft).
2. **Root zone residence time:** The duration of saturated/near saturated conditions after water application must be acceptable for the crops grown on lands under consideration for groundwater banking throughout the entire crop root zone.
3. **Topography:** Slopes that negatively influence the even distribution of water will be more difficult to manage.
4. **Chemical limitations:** High soil salinity may result in saline leachate (poor water quality) that must be avoided to protect groundwater quality.
5. **Soil surface condition:** Certain soils may be susceptible to compaction and erosion if large volumes of water are applied. Surface horizons with high sodium are prone to crusting that may contribute to decreased surface infiltration rates.



Wine grapes are especially tolerant of flooding. This field flooded following heavy rains in 2006; while the crop was reduced that year, the vines survived and are thriving today.

Paul Verdegaal

Groundwater recharge

Natural groundwater recharge is the predominant source of groundwater replenishment in almost all basins. It is typically unmanaged and can be slow. Water percolates into aquifers from a variety of surface water sources including precipitation, streams, rivers, lakes, surface water conveyance facilities — such as unlined canals — and applied irrigation water. Natural recharge also may occur from horizontal subsurface inflow from one part of a groundwater basin to another. Natural recharge requires no dedicated infrastructure or land.

Groundwater banking is a management strategy that stores surface water in aquifers for future withdrawal. It expands managed water storage capacity, which in California consists mainly of surface water reservoirs. Groundwater banking is achieved through the intentional application of surface water. During hydrologic cycles when surface water is abundant, extra surface water can be "deposited" in a groundwater bank by application to constructed percolation basins, through injection wells, or through joint management of rivers and groundwater to effect riverbed infiltration into underlying aquifers.

A key limitation to groundwater recharge is the lack of suitable percolation basins available for deliberate flooding. In this paper, we consider a new strategy for groundwater banking that involves applying water to agricultural lands outside of the usual irrigation season for the specific purpose of recharging a groundwater basin. Given the millions of acres of irrigated farmland in California, using agricultural lands as percolation basins has the potential to increase groundwater recharge during wet periods when surface water is available.

In California, one potential source of water for recharge on agricultural land is river floodwaters, because surface water rights may be easily re-negotiated (or may not apply) for the excess water. This floodwater approach has the dual benefit of withdrawing large amounts of water from a river that is at or near flood stage and reducing downstream flood risks (Bachand et al. 2011). The frequency and intensity of river flooding is difficult to forecast. For instance, flood flows on the Kings River from 1975 to 2006 had an average reoccurrence interval of 2 to 3 years, though flooding has not occurred in recent years (Bachand et al. 2011). As the climate warms, flooding may become more frequent and extreme as a result of episodic snowmelt events driven by warm winter rains. Recycled water (highly treated wastewater) is another potential source.

There are a variety of institutional and other barriers to widespread agricultural groundwater banking in California. Water rights for operation of aquifers as reservoirs are challenging to navigate; water conveyance infrastructure has limited capacity; regional planning to capture river flood waters may be difficult to organize; fields with high percolation rates at the surface may be underlain by low-percolation layers that slow or block the recharge of deeper aquifers; it can be difficult to assess how much capacity a given aquifer has to store banked groundwater; certain crops and certain stages of crop growth do not tolerate flooded conditions; and the quality of water recharged to an aquifer via agricultural land may be degraded due to excessive leaching of contaminants from soil such as pesticides and nitrates.

To date, few well-documented trials of groundwater banking have been conducted on agricultural land. Since nearly all agricultural land is privately owned and operated, participation in groundwater banking programs depends on cooperation from the landowner or land manager. Therefore, a clear understanding of the risks and best practices associated with this practice is paramount.

In this study, we take a first step toward better understanding opportunities to recharge groundwater using agricultural landscapes in California by identifying and mapping the soil and topographic conditions most conducive to groundwater recharge.

Groundwater banking index

This study developed a Soil Agricultural Groundwater Banking Index (SAGBI) that provides a composite evaluation of soil suitability to accommodate groundwater recharge while maintaining healthy soils, crops and a clean groundwater supply. The SAGBI is based on five major factors that are critical to successful agricultural groundwater banking: deep percolation, root zone residence time, topography, chemical limitations and soil surface condition (see sidebar, this page).

We modeled each of the five factors using U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) digital soil survey data. The suitability of each factor was expressed through a scoring system based on a combination of fuzzy logic functions and crisp ratings (see sidebar, this page).

Deep percolation factor. Successful groundwater banking depends on a high rate of water transmission through the soil profile and into the aquifer below. A high percolation rate is especially important if floodwaters are the water source used because floodwaters are available for diversion over a narrow time frame. The deep percolation factor is derived from the saturated hydraulic conductivity (K_{sat}) of the limiting layer (the soil horizon with the lowest K_{sat}). Saturated hydraulic conductivity is a measure of soil permeability when soil is saturated. Many soils in California have horizons (layers) with exceptionally low K_{sat} values that severely limit downward percolation, such as cemented layers (duripan, petrocalcic), claypans (abrupt increases in clay content) and strongly contrasting particle size distributions. Soils with these horizons were given crisp scores of 1. For other soils, a "more is better" fuzzy logic rating curve was applied to a soil profile's lowest K_{sat} to score the likelihood of deep percolation (fig. 1).

Root zone residence time factor. Prolonged duration of saturated or nearly saturated conditions in the root zone can cause damage to perennial crops, and in some cases, crop loss (table 1). About one-third of California's irrigated cropland is occupied by perennial crops and vines. Table 1 provides estimates of tolerance to saturation for some common tree and vine crops before and after budbreak compiled through a survey of UC ANR Cooperative Extension (UCCE) commodity experts. Annual crops were not included in the survey because we assumed that these fields generally would be fallow during times of excess surface water availability. In general, crops become prone to damage after budbreak and there is a range in tolerance among crops and rootstocks (table 1). For example, wine grapes and pears may be able to withstand more than two weeks of saturated conditions before budbreak, while avocados and citrus have no tolerance.

Our survey identified that many crops are unable to withstand long periods of saturated conditions in the root zone. To account for this potential adverse outcome, we included in the model a saturation residence time factor for soils. The root zone residence time factor estimates the likelihood of maintaining good drainage within the root zone shortly after water is applied. This rating is based on the harmonic mean of the K_{sat} of all horizons in the soil profile, soil drainage class and shrink-swell properties. The harmonic mean is typically used when reporting the average value for rates and tends to be lower than a standard average. Poorly drained soils and soils with high shrink-swell received the lowest scores with a crisp rating of 1. All other soils were

TABLE 1. Survey results of tree crop vulnerability to saturated conditions

Crop	Rootstock	Tolerance to saturation before budbreak	Tolerance to saturation after budbreak	Recommended N fertilizer rate
				lbs N/ac/yr
Almonds	Peach; peach x almond hybrid	1	1	250
Almonds	Plum; peach x plum hybrid	2–3	1	250
Avocados	—	0	0	150
Cherries	—	1	0	60
Citrus	—	0	0	100
Wine grapes	—	4	2	15–30
Olives	—	?	?	<100
Pears	*P. betulaefolia*	4	4	100–150
Pears	*P. communis*	4	3	100–150
Pears	*Cydonia oblonga*	3–4	2–3	100–150
Pistachios	—	?	?	200
Plums/prunes	Peach	1	1	150
Plums/prunes	Plum; peach x plum hybrid	2–3	1	150
Pomegranate	—	?	?	100
Walnuts	—	2–3	1	200

The following scores were used to estimate vulnerability: 0 - No tolerance for standing water; 1 - tolerant of standing water up to 48 hours; 2 - tolerant of standing water up to 1 week; 3 - tolerant of standing water up to 2 weeks; 4 - tolerant of standing water > 2 weeks; ? - tolerance unknown.

Tolerance to saturated conditions is based on expert opinion and has not been supported by controlled experimentation.

Fuzzy logic and crisp scores

Fuzzy logic is a method by which membership to a class or condition can be partial (maybe) rather than discrete (true or false; or A or B). Thus, fuzzy logic allows reasoning to be approximate rather than fixed and exact. Variables are evaluated via fuzzy logic scores that range between 1 and 100, reflecting the degree of vagueness of a membership being completely false (1) or completely true (100). Fuzzy logic is appropriate for this model analysis because in agricultural landscapes, the above five factors are relative as opposed to absolute, which poses challenges in quantifying them using the raw data.

We used fuzzy logic statements such as (1) "more is better" where the score increases with higher factor values; (2) "less is better" where the score increases as factor values decrease; and, (3) "optimum range" where the score is highest across a certain range of factor values and decreases above and below that range. Using the suitability of root zone residence time as an example, the fuzzy logic statement "less is better" enables the suitability of that factor to vary between 1 and 100 (from unsuitable to optimally suitable) rather than having to choose between absolutes, e.g., suitable (true) or not suitable (false). Crisp ratings are defined scores that apply to a well-understood system, and hence do not require fuzzy scoring. For example, slope classes as reported in soil surveys reflect limitations of common practices such as irrigation and cultivation practices and are scored in our model with crisp ratings.

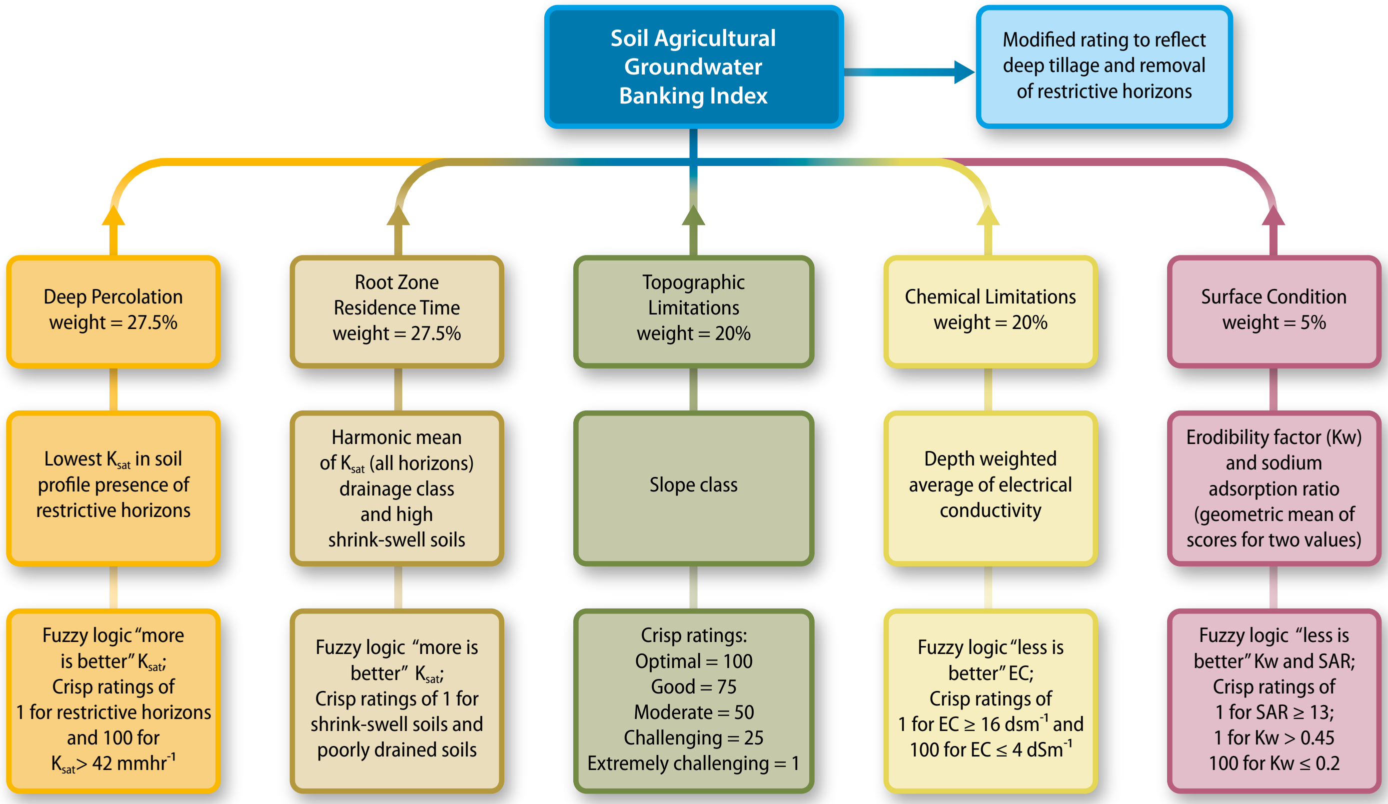


Fig. 1. Schematic of the Soil Agricultural Groundwater Banking Index.

scored using a fuzzy logic rating curve of "more is better" for K_{sat} (fig. 1).

Topographic limitations factor. Agricultural groundwater banking will likely be implemented by spreading water across fields. Level topography is better suited for holding water on the landscape, thereby allowing for infiltration across large areas, reducing ponding and minimizing erosion by runoff. Ranges in slope percent were used to categorize soils into four slope classes: Optimal (slope classes 0%–1% and 0%–3%), good (slope classes 0%–5% and 2%–5%), moderate (slope classes 0%–8% and 3%–8%), challenging (slope classes 5%–8%, 3%–10% and 5%–15%), and extremely challenging (slope classes 10%–30% and 15%–45%) (fig. 1). Topographic limitations were scored using crisp ratings that generally reflect the USDA-NRCS slope classes because these classes were designed in consideration of limitations for standard agricultural management practices (Soil Survey Division Staff 1993).

Chemical limitations factor. Salinity is a threat to the sustainability of agriculture and groundwater in California, especially along the west side of the Central Valley (Kourakos et al. 2012; Schoups et al. 2005), where sediments are derived from marine sediments in the Coast Range. The chemical limitations factor was quantified using the electrical conductivity (EC) of the soil, which is a measure of soil salinity. A fuzzy logic rating curve "optimum and less is better" was used to score chemical limitations. The "less is better" statement implies that soils with low salinity score high and soils with high salinity values score low. Soil profiles with EC < 4 dS/m were considered optimal (score of 100). Beyond this threshold, scores decreased with increasing EC. Soils with EC values above 16 dSm^{-1} received a score of 1 (fig. 1). A variety of other contaminants such as pesticides and nitrate are also present in agricultural soils. However, because this type of contamination is dependent on management history, the USDA-NRCS soil survey does not document it and we were unable to evaluate it.

Surface condition factor. Groundwater banking by flood spreading can subject the soil surface to changes in its physical condition. Depending on the quality of the water and depth of water, standing water can lead to the destruction of aggregates, the formation of physical soil crusts and compaction, all of which limit infiltration (Le Bissonais 1996). We used two soil properties to diagnose surface condition, the soil erosion factor and the sodium adsorption ratio (SAR). The surface condition factor was calculated by the geometric mean of fuzzy logic scores from these two properties. A geometric mean is a way to identify the average value of two or more properties that have different ranges in value. SAR values greater than 13 indicate that the soil is prone to crusting. A "less is better" fuzzy logic curve was used to evaluate SAR, where values greater than 13 were assigned a crisp rating of 1, and values of 0 were assigned an optimal rating of 100. Soil surface horizon Kw, the soil erodibility factor of the Revised Universal Loss Equation, was used to estimate the potential soil susceptibility to erosion, disaggregation and physical crust formation (USDA-NRCS 2014). A fuzzy logic rating curve, "optimum and less is better," was used for scoring the surface condition factor. Kw values < 0.20 were considered ideal (score = 100); beyond this threshold, factor scores decreased with increasing Kw values.

SAGBI calculation. Each of the five model factor scores was assigned a weight based on its significance to groundwater banking (fig. 1). The SAGBI score was calculated by the weighted geometric mean of the scaled factors. The factors were weighted as follows: Deep percolation (27.5%), root zone residence time (27.5%), topographic limitations (20%), chemical limitations (20%) and surface condition (5%). Factor weights were applied based on expert opinion. Factors with greater relevance to groundwater recharge were weighted more heavily, while factors that may be modified by management, such as surface condition, were given a lower weight. SAGBI scores were categorized into six groups: Excellent, Good, Moderately Good, Moderately Poor, Poor and Very Poor based on the natural groupings of the dataset.

Soils modified by deep tillage. In recent decades, high value orchard and vineyard crops have expanded onto soil landscapes that contain restrictive horizons. A standard practice for tree and vine establishment on these soils is deep tillage up to a depth of 6 feet to destroy restrictive layers that impede root penetration. This practice increases deep percolation rates and drainage conditions compared to naturally occurring soils. Soils with root- and water-restrictive horizons in California have been altered to the point that they are now considered endangered in the Central Valley (Amundson et al. 2003).

As a result, soil surveys of much of the region — many of which were conducted decades ago — are outdated with respect to alterations by deep tillage. To address this problem, we created an updated soil disturbance map using geospatial analysis. A map of orchard and vineyard crops was created using California Department of Water Resources land use maps (issued between 2001 and 2011) and aerial imagery from the National Agricultural Imagery Program (NAIP) and Google Earth (2012 to 2014). This file was overlain in a geographic information system with a map of soils with water-restrictive horizons. We assumed that all tree and vine cropland with restrictive soil layers (based on soil survey data) has been modified by deep tillage, generating an updated map of modified soils.

To reflect the mixing of soil horizons in the calculation of the deep percolation factor, the depth-weighted average of K_{sat} for the entire soil profile was used in place of the lowest K_{sat} for each profile. We reduced the deep percolation factor rating for soils with claypans by 20% to reflect the risk that modified claypans will reform, which can occur in as little as four years in soils with weak structure (White et al. 1981). Cemented layers (not including bedrock) were assumed to have been removed by deep tillage and were not included in the weighted average. Data below the restrictive horizon was included in the depth-weighted average if populated in the database. The depth-weighted average of K_{sat} was used in place of the harmonic mean to estimate hydraulic conductivity for the root zone residence time factor.

Map unit aggregation. SAGBI scores were calculated for most agricultural soils populated in the USDA-NRCS Soil Survey Geographic Database (SSURGO). Soil survey delineations represent map units, which often contain more than one soil type. The map units range in size from 5 acres to roughly 500 acres. To create a regional map, each map unit was scored with the SAGBI value using the soil component that comprised the largest percentage of the map unit area. If there was a tie (i.e., one map unit containing two components of equal area), the most limiting (lowest) SAGBI score was chosen for the map unit.

Spatial patterns of SAGBI

Our study area included over 17.5 million acres of agricultural land (irrigated and non-irrigated) as identified by the state Farmland Mapping and Monitoring Program. Based on our initial modeling, which did not initially consider the effects of deep tillage, soils in the Excellent, Good and Moderately Good suitability groups comprised over 5 million acres, or 28% of the study area (fig. 2 and table 2). These highly rated soils were most abundant on broad alluvial fans on the east side of the Central Valley stemming from the Mokelumne, Stanislaus, Merced, Kern and Kings rivers (fig. 2). Excellent, Good and Moderately Good ratings are also found throughout much of Napa, Salinas and Santa Maria valleys and in patches

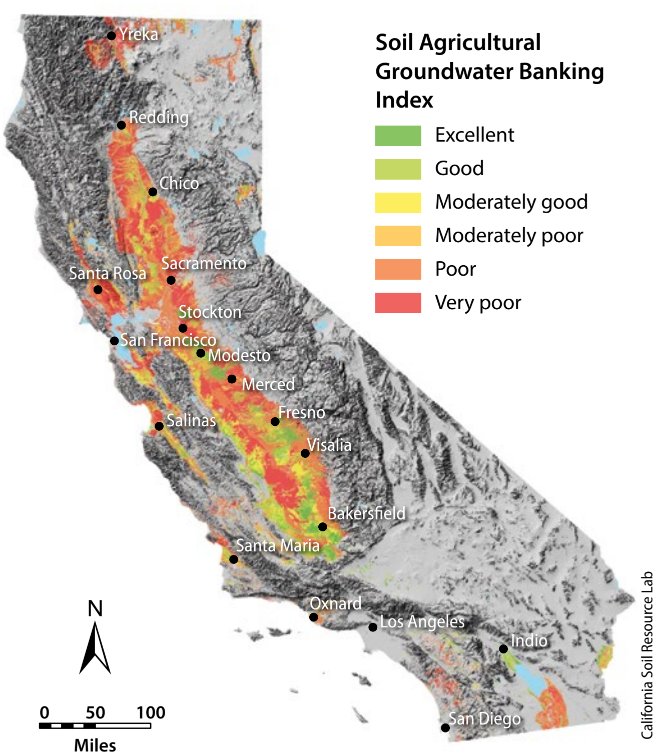


Fig. 2. Spatial extent of Soil Agricultural Groundwater Banking Index suitability groups when not accounting for modifications by deep tillage.

TABLE 2. Summary of the areal extent of Soil Agricultural Groundwater Banking Index groups generated from soil survey data

SAGBI group	Original SSURGO data		SSURGO modified by deep tillage	
	acres	*%**	*acres*	*%**
Excellent	1,477,191	8	1,557,035	9
Good	1,747,712	10	2,020,921	11
Moderately Good	1,786,972	10	1,984,414	11
Moderately Poor	1,343,250	8	1,364,066	8
Poor	4,866,942	28	4,586,645	26
Very Poor	6,375,277	36	6,084,142	35
Total†	17,597,345		17,597,222	

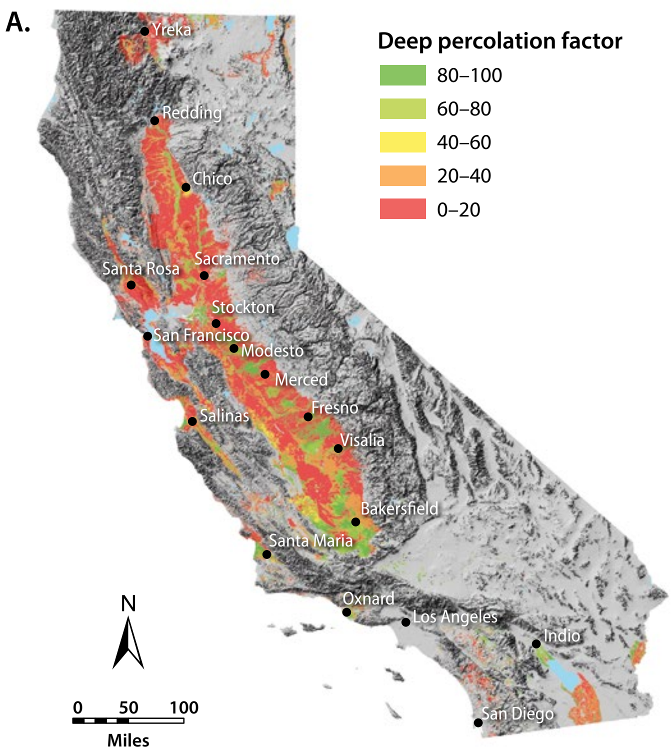
* Percent of total study area.
† Modified SAGBI ratings had 123 fewer acres because two soils lacked sufficient data to adjust.

along the Russian River in Mendocino and Sonoma counties and the northern parts of the Coachella Valley. The best soils — the Excellent and Good groups — occupied about 3.2 million acres, representing 18% of the study area (fig. 2 and table 2). Some areas of Good and Excellent ratings were found on sandy floodplains of rivers and streams, especially along the Sacramento and Feather rivers.

Floodplains may not be ideal locations for groundwater banking because of the potential for applied water to flow, by subsurface transport, into rivers and streams. Thus, these systems should not be prioritized for groundwater banking unless it is known that the surface water bodies are losing streams — that is, surface water bodies that discharge to groundwater. Most major streams that traverse the San Joaquin Valley, for instance, are known to be losing streams.

Extensive Moderately Good areas were mapped on the western margins of the San Joaquin and Sacramento valleys where soils tend to be finer textured and sometimes salt-affected (saline). Moderately Good groups were also mapped in basin alluvium where low energy flood events have deposited fine sediments. Moderately Good groups occupied 1,786,972 acres or 10% of the study area. These areas may require careful consideration for groundwater banking.

The majority of land in the study area (72% or ~12.6 million acres) was classified as Moderately Poor, Poor or Very Poor SAGBI groups (fig. 2 and table 2). Soils with low SAGBI scores were abundant throughout the basin margins of the Sacramento and San Joaquin valleys as well as across land interstratified between recent alluvial fan deposits of



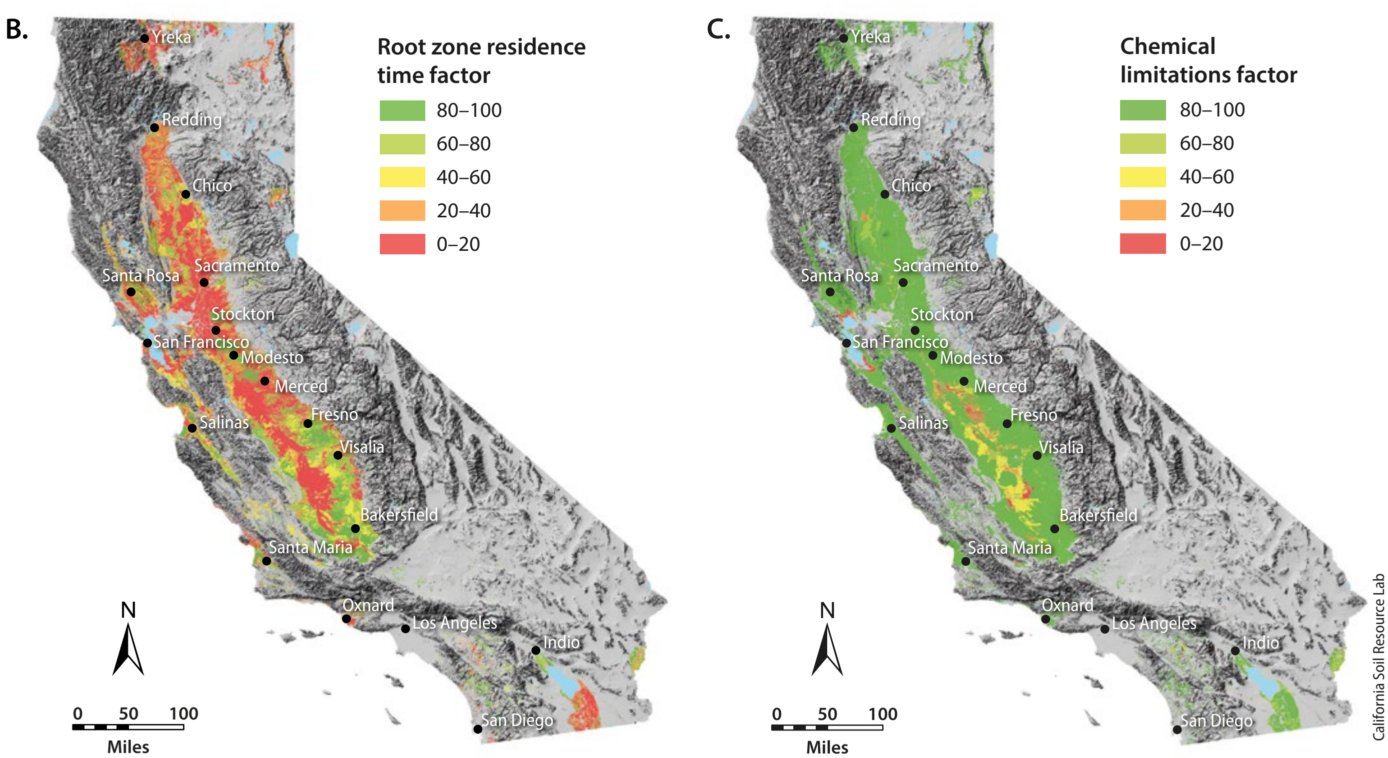


Fig. 3. Spatial extent of Soil Agricultural Groundwater Banking Index factors (A) deep percolation, (B) root zone residence time and (C) chemical limitations.

the Mokelumne, Tuolumne, Stanislaus, San Joaquin, Kings and Kern rivers. Very Poor and Poor ratings are also found on the northern portions of the Salinas and Santa Maria Valleys and throughout most agricultural regions in Sonoma County and southern parts of the Coachella Valley.

Of the SAGBI components, the deep percolation factor was limiting over the greatest area (fig. 3A). These limiting conditions arise from different characteristics of soils. For example, old, highly developed soils found along the margins of the Central Valley contain water-restrictive horizons (either cemented hardpans or claypans). The center of the valley contains young soils with fine (clay-rich) texture throughout the soil profile. Both of these soil landscapes contain at least one soil horizon with low permeability. In contrast, high deep percolation scores were found on coarse-textured soils derived from recent (e.g., < 80,000 years) alluvial fans with drainages sourced in granitic terrain of the Sierra Nevada and the Salinian block within the Coast Range.

Areas limited by the root zone residence factor typically had soils with uniformly fine texture throughout the soil profile and poor drainage. Poorly and very poorly drained soils have properties or conditions that promote saturation in the upper parts of the soil profile, such as high clay content, water restrictive layers or regionally shallow water tables. The least suitable soils in this factor were those with poor drainage or high shrink-swell properties. Low scores for root zone residence factor were widespread along the west side of the San Joaquin and Sacramento valleys in soils weathering from Coast Range alluvium (fig. 3B). Poor drainage and fine textured soils were also found in the basin alluvium towards the center of valleys. Low scores for this factor were also found on alluvial fans that have drainages confined to the metamorphic portions of the Sierra Foothills such as the Calaveras River fan, which tend to have fine textured sediments compared to fans sourced in granitic terrain in the high Sierra Nevada.

Chemical limitations had a localized influence on the distribution of SAGBI ratings. Most of the salt-affected soils are present along the west side of the San Joaquin Valley and to a lesser extent along the western margin of the Sacramento Valley (fig. 3C). The distribution of salt-affected soils results from a combination of the salt-rich nature of the marine sediments within the Coast Range and poor drainage conditions on the west side that prevent salts from leaching out of soil. There are other chemical limitations of soils we could not evaluate that would influence groundwater banking, most notably the concentration of residual nitrate in soil. Crops with high nitrogen demand or high residual nitrate in soil in the fall after harvest may not be suitable for groundwater banking (table 1).

The surface condition factor was weighted lowest among all other factors because compaction from standing water can be fixed with tillage and amendments. Low surface condition factor ratings were abundant in soils with loamy surface textures or high SAR and were located throughout the study area but tended to be concentrated on the west side of the Central Valley where sodium-affected soils are common (fig. 4A).

Soil landscapes with low slope factor ratings were limited to the margins of the valleys (fig. 4B). This sloping terrain is a result of uplift by the Coast Range and Sierra Nevada over geologic time scales, which increased slope gradients and accelerated erosion. The natural erosion of the valley margins has created gentle to

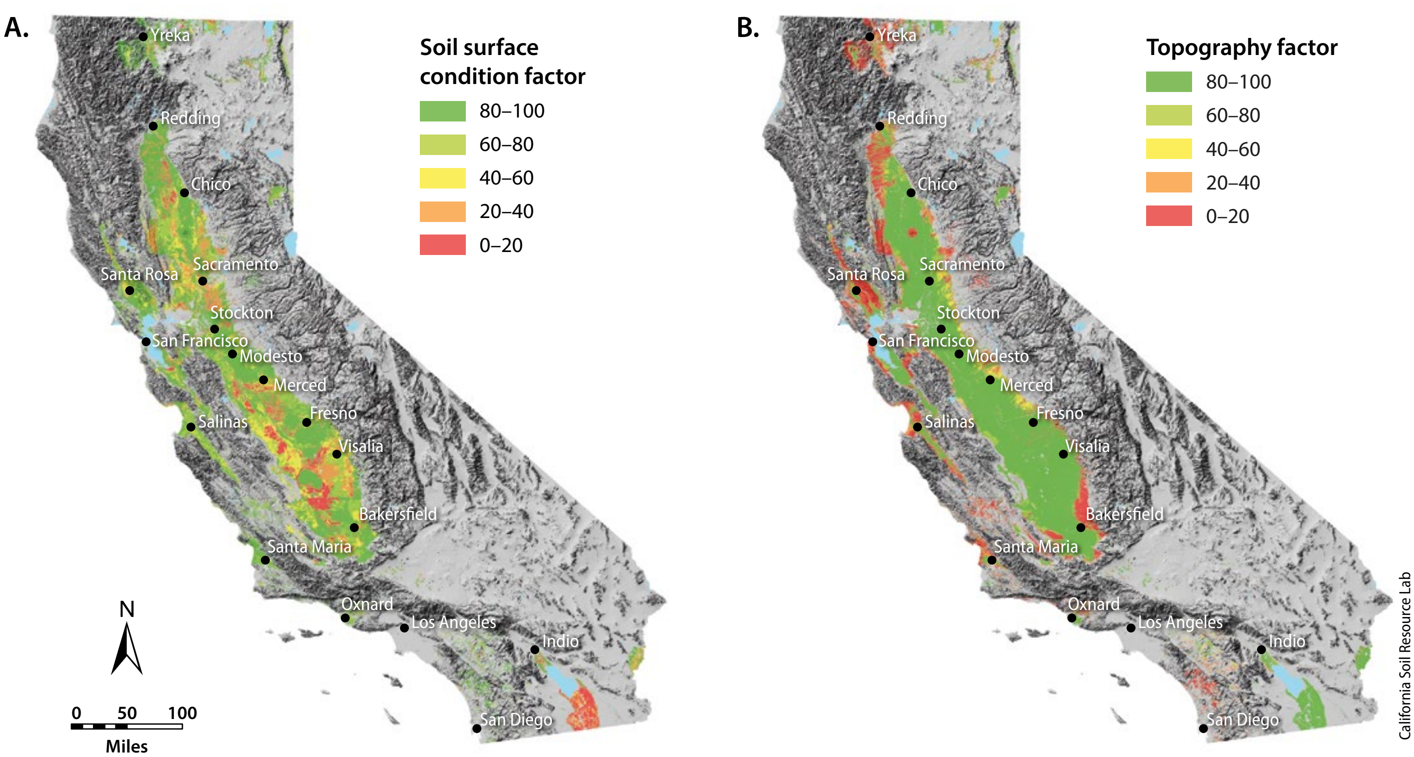


Fig. 4. Spatial extent of Soil Agricultural Groundwater Banking Index factors (A) surface condition and (B) topographic limitations.

steeply undulating landforms (see photo, below).

Modified SAGBI scores to reflect deep tillage

When deep tillage on orchard and vineyard croplands was incorporated into the model, the Excellent, Good and Moderately Good SAGBI suitability groups increased from 28% to 31% of the land area, adding 550,494 acres of suitable agricultural land for groundwater banking (table 2). A majority of improved SAGBI scores were located in the eastern San Joaquin Valley and Tulare Basin, where soils with restrictive horizons are common (fig. 5). It is possible that over time, more suitable land for groundwater banking will become available as marginal soils continue to be developed and modified for agricultural purposes (Charbonneau and Kondolf 1993).

The final SABGI that accounts for deep tillage represents the best estimate of soil suitability for groundwater banking. Over 12 soil survey areas are classified as out-of-date in agricultural regions of California (USDA-NRCS 2014) and do not accurately document the extent of soil modification by deep tillage. These modified SAGBI ratings provide an updated assessment of the current state of soils in the study area.

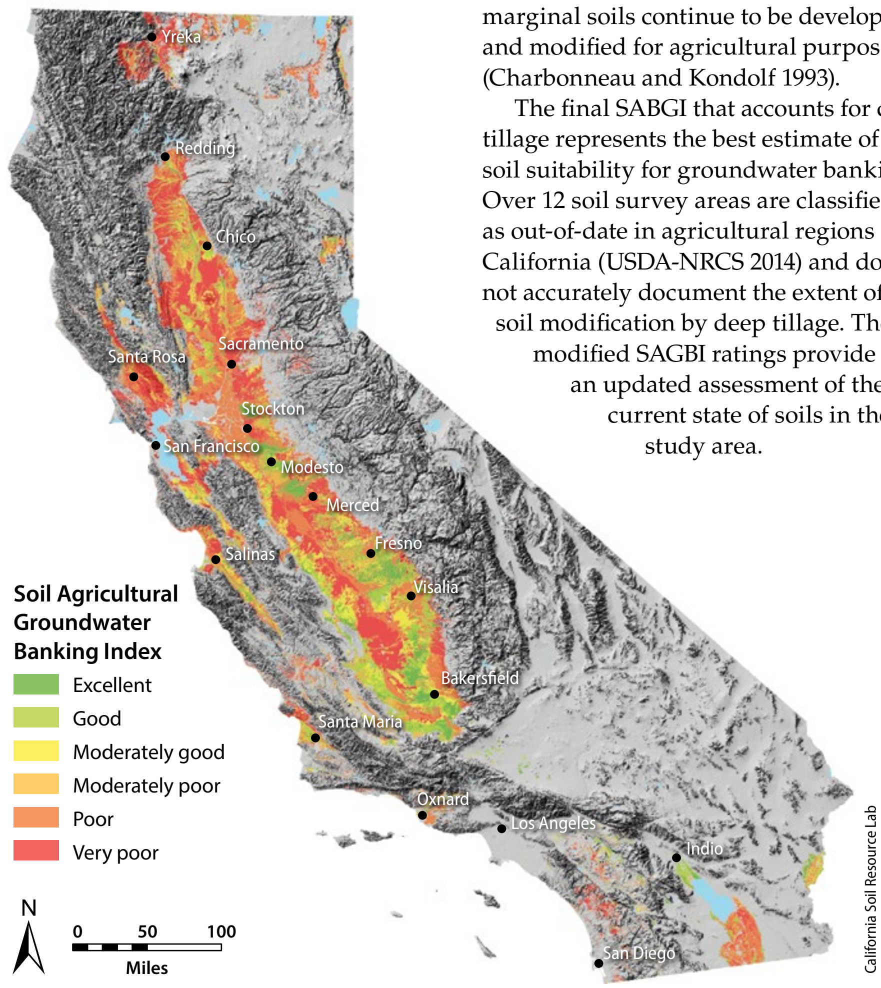


Fig. 5. Spatial extent of Soil Agricultural Groundwater Banking Index suitability groups accounting for modifications by deep tillage.

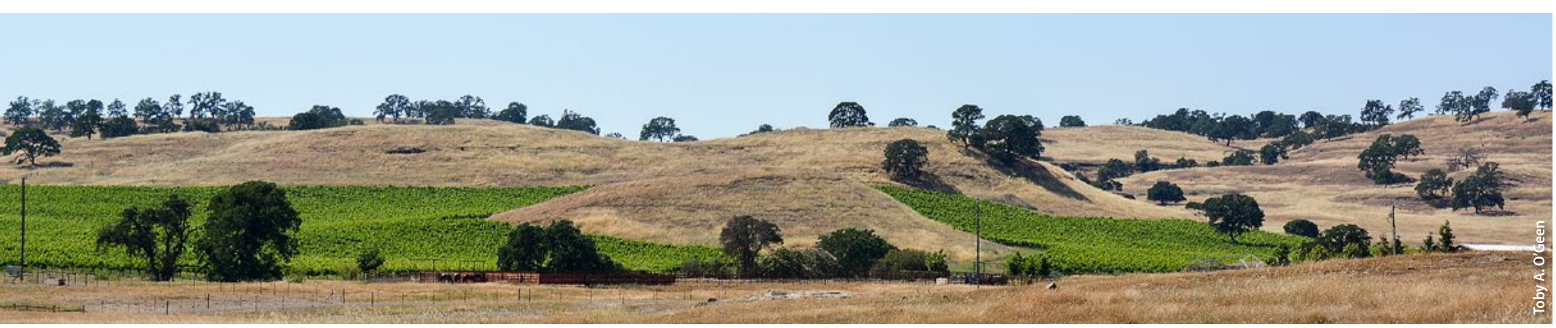
Implications

There are approximately 5.6 million acres of land with soils in Excellent, Good and Moderately Good SAGBI suitability groups, a significant amount of agricultural land capable of accommodating deep percolation with low risk of crop damage or contamination of groundwater by salts. Most suitable soils for agricultural groundwater banking occur on or near alluvial fans created by rivers draining the Sierra Nevada. Perhaps not coincidentally, these are also the areas that have California's most successful groundwater banking programs (Water Association of Kern County 2014).

Our preliminary survey of UCCE perennial crop experts suggests that pears, wine grapes and some rootstocks of various *Prunus* species (i.e., almond, peaches and plums) are best suited for groundwater banking if planted on suitable soils and managed appropriately, especially after budbreak. While extensive in acreage, almonds may be less ideal because of the trees' sensitivity to saturated conditions and high nitrogen demand (table 1). Walnuts may be an option given that budbreak typically occurs in late April. Wine grapes may be the best option because of the extensive acreage planted, low nitrogen demand and tolerance to standing water (table 1). Almonds with plum rootstocks may also be suitable; however, currently almonds with water tolerant rootstocks are generally planted in soils that are poorly drained and thus less likely to be suitable for groundwater banking.

Recharge potential

A preliminary calculation based only on soil properties and crop type shows that landscapes rated Excellent or Good could be used to bank as much as 1.2 million acre-feet of water per day. This



The undulating agricultural land found along many valley margins in California is poorly suited to groundwater banking because application of floodwater or waste water would be difficult to apply at these sites, which are typically drip irrigated.


Josh Viers, UC Merced


David Doll

Orchards of walnuts (above) and almonds (below) may be viable sites for groundwater recharge, though the potential for water damage to such high-value crops adds risk.

estimate assumes 1 foot per day of water infiltration on lands in the Excellent and Good categories that are planted with grapes (460,000 acres) or alfalfa (300,000 acres), or fallowed (440,000 acres). There are significant limitations to this estimate. Most importantly, California lacks the infrastructure to accommodate and route such large volumes of water to the fields in such a short time (presuming that floodwater is the source of the water). Plus, the heterogeneity in precipitation across the state makes this estimate improbable (that is, it is unlikely that floodwater availability would be geographically close to the best lands for recharge). Offsetting these limitations to some degree are other crop types that would be suitable for recharge (i.e., annual crops) but were not included in this estimate.

Agricultural groundwater banking must be approached with caution. The financial risk associated with crop loss may exceed the potential benefits of water savings. Perennial crops carry particular risks and uncertainties. For instance, while trees and vines are generally more tolerant of saturation before budbreak than after (table 1), determining a reliable cutoff date for this increased tolerance is difficult. Tree and vine roots generally start to grow several weeks before budbreak, so damage from waterlogging can occur well before budbreak. Moreover, budbreak for a given species varies by location across the state. In addition, standing water on trunks can lead to aerial *Phytophthora* or other diseases. Investigating this opportunity in less valuable cropping systems, such as alfalfa, irrigated pasture and annual crops may be more promising until further research on tree crop sensitivity to standing water has been conducted.

If groundwater banking on agricultural lands becomes a priority, coordination at the policy, market and planning levels would be needed to provide an adequate land base ready to opportunistically capture floodwaters. Adoption of this practice would likely require some form of support to mitigate or protect growers from the risks of crop failure. For example, growers who make their land available for floodwater capture and groundwater banking could receive credits from municipalities or irrigation districts. They could also receive credits from irrigation districts for enrolling in a long-term program. Long-term commitments from growers likely would be needed for basin-scale planning purposes.

Although not included among the crops listed in table 1, alfalfa may be an ideal crop for groundwater banking because it requires little or no nitrogen fertilizer, reducing the risk that groundwater recharge would transport nitrates into aquifers. Alfalfa is sensitive to flooding and saturated conditions; thus the timing of flooding should coincide with older fields (typically 4 to 5 years old) slated for replanting. Because the financial risk associated with crop damage is lower in alfalfa than in tree and vine crops, the financial incentive needed to drive grower participation in groundwater banking programs likely would be lower as well.

Most annual cropping systems would be suitable for groundwater banking if water is applied when land is fallow. The major risk in annual crops is leaching of residual pesticides or fertilizer in the soil. Appropriate management practices for groundwater banking with specific annual crops would need to be developed. If agricultural groundwater banking becomes an important water security practice, the SAGBI may provide valuable information to guide future changes in cropping systems.

SAGBI can be a powerful aid to decision makers and stakeholders when considering the tradeoffs associated with the implementation of groundwater banks utilizing agricultural land for direct recharge. It was also developed with the intention of informing growers of the potential hazards associated with this practice. As is the case with any model, and with soil survey information in particular, ground-truthing at the field scale is necessary to verify results.

If agricultural groundwater banking becomes an important water security practice, the SAGBI may provide valuable information to guide future changes in cropping systems.

We acknowledge limitations to our model. It does not consider proximity to a surface water source, which is an issue especially in areas that are irrigated solely from groundwater wells and are not connected to conveyance systems that supply surface water. The SAGBI also does not consider characteristics of the vadose zone (the unconsolidated material below soil and above the groundwater table) or depth to groundwater. In arid regions, deep vadose zones may contain contaminants such as salts or agricultural pollutants that have accumulated over years of irrigation and incomplete leaching. These deep accumulations of contaminants could be flushed into the water table when excess water is applied during groundwater banking events. Furthermore, deep sediment likely contains hydraulically restrictive horizons that have not been documented, creating uncertainty as to where the water travels. An understanding of the depth to the groundwater table is also needed.

Given these issues, SAGBI may be most useful when used in concert with water infrastructure models and hydrogeologic models — which generally do not incorporate soil survey information in a comprehensive way — to develop a fuller assessment of the processes and limitations involved in a potential groundwater banking effort.

Information delivery

Our goal is to make SAGBI an interactive, web-based app. The decision support tool will display SAGBI groups as a map in Google Maps. Users will be able to navigate via standard map interface operations such as zoom tools and panning, or by entering a location in a search field to obtain SAGBI ratings. Users will also be able to query and display the individual ratings of each SAGBI factor for any location that has a SAGBI rating, illustrating the transparency of the model and allowing for further investigation of individual factors. CA

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California Pollution Control Financing Authority

TAX-EXEMPT BOND FINANCING PROGRAM

2014 ANNUAL REPORT TO THE CALIFORNIA STATE LEGISLATURE

March 2015

About the California Pollution Control Financing Authority:

Mission Statement: As public servants, we are committed to promoting access to capital through the delivery of diverse financing options to California business and environmental industries by being:

- A driving force of public and private partnerships.
- A leader in offering customized risk mitigation tools.
- At the forefront of projects that protect and restore the environment.

The California Pollution Control Financing Authority (CPCFA) provides California businesses with a reasonable method of financing pollution control facilities and fosters compliance with government imposed environmental standards and requirements. Over the last forty years CPCFA has evolved to meet California's needs as follows:

- For solid waste, recycling, water and wastewater projects through its Tax-Exempt Bond Program.
- For small businesses through the California Capital Access Program and other financing initiatives.
- With the reuse and redevelopment of brownfields through the California Recycle Underutilized Sites Program.

During the 2014 Calendar Year, the CPCFA board members were:

Bill Lockyer, Chair
State Treasurer

John Chiang
State Controller

Michael Cohen
Director of Finance

Table of Contents

Pollution Control Tax-Exempt Bond Financing Program
2014 Annual Report

PROGRAM SUMMARY

The Pollution Control Tax-Exempt Bond Financing Program (the "Program") stimulates environmental cleanup, economic development and job growth throughout the State of California. The Program allows California businesses to meet their growth and capital needs by providing access to low-cost financing through private activity tax-exempt bonds that provide qualified borrowers with lower interest borrowing costs than conventional financing.

In addition, CPCFA maintains a Small Business Assistance Fund (SBAF) to pay for qualified costs of issuance of tax-exempt bonds issued on behalf of certain small businesses. The assistance reduces the net cost of financing tax-exempt bonds for small businesses. SBAF can pay for letter of credit fees, transaction fees and other costs associated with the issuance of bonds.

CPCFA staff has chosen two projects from calendar year 2014 which highlight the environmental benefits being achieved in the State of California using tax-exempt financing.

PROJECT HIGHLIGHTS –

Bay Counties Waste Services, Inc. Issued Bonds worth $8,820,000 to finance the acquisition of solid waste processing equipment

Bay Counties Waste Services, Inc. dba Bay Counties SMaRT (the “Company”) was incorporated in California on April 18, 1960 and currently has approximately 189 employees. The Company provides residential and commercial recycling and solid waste disposal services in the cities of Sunnyvale, Mountain View, and Palo Alto.

The Company was awarded a new contract to operate an existing material recovery facility and transfer station owned by the City of Sunnyvale. Solid waste collected within the cities of Sunnyvale, Mountain View, and Palo Alto is delivered and processed at this facility. In order to meet its contractual obligations, the Company needed additional equipment to service the anticipated waste volume.

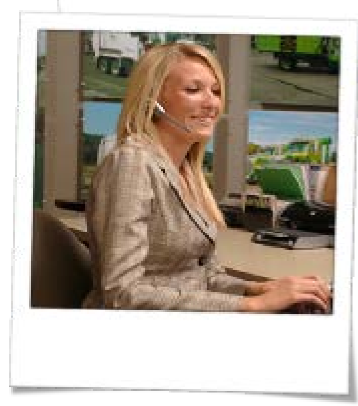
CPCFA issued tax-exempt bonds on October 15, 2014 for an amount of $8,820,000 to finance the acquisition of solid waste processing equipment such as containers, conveyors, sorters, rolling stock and related equipment.

Since the Company is a small business, it was eligible for assistance from the Small Business Assistance Fund. The Company received $118,320 to offset certain costs of issuance.

GreenWaste Recovery, Inc. Issued Notes worth $28,300,000 to finance the purchase of waste processing equipment.

GreenWaste Recovery, Inc. (GreenWaste) is a privately owned recycling and waste diversion company specializing in the collection and processing of residential and commercial waste, curbside recyclables, food waste, construction and demolition debris and yard trimmings throughout the City of San Jose. Additionally, the company owns and operates several facilities, including material recovery facilities and transfer stations located in the San Jose Area. GreenWaste was incorporated in May of 1991 and serves the cities of San Jose, Marina, and Watsonville.

GreenWaste was recently awarded contracts for waste collection and recycling for several Monterey peninsula cities. The Company anticipates leasing property for a corporate yard from the Monterey Regional Waste Management District (MRWMD) located in the City of Marina. The MRWMD will provide a CNG fueling system and will build a maintenance and operations facility. The Company will use the note proceeds to purchase equipment including CNG powered vehicles, bins, carts, and dumpsters. Additionally, GreenWaste Recovery, Inc. plans to use proceeds to purchase new sorting equipment for an existing facility in San Jose which processes yard waste and debris box materials.



CPCFA issued tax-exempt notes on November 18, 2014 for an amount of $28,300,000 to finance the acquisition and installation of new equipment including CNG powered vehicles, bins, carts, dumpsters, and state-of-the-art sorting equipment.

REPORT OF 2014 ACTIVITIES

This report of activities for the California Pollution Control Tax-Exempt Bond Financing Program is submitted pursuant to Health and Safety Code Section 44538 for the calendar year ending December 31, 2014.

1. APPLICATIONS RECEIVED

Authority staff received six new applications for a total dollar amount of $196,880,000. (See Table 1)

2. INITIAL RESOLUTIONS ADOPTED

The Authority took initial action on six applications for a total dollar amount of $196,880,000. (See Table 2)

3. FINAL RESOLUTIONS ADOPTED

The Authority took final action to approve the sale of bonds on eight applications for a total dollar amount of $260,595,000. (See Table 3)

4. BONDS SOLD

The Authority sold eight bond issues for a total of $260,590,000 ($260,525,000 in tax-exempt bonds and $65,000 in taxable bonds). (See Table 4)

5. PROJECTED NEEDS AND REQUIREMENTS FOR 2015

The Authority has sufficient funds to operate its programs for the coming year and has no need for General Fund assistance.

6. ANALYSIS OF CHANGE IN CASH BALANCE FOR FISCAL YEAR ENDED JUNE 30, 2014.

The Authority's cash balance for fiscal year 2013/2014 decreased by $2,229,615.
The Authority's ending balance for fiscal year 2013/2014 is $29,515,371. (See Table 5)

Table 1

CALIFORNIA POLLUTION CONTROL FINANCING AUTHORITY

APPLICATIONS RECEIVED IN 2014

APPL. NO.	DATE RECEIVED	APPLICANT NAME	PROJECT TYPE	AMOUNT
873	03/14/14	Elite Energy Systems, LLC	SWD*	$ 40,000,000
874	04/01/14	Recology, Inc.	SWD	$100,000,000
875	06/13/14	Bay Counties Waste Services, Inc.	SWD	$ 8,820,000
876	08/21/14	Greenwaste Recovery, Inc.	SWD	$ 33,160,000
877	09/24/14	Pena’s Disposal, Inc.	SWD	$ 3,400,000
878	10/30/14	Eco-Modity LLC	SWD	$ 11,500,000
		TOTAL:		**$ 196,880,000**

* Solid Waste Disposal

Table 2

CALIFORNIA POLLUTION CONTROL FINANCING AUTHORITY

INITIAL RESOLUTIONS (IR) ADOPTED IN 2014

IR NO.	DATE APPROVED	APPLICANT NAME	PROJECT TYPE	AMOUNT
14-01	04/15/14	Elite Energy Systems, LLC	SWD*	$ 40,000,000
14-02	05/20/14	Recology, Inc.	SWD	$100,000,000
14-03	07/15/14	Bay Counties Waste Services, Inc.	SWD	$ 8,820,000
14-04	09/16/14	Greenwaste Recovery, Inc.	SWD	$ 33,160,000
14-05	10/21/14	Pena’s Disposal, Inc.	SWD	$ 3,400,000
14-06	11/18/14	Eco-Modity LLC	SWD	$ 11,500,000
		TOTAL:		**$ 196,880,000**

*****Solid Waste Disposal

Table 3

CALIFORNIA POLLUTION CONTROL FINANCING AUTHORITY

FINAL RESOLUTIONS (FR) ADOPTED IN 2014

DATE APPROVED	FR NO.	APPLICANT NAME	PROJECT TYPE	AMOUNT
01/21/14	535	Mill Valley Refuse Service, Inc.	SWD	$ 4,675,000
03/18/14	531	Arakelian Enterprises, Inc. dba Athens Services	SWD*	$138,525,000
03/18/14	533	Zerep Management Corporation	SWD	$ 27,570,000
09/16/14	536	Sierra Pacific Industries	SWD	$ 30,000,000
09/16/14	537	Bay Counties Waste Services, Inc.	SWD	$ 8,820,000
09/16/14	538	Garden City Sanitation, Inc.	SWD	$ 8,905,000
11/18/14	539	Greenwaste Recovery, Inc.	SWD	$ 28,300,000
10/21/14	540	Synagro Organic Fertilizer Company/ Sacramento Project Finance, Inc.	SEW**	$ 13,800,000
		TOTAL:		**$260,595,000**

*Solid Waste Disposal
**Sewage Facilities

Table 4

CALIFORNIA POLLUTION CONTROL FINANCING AUTHORITY

BONDS SOLD IN 2014

CLOSING DATE	BOND NAME	PROJECT TYPE	AMOUNT OF ISSUE	BEGINNING INTEREST RATE	MODE
02/04/14	Mill Valley Refuse Service, Inc.	SWD*	$4,675,000 $4,115,000 new money $560,000 refunding	0.07	weekly
04/02/14	Arakelian Enterprises, Inc. dba Athens Services	SWD	$138,525,000 $55,000,000 new money $83,525,000 refunding	0.81	weekly
05/15/14	Zerep Management Corporation	SWD	$27,570,000	0.14	weekly
09/24/14	Garden City Sanitation, Inc.	SWD	$8,905,000	0.08	weekly
09/25/14	Sierra Pacific Industries	SWD	$30,000,000	0.08	weekly
10/15/14	Bay Counties Waste Services, Inc.	SWD	$8,820,000	0.08	weekly
11/25/14	Synagro Organic Fertilizer Company/ Sacramento Project Finance, Inc.	SEW**	$13,730,000 TE $485,000 new money $13,245,000 refunding $65,000 Taxable	3.27 4.04	fixed fixed
12/04/14	Greenwaste Recovery, Inc.	SWD	$28,300,000	0.98	monthly
	TOTAL:		**$260,590,000**		

*Solid Waste Disposal

** Sewage Facilities

Note: All bond sales negotiated.

Table 5

CALIFORNIA POLLUTION CONTROL FINANCING AUTHORITY

ANALYSIS OF CHANGE IN CASH BALANCE
FISCAL YEAR ENDED JUNE 30, 2014

CASH BALANCE	**JULY 1, 2013**	**$31,744,986***
ADDITIONS:		
	REVENUE/OPERATING REVENUE	$29,643,538
DEDUCTIONS:		
	OPERATING EXPENDITURES	$31,873,153
CASH BALANCE	**JUNE 30, 2014**	**$29,515,371**

The cash balance represents the total agency, including other programs, not just the bond program.

*This beginning cash balance differs from the ending cash balance that was reported on the 2013 Annual Report due to an accounting adjustment made to more accurately report an expense regarding the amortization of computer software. This adjustment resulted in an increase in the cash balance from $31,004,311 to $31,744,986.

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