APRIL–JUNE 2013 • VOLUME 67 NUMBER 2

California Agriculture

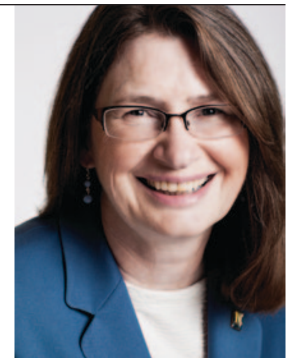
New life for conservation banks:

Reforms streamline landmark program

Also:
Switchgrass,
buffer zones,
stinkwort

How will we feed 8 billion people in 2025?

Public investment in UC fosters answers for global food system



Barbara Allen-Diaz
Vice President
UC Agriculture and
Natural Resources
University of California

In the 67 years that *California Agriculture* journal has published landmark research by UC scientists, more than 6,000 articles have reported UC Agriculture and Natural Resources (ANR) research and extension to a diverse audience of academics, policy-makers and engaged members of the public. The journal has also provided evidence of a remarkable cooperative investment to bring science-based solutions to everyday problems.

The year 2014 marks the centennial of the Smith-Lever Act forming Cooperative Extension. Together with the Morrill Act (1862) that launched public colleges and universities, and the Hatch Act (1877) that funded agricultural experiment stations at those institutions, the Smith-Lever Act played a crucial role in forming the land-grant system that today provides accessible public higher education, produces research in the public interest, and extends that knowledge for the public good. The return on those investments has been remarkable.

Today, ANR works with partners in virtually every sector, disseminating research and education that directly benefits citizens, communities, businesses and the environment of the state. As a result of those partnerships, California has been and continues to be the nation's top agricultural state. By every measure, California's command of this top ranking is growing larger, with every $1 invested in agricultural research resulting in $21 in economic benefit to every Californian.

In 2011, California farm revenue topped $43 billion, directly providing 800,000 jobs on more than 80,000 farms. Of more than 400 crops produced in the state, 11 exceeded $1 billion in revenue. Our agricultural exports returned $14.7 billion to the state's economy, and these statistics continue to climb. In one year alone, from 2010 to 2011, agricultural revenues were up 15%.

Driven by the innovation and entrepreneurship of California growers and processors, UC research has been adapted to increase productivity in all major crops, benefitting the whole food system. Over the past 30 years, average yields of almonds are up 122%, processing tomato yields are up 69%, and per-cow milk production is up 44%. UC-developed plant varieties account for 90% of the wheat grown in the state, 65% of California's strawberries, and 40% of world strawberry production. Looking forward, UC academics are advancing research to foster solutions to global climate change, hunger and obesity, invasive pests, endangered natural resources, and water quality and quantity concerns.

Additional information on the scope and impact of UC research and the economic power of California agriculture can be found in new UC ANR publications available on the web at http://ucanr.edu/files/141870.pdf and http://ucanr.edu/sites/Toolkit/files/162595.pdf.

In 2025, providing 8 billion people with quality, affordable and accessible food will be the defining economic, sociopolitical and ethical issue of our time. It is a global challenge. But as the number-one agricultural state in the United States, and one of the world's top food producers, it is also a challenge to California.

On April 9, 2013, ANR will host the Global Food Systems Forum. Producers, geopoliticists, ethicists, economists, humanists and others will address the challenges of protecting our natural resource base (water, soil, air, plants and animals) upon which our food supply depends, the risks we face if we do not, and potential solutions for California and the world.

Keynote speakers include Mrs. Mary Robinson, former president of Ireland and president of the Mary Robinson Foundation — Climate Justice, and Wes Jackson, founder and president of the Land Institute. In addition, two distinguished panels will focus on the geopolitical, ethical, economic and technical challenges facing food systems from a global and California perspective. We invite you to view these discussions via webcast.

To register for the Global Food Systems Forum webcast, please go to our website, http://food2025.ucanr.edu/. Additional information on speakers, panelists and moderators, as well as links to social media blogs and tweets can be found at http://food2025.ucanr.edu/Blog/.

I hope you will join us for the webcast and contribute to an ongoing conversation on how best to secure an abundant, affordable, and secure food supply while protecting the natural resource base for California and the world.

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COVER: Conservation banks enable farmers, ranchers and other landowners to receive income for managing their lands to benefit wildlife. The Golden State established the nation's first such program in 1995, and has pioneered protection of biodiversity and species at risk. However, since 2009 the number of conservation banks approved yearly has declined to zero, partly due to an unwieldy application process. Now a new law (page 85) and further proposed reforms (page 86) promise to streamline the program. Additional conservation banks could restore critical habitat and protect riparian corridors. Shown is the Thomes Creek tributary coming into the Sacramento River, above Chico at River Mile 326. *Photo by Geoffrey Fricker*

New life for conservation banks:

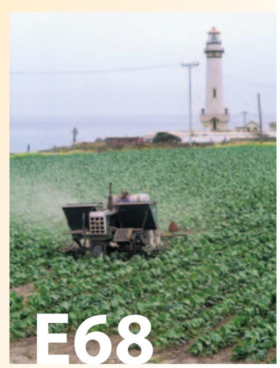
Reforms streamline landmark program

Research and review articles

New pests and diseases

Now in print

This article was published online (January–March 2013) on the *California Agriculture* website; it now appears in print after page 115.



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About *California Agriculture*

University *of* California
Agriculture and Natural Resources

California Agriculture is a quarterly, peer-reviewed journal reporting research and reviews, published by the University of California Agriculture and Natural Resources (ANR). The first issue appeared in 1946, making *California Agriculture* one of the oldest, continuously published, land-grant university research journals in the country. There are about 15,000 print subscribers, and the electronic journal logs about 5 million page views annually.

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

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

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

Authors and reviewers. Authors are primarily but not exclusively from ANR; in 2010 and 2011, 23% were based at other UC campuses, or other universities and research institutions. In 2010 and 2011, 33% and 40% (respectively) of reviewers came from universities, research institutions or agencies outside ANR.

Rejection rate. The rejection rate has averaged 34% in the last 3 years. In addition, associate editors and staff may send back manuscripts for revision prior to peer review.

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

Editing. After peer review and acceptance, all manuscripts are extensively edited by the *California Agriculture* staff to ensure readability for an educated lay audience and multidisciplinary academics.

Submissions. *California Agriculture* manages the peer review of manuscripts online. Please read our Writing Guidelines before submitting an article; go to: http://californiaagriculture.ucanr.edu/submit.cfm.

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1301 S. 46th St., Bldg. 478, Richmond, CA 94804-4600
Phone: (510) 665-2163; Fax: (510) 665-3427; calag@ucanr.edu
http://californiaagriculture.ucanr.edu

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California enacts law to strengthen conservation bank program

California's landmark conservation banking program, launched by executive order in 1995, was the first of its kind nationwide — but until now was never part of statutory law.

Now this 18-year-old program is backed by new legislation (SB 1148), effective in January.

Although a bellwether program that led to establishment of 29 banks, the executive order lacked clear regulatory standards or procedures, says David Bunn, researcher for the Wildlife Health Center at UC Davis. Bunn authors an article in this issue (page 86) reporting findings from the first assessment of the program.

For more information: http://www.dfg.ca.gov/habcon/conplan/mitbank/

"The lack of statutory standards reduced the program's usefulness and caused negotiations over potential new banks to drag on for 5 or more years," he added.

New bank approvals have dropped in recent years; most of the state's conservation banks were approved before 2006, and none have been approved since 2009.

"The economic recession also contributed to the dwindling use of the program," said Bunn. "These banks achieve conservation goals by providing credits to developers who need to mitigate environmental impacts of development. There was much less demand for credits after the dropoff in construction statewide — so less market incentive to establish them."

Now Senate Bill 1148 has created a clear regulatory framework for the program that could become a model for other states, according to Bunn.

Bunn's study finds that three key actions are needed to address the many difficult challenges of conservation banking in the state: 1) enacting standards in statutes for critical program components such as prioritizing potential bank sites, 2) adding experienced program-dedicated staff to implement the program and 3) establishing a regional approach to planning and monitoring.

"The passage of SB 1148 is a good first step to addressing some of the major program challenges identified in our research, and the new authorizations for fees make it possible to fund additional dedicated staff for the program," said Bunn, lead investigator of the research. "The bill adds clarity to application procedures. However, further legislation is needed to establish standards for prioritizing potential conservation bank sites within a region."

— *Janet White*

Letters

Issues in contemporary agriculture

In Albany, in the aftermath of the illegal occupation of the Gill Tract, members of the Albany City Council have been in discussion with Dean Keith Gilless of the UC Berkeley College of Natural Resources on the future of the Gill Tract and the sort of community programs that could be available there.

California Agriculture journal, especially the January-March 2013 issue, provides the council with an excellent overview of contemporary issues in agriculture and of the variety of educational, environmental and nutritional programs sponsored by ANR.

Michael Barnes
Albany City Council Member

Correction: Location of Pigeon Point lighthouse

Great job on the January-March 2013 *California Agriculture* issue! We are interested in UC agricultural and natural resources research because our company specializes in alternative urban farming and gardening, and the Food and Solar Energy Co-Production Project.

On page 62, "Nitrogen fertilizer use in California: Assessing the data, trends and a way forward," the picture of Pigeon Point Lighthouse with cole crop plants in the foreground was identified as located in Santa Cruz County. Pigeon Point Lighthouse is in San Mateo County.

Greg Scott
Emergence Farms and Gardens
Newark/Fremont, CA (South Alameda County)

Editor's note: Thank you for the correction; we entered it in the E-Edition, and the print version in this issue. California Agriculture *regrets the error.*

Production and access to nutritious food

Thank you for the coverage in the January-March 2013 edition. At UCCE Marin, we are providing steering committee leadership for the Marin Food Policy Council. This is a broad stakeholder body focusing on the development and implementation of policy to increase production of, and access to, healthy nutritious food.

Everything in the issue is relevant to our current and upcoming discussions.

David J. Lewis, Director
University of California Cooperative Extension
Marin County

RSVP

WHAT DO YOU THINK?

The editorial staff of *California Agriculture* welcomes your letters, comments and suggestions. Please write to us at: 1301 S. 46th St., Building 478 - MC 3580, Richmond, CA 94804, or calag@ucanr.edu. Include your full name and address. Letters may be edited for space and clarity.

January–March 2013
California Agriculture

RESEARCH ARTICLE

Reforms could boost conservation banking by landowners

by David Bunn, Mark Lubell *and* Christine K. Johnson

California pioneered the first conservation banking program in the nation in 1995. In contrast to the regulatory approach that penalizes landowners for harming protected species, conservation banking creates a market incentive for landowners to conserve wildlife. We investigated the implementation of the California Conservation Banking Program including a preliminary assessment of factors that limit the program's potential, both as an effective approach to conserving wildlife and as an economically rational option for ranchers and other landowners. We then surveyed the majority of wildlife agency conservation bank staff and conservation banking practitioners, and analyzed monitoring programs and ecological parameters of all approved banks. Most of the major challenges facing the Conservation Banking Program are linked to three fundamental problems: (1) the lack of clear standards and regulations, (2) the lack of adequate funding for dedicated wildlife agency coordinators and (3) the inefficiency and ecological constraints of managing stand-alone banks. Many of the challenges inhibiting conservation banking could be eliminated or reduced by enacting standards in statutes as well as by implementing a regional approach to planning for future sites.

rayyee/Shutterstock.com

Conservation banks protect vernal pools on the Santa Rosa Plain and in the Central Valley. The California program mitigates impacts of development projects on endangered species and is modeled on the federal wetlands mitigation bank program.

Conservation banking provides a mechanism for ranchers and other landowners to receive income for managing their lands to benefit wildlife. California established the first conservation bank program in the nation and is recognized as a world leader in implementing biodiversity offsets as a means to conserve species (Mead 2008). Modeled on the federal wetlands mitigation bank program, conservation bank programs are applied to mitigating impacts of development projects on endangered species and species of concern. Conservation banks are publicly or privately owned lands that are protected in perpetuity by fee title or easement and managed to provide habitat for at-risk species. The owner, or management firm owning the bank, is authorized by wildlife agencies to sell credits to developers to mitigate impacts of their proposed development projects on wildlife.

The 18-year-old California Conservation Banking Program, the largest such state program, was launched by a state executive policy rather than by legislation (Wheeler and Strock 1995). The purposes of the program are to (1) conserve important habitats and habitat linkages, (2) provide a better alternative to the piecemeal project-by-project mitigation approach, (3) take advantage of economies of scale not available to individual mitigation projects, (4) provide incentives for private landowners to protect species and (5) provide an additional funding mechanism for ecosystem reserves within regional conservation plans (Wheeler and Strock 1995). In 2003 the U.S. Fish and Wildlife Service released a guidance document for establishment and operation of conservation banks across the nation.

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v067n02p86&fulltext=yes
doi: 10.3733/ca.v067n02p86

In California, mitigation for development projects that harm wildlife is implemented through one of four mechanisms: (1) mitigation on a project-by-project basis, (2) mitigation within a multispecies regional plan (under the state Natural Community Conservation Planning Program, coupled with a Habitat Conservation Plan for federally listed species), (3) purchasing offset credits in a conservation bank (Mead 2008; Wheeler and Strock 1995) or (4) payment of in-lieu mitigation fees.

Regional conservation planning

Regional conservation planning is the most comprehensive approach to conserving species and natural communities. Large-scale regional conservation plans, as developed under the state Natural Community Conservation Planning Program, are designed to conserve habitat and ecosystem functions that are critical to sustain at-risk species covered by the plan over a large landscape (Calif. Fish & Wildlife Code § 2800 et. seq.; Pollack 2001). A broad range of ecological considerations is incorporated into the design of regional conservation plans and the protected reserve sites within them. These considerations include the distribution of plant communities, size of habitat patches required by various species, vital corridors, heterogeneity of the landscape, water resource commitments and management, appropriate recreational uses of the lands, the network design of protected areas and reliable long-term management funding (Calif. Fish & Wildlife Code § 2800 et. seq.; Noss et al. 1997). In addition, Natural Community Conservation Plans (NCCPs) require a monitoring program capable of assessing the biological status of covered species and habitats, and the ecological performance of the conservation plan. Monitoring is also necessary to inform adaptive management (Atkinson et al. 2004; Calif. Fish & Wildlife Code § 2800 et. seq.).

Conservation Banking Glossary

Fee title or easement: Conservation banks may be protected in perpetuity either by purchase of fee title or by easements on the land to ensure it is managed for conservation values. A key decision is who will own the land or hold the easement. A conservation banker may initially own a bank but later transfer ownership to the California Department of Fish and Wildlife (CDFW) or to a nonprofit land management firm.

Credit and debit values: A credit is a unit used to quantify the species or habitat conservation values within a conservation bank. For example, 1 acre of habitat is often worth one credit. A debit is a unit used to quantify adverse impact to species or habitats of concern on lands being developed. The wildlife agencies decide how many credits must be purchased to offset the impact of a development project, and these terms are a requirement for mitigation and permit approvals.

Service area: The service area is a geographic region where the adverse impacts of development projects can be covered by a particular conservation bank. The service area should be justified based on ecological considerations, including watershed boundaries as well as the population structure and distribution of covered species, and must be approved by the wildlife agencies. In addition, conservation banks that offer credits for multiple species may have more than one service area. Bankers are critically interested in the service area because it determines the potential market for credits. Wildlife agencies want to be sure of the ecological justifications for using the conservation bank to offset development impacts anywhere in the service area. Local governments may be concerned about the service area because they usually want the benefits of mitigation for local projects to occur within the county.

Endowment and financial commitments: To cover the costs of management and monitoring in perpetuity, conservation banks must use a portion of the income from credit sales to set up a nonwasting endowment, in which only the interest on the endowment funds is spent each year. A key issue to address in bank agreements is how to ensure funding of management and monitoring in the first few years of the bank operation, prior to full investment in the endowment from the sale of credits. In addition, if a bank is failing to meet conservation performance goals, financial commitments for managing the bank site may be secured with bonds or other means.

Site management plan: Bank agreements must include a management plan and designated management entity, usually a nongovernmental organization that is responsible for implementing conservation measures — such as habitat management, restoration or creation — and for managing the site in perpetuity. These management responsibilities may be transferred. For example, a banker may provide management during the habitat creation phase and then transfer management to the state or a nonprofit for ongoing maintenance of the site. Bank agreements typically require that annual management reports be submitted to wildlife agencies.

Monitoring plan: Conservation banks establish a monitoring program to determine whether biological goals are being met as well as to inform adaptive management (adjusting management actions in the field based on changes detected through monitoring). Monitoring results are included in the annual management reports (Wheeler and Strock 1995).


Patrick Huber

Conservation banks could enable farmers to restore and broaden riparian habitat corridors on the edges of their fields. *Above*, narrow strips of habitat adjacent to irrigation ditches in Sutter County.

However, development of a Natural Community Conservation Plan usually requires 5 to 10 years of analyses and dozens of meetings for scientific and public review. Due to limited state resources, the vast majority of development over the next couple of decades will occur without the Natural Community Conservation Plan level of regional planning (Bunn et al. 2007).

Conservation banking

Benefits. Expanding the use of conservation banks has the potential to provide conservation design features and benefits similar to those of Natural Community Conservation Plans, but with more efficiency. Creating a conservation bank requires less scientific review and needs to satisfy fewer interests; negotiations usually involve just one landowner, a few stakeholders such as a conservation firm, and the wildlife agencies. The review process and agreement on a proposed conservation bank may be accomplished in about 2 years, as they were in the early years of the program. This is less than one-half the time it typically takes to reach agreement on a regional conservation plan (Ruhl et al. 2005).

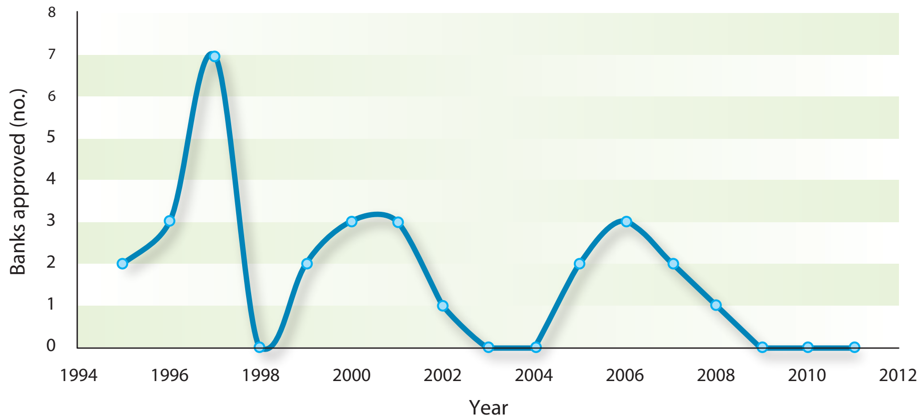

Fig. 1. Number of conservation banks approved each year in the California program between 1995 and 2011.

Establishment. The selection and approval process for most proposed conservation banks usually begins with the bank proponent identifying a property that meets ecological and financial criteria. The proponents are conservation bank practitioners, including small conservation firms, landowners, biological consultants, real estate companies, developers and nonprofit land management organizations. The basic site criteria proponents seek to satisfy are whether a property is good habitat for impacted species within a region and whether there is a good market for conservation credits due to new development. Next, the bank proponent has preliminary discussions with the wildlife agencies (CDFW 2012). If the wildlife agencies agree that the site has good potential to be a conservation bank, the bank proponent prepares assessments of the biological resources and compiles information on the property title and restrictions. After the site's assessments are completed, the bank proponent and wildlife agencies negotiate the species and/or habitat to be covered by the bank, compatible land uses, mitigation credit values, service area, monitoring plan, habitat needs (creation, restoration or preservation), management plans and the property ownership or easement.

A draft conservation bank agreement and management plan must be prepared and approved by the agencies. After agreements are approved, and land purchases or easements are executed, credits from the bank may be sold (CDFW 2012).

Status. There is great interest in the potential of conservation banking because — in contrast to the regulatory approach that penalizes landowners for harming species — it creates a market incentive for ranchers and other landowners to conserve wildlife. However, based on the number of new banks approved each year, the program appears to be in decline (fig. 1). Here, we report results of a preliminary investigation into the California Conservation Banking Program, including results of a survey, with particular attention to factors limiting the program's potential to conserve wildlife and natural communities. We also analyze potential reforms to improve the conservation performance of banks while reducing barriers to landowner participation.

Fig. 2. Regional clusters of conservation banks in California.

Assessing conservation banks

California has 29 state-approved conservation banks, averaging about 600 acres each (the range is large, from 8 to 6,000 acres). They are clustered in five geographic regions: the South Coast, southern San Joaquin Valley, Sacramento region, East Bay Hills and Santa Rosa Plain (fig. 2). Some of these banks were established within the context of a regional conservation plan, such as a Natural Community Conservation Plan or a Habitat Conservation Plan (HCP). Eight of the 10 banks on the South Coast are within a Natural Community Conservation Plan. Elsewhere, banks were established as stand-alone areas outside of any regional conservation plan; their acreage was selected without benefit of comprehensive regional prioritization of the most ecologically valuable lands.

Watercourses and riparian corridors are important areas to protect and restore to maintain habitat connectivity in a region. Conservation banks are an ideal way to conserve or restore riparian habitats along the edges of agricultural lands.

Due to the small number of banks statewide, we did not limit our survey to a statistical sample. Instead, we made the effort to interview most of the individuals involved in developing, managing and providing oversight of all the conservation banks in the California program.

The interviews included 36 individuals who have worked on conservation banks in California over the past 15 years: 20 who work for wildlife agencies (the California Department of Fish and Wildlife, or the U.S. Fish and Wildlife Service) and 16 who work in the private sector, including bank owners, conservation bank firms and land management nonprofits and consultancies:

- The Department of Fish and Wildlife has one staff person assigned to managing conservation banks in each of the six regional offices. We interviewed all current Fish and Wildlife regional conservation bank managers as well as former managers who had been reassigned in the last 5 years. We also interviewed current and former Fish and Wildlife deputy directors and headquarters staff who have engaged in management of the conservation bank program.
- The U.S. Fish and Wildlife Service has only a couple of field staff devoted to conservation banks in California. We interviewed two senior managers involved in conservation banks in the Pacific Southwest regional office in Sacramento and two field staff serving Southern California.
- With regard to conservation banking practitioners, we attempted to interview managers covering all of the conservation banks in the state. From bank agreement records, we obtained names of the conservation banking firms or private companies and the managers for all of the conservation banks. We completed interviews of current owners, management consultants or management firm representatives of 79% of the banks.

All interviews were conducted by a single investigator either in person or by telephone during December 2011 and January 2012. Answers were summarized and recurring responses were tallied, scoring one point for each person who gave that particular response. We then ranked the answers by total scores (figs. 3 to 6). Respondents were identified as either associated with wildlife agencies or conservation bank practitioners, so differences in responses or priorities of wildlife agencies versus the private sector could be analyzed.

Survey questions were designed to (1) assess the criteria used to select new conservation banks and identify what changes may be needed to ensure that the

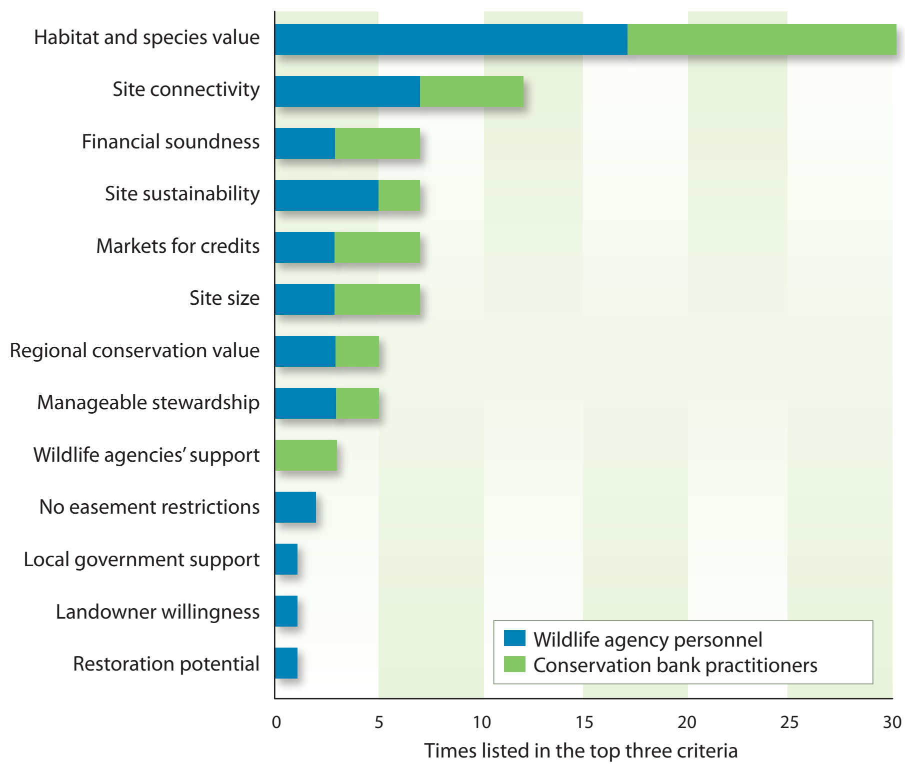

Fig. 3. Most important criteria for selecting and approving conservation banks identified by survey respondents.

best sites are selected, (2) assess the challenges and barriers to implementing an effective program and (3) identify policy changes that will improve the program.

For each of the 29 bank sites of the California Conservation Banking Program approved by 2011, we also reviewed bank agreements, biological assessments, management and monitoring plans, and annual monitoring reports from the files of regional offices of the California Department of Fish and Wildlife. With regard to monitoring, we assessed whether covered species were useful indicators of the impact of conservation measures (Bunn, unpublished). We also compared regional conservation values of the banks based on the estimates of size, habitat connectivity and habitat diversity (Bunn, unpublished).

Barriers and reforms

The wildlife agency staff and conservation bank practitioners have very firm ideas regarding the difficulties of conservation banking, and most also had recommendations for reforms.

Karen McClymonds

The giant garter snake and red-legged frog are species of concern protected by conservation banks in the California program.

Site selection criteria. Survey respondents generally agreed on key criteria for selecting a bank site (fig. 3). Among 14 criteria identified, the top two were quality of habitat (score = 29) and site connectivity to similar habitats within the region (score = 12). The next most common criteria were site size, market for credits, and financial soundness and sustainability (score = 7 for each). As expected, conservation banking practitioners emphasized the importance of the market for credits and financial risks more often than wildlife agency respondents.

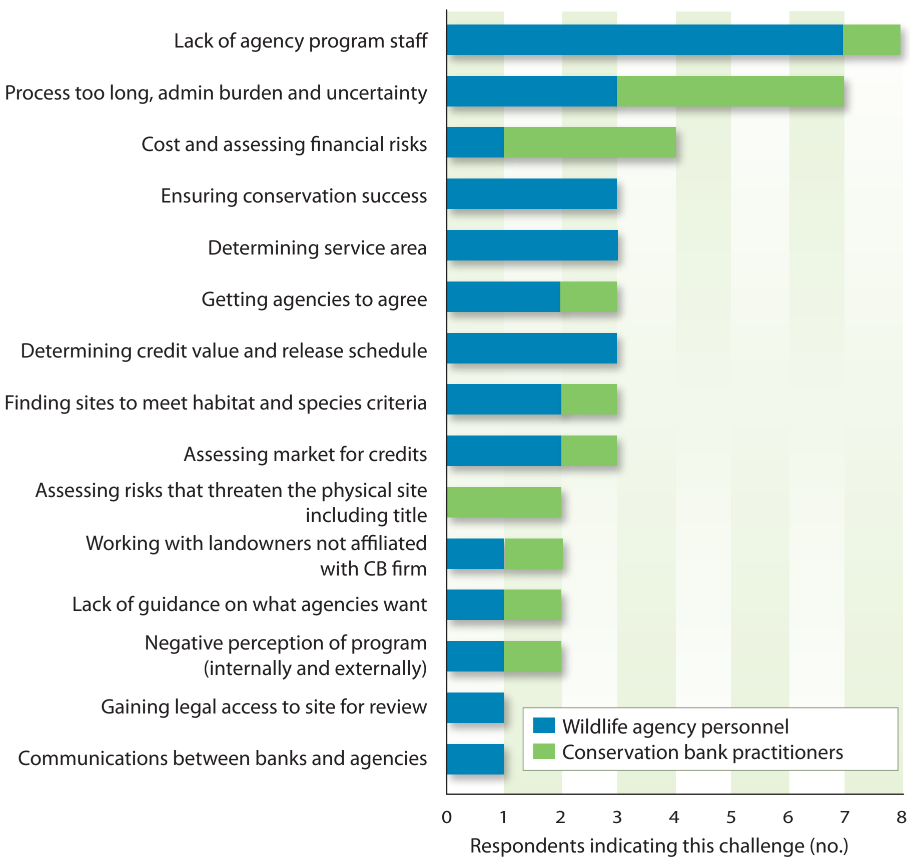

Fig. 4. Challenges of site selection and approval identified by respondents.

Barriers to site selection or approval. Interviewees were asked to identify the three greatest challenges to selecting or approving a conservation bank site (fig. 4). Fifteen different challenges were identified. Among all respondents, the three most frequently mentioned were (1) lack of staff in wildlife agencies dedicated to handling conservation banks (score = 8), (2) the long and bureaucratic approval process (score = 7) and (3) difficulty in assessing costs and financial risks (score = 4). The next most common challenges identified were ensuring conservation success, determining service area, getting agencies to agree, determining credit value and release schedule, finding sites that meet habitat and species criteria, and assessing the market for credits (score = 3 for each).

Tough issues to resolve. Respondents identified 19 issues that were the most difficult to resolve for approval of a conservation bank (fig 5). Of these, the two identified most often by wildlife agency respondents were reaching agreement on the number of credits warranted by the wildlife values at the site (score = 7) and determining the service area (score = 6). Conservation banking practitioners had scattered responses, with only one or two points each identifying a dozen issues, including title and easement issues (score = 2), estimating cost (score = 2) and length of the process (score = 2) (fig. 5). The number of challenges identified highlights the complexity of the process. Negotiations regarding approval can be stalled over disagreement on any or several of these difficult issues.

Major barriers to approval. Conservation banking practitioners most frequently said that the number one challenge is the lengthy approval process, requiring 2 to 7 years. The wildlife agencies indicated that the excessive length of the process is mainly due to the lack of staff dedicated to the program, which slows site reviews and conservation bank application processing. Conservation banking practitioners said that the second most difficult challenge is assessing the costs and financial risks of a proposed bank.

Agreement on major barriers. Considering all of these challenges and issues, wildlife agencies and conservation banking practitioners were in close agreement on the major barriers to the development of new conservation banks (fig. 6). The most commonly identified barriers were (1) the approval process is too long (score = 16), (2) the upfront and management costs are too high (score = 12), (3) a market for credits is lacking (score = 7) and (4) parties disagree over who should hold the bank endowment for management in perpetuity (score = 6).

Guidelines for creation. Wildlife agencies have provided very general guidelines for the selection of conservation bank sites. When asked if they recommended changes to state and federal guidance on conservation bank selection criteria, three-quarters of the wildlife agency respondents and more than half of the conservation banking respondents recommended changes. The most frequent recommendation by wildlife agency respondents was to include clear selection criteria in regulations (score = 7). The next most common point, emphasized more by conservation banking practitioners, was that criteria must have flexibility due to the tremendous variability of regions and environmental conditions. (Data not shown.)

Reforms to facilitate creation. When asked to recommend changes to the site selection and approval process that would facilitate creation of conservation banks with high habitat and ecological value, the most common response by far was to determine the highest-priority lands for conservation in a region before designating banks there (score = 10). The next most common responses were early communication between bankers and agency staff regarding the site of a proposed bank (score = 4) and adding dedicated conservation banking program staff in the agencies (score = 3). (Data not shown.)

Major barriers to long-term viability. We also asked respondents to assess the greatest challenges of managing or

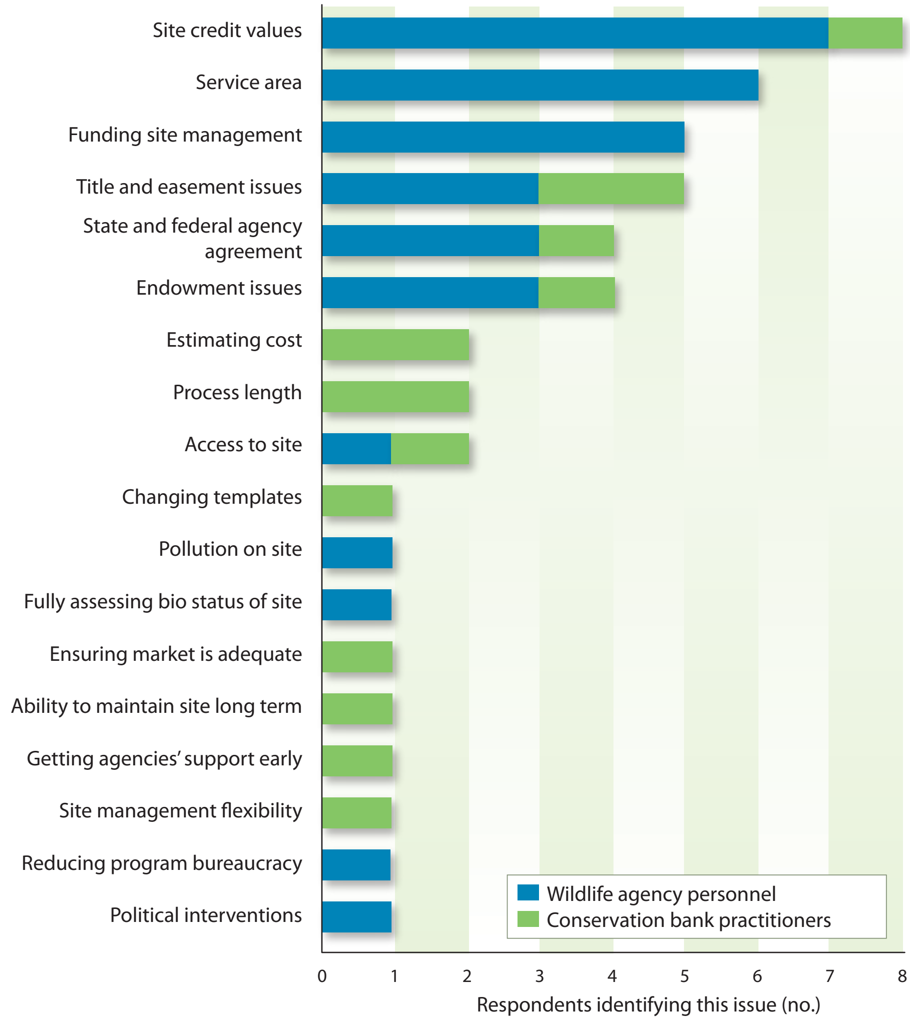

Fig. 5. Most difficult issues to resolve for approval of a conservation bank identified by survey respondents.

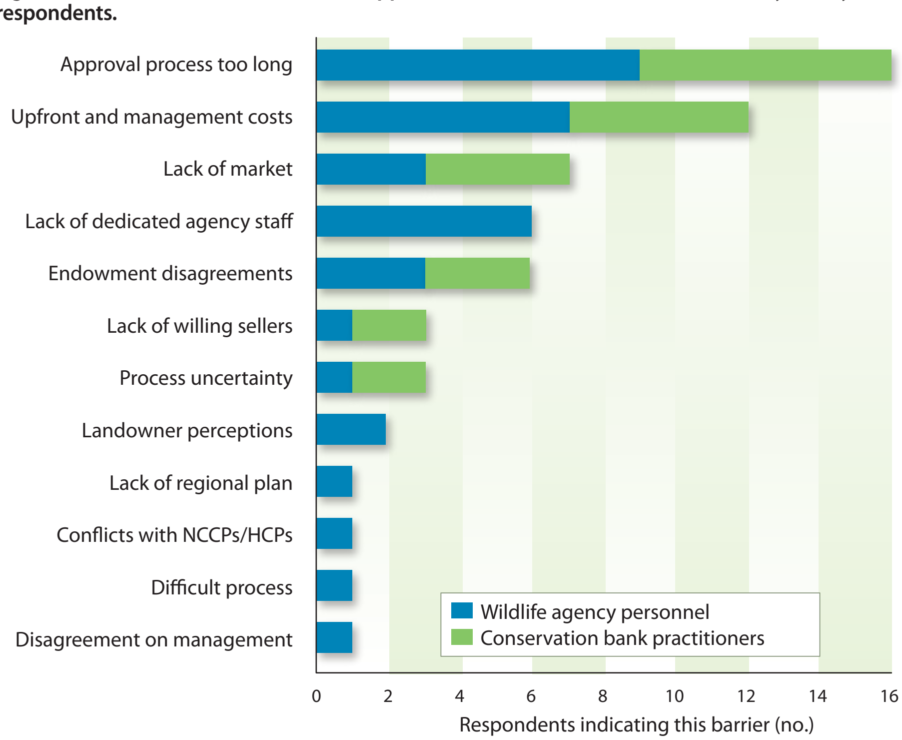

Fig. 6. Barriers to new conservation banks identified by survey respondents.

supervising established banks. Lack of staff was the most common response of wildlife agency respondents (score = 14). Some wildlife agencies also pointed to weak monitoring programs and difficulty making changes as part of adaptive management. Conservation banking practitioners tended to highlight site operational issues, including incompatible uses of adjacent lands, controlling invasive vegetation, preventing unauthorized use and keeping management costs down. (Data not shown.)

Reforms to facilitate long-term viability. Interviewees were asked if there are any issues that need to be resolved to ensure the long-term viability of the conservation bank program. Three-quarters of the interviewees — including 80% of the wildlife agency and 66% of the conservation banking practitioner respondents — said that reform would be required for the long-term viability of the program. (Data not shown.)

Wildlife agency respondents said that the most important issues to resolve were adding dedicated agency staff (score = 8) and establishing new policy about who should be permitted to hold endowments (score = 4). Conservation banking practitioners said that the most important issues to resolve for the program's long-term viability were agency cooperation and consistency (score = 5) and establishment of regional management of conservation banks (score = 4). Both wildlife agency and conservation banking practitioner respondents highlighted the need for common standards for conservation banks. Wildlife agency respondents are more inclined to suggest that these standards and other requirements of the conservation bank program be formalized in statutes and regulations.

Evaluating conservation banks. In the 1990s, there were high expectations that California's innovative conservation banking program would provide an effective market-driven mechanism for developers, ranchers and other landowners to conserve species and natural communities impacted by rapid development. Conservation banking was authorized with just a brief executive policy statement; there was no legislative deliberation or mandate (Wheeler and Strock 1995). Now with a record of 18-plus years, it is time to evaluate whether the program is meeting expectations and contributing to achieving conservation goals.

We analyzed the challenges and potential improvements of the California program with both the conservation and financial requirements in mind. In addition to conserving species, program success requires that the business of conserving priority lands and achieving conservation objectives be profitable for landowners and conservation banking firms. If conservation banks fail to conserve species and natural communities as planned, the wildlife agencies will be under pressure from the public and policymakers to discontinue the program. If the financial risks of conservation banking are too high, the private sector will cease to develop new banks.

Ecological value. The 29 conservation banks under the California program were established under a wide variety of environmental circumstances and differ in their regional ecological value. Even within regions (fig. 2), the value of banks varies widely based on the ecological criteria of size of the site, connectivity to adjacent natural lands and biodiversity. For example, the ecological values of sites on the Santa Rosa Plain were similar, while values varied widely among sites in the Central Valley. Eight of the 10 banks on the South Coast were established within the context of a regional conservation plan. Still other banks were established as stand-alone projects without the benefit of any regional plan or comprehensive prioritization of ecologically valuable areas.

Clear and stable standards reduce uncertainty and the length of the approval process — two of the greatest barriers and risks for landowners and conservation bank firms.

Monitoring. Conservation banks generally support only very limited monitoring programs, and very basic annual or seasonal surveys of species and parameters such as water level in vernal pools or depth of thatch in upland grasslands. Monitoring programs will provide data of limited value unless they are carefully designed, with defined goals, hypotheses and consideration of statistical power (Field et al. 2005; Legg and Nagy 2006; Lindenmayer and Likens 2010; Noon 2003). A preliminary review of the monitoring plans and annual monitoring reports for each bank found that monitoring usually focuses on the covered species for which a bank was established. However, a bank's conservation measures are not likely to be related to the abundance of highly mobile at-risk species such as Swainson's hawk (*Buteo swainsoni*), burrowing owl (*Athene cunicularia*) and kit fox (*Vulpes macrotis*) because they have home ranges much larger than the typical bank. Furthermore, monitoring of such species at bank properties is not

The California Conservation Banking Program protects Swainson's hawk, another species of concern in the state.

likely to elucidate whether changes in abundance are due to factors at the site or due to regional factors.

Challenges and key reforms

The results of our survey indicate that both the private and public sectors of the conservation banking community understand the principles of conservation biology and generally agree on the important ecological and financial criteria for good bank sites (fig. 3). This is significant because efforts to improve a program involve change, and change is always easier when the stakeholders agree on the goals. Most survey respondents agree that the conservation banking program has numerous challenges and that changes are needed to the site approval process, program standards, guidelines and policies.

Challenges. The approval of new conservation banks and long-term management of established banks face many challenges (table 1). Conservation bankers identified the lengthy and uncertain review process as the number one challenge to gaining approval for a new conservation bank (figs. 4 and 6). By a wide margin, wildlife agency staff identified the number one problem as the lack of staff assigned to the program, which is also partly responsible for the slow review process. Several agency staff also agreed with the bankers that the lengthy process is a major problem.

Altogether, our survey of the conservation banking community and our analyses of the bank monitoring programs and site ecological parameters identified 22 site selection challenges and 15 management challenges (table 1), all of which can be linked to three fundamental problems: (1) lack of clear standards and regulations, (2) lack of sufficient well-trained program-dedicated wildlife agency staff and (3) the inefficiency and ecological constraints of approving and managing stand-alone banks. Solving these three problems will solve or reduce many of the other issues identified by wildlife agency staff, the private sector and our program analyses (table 1). Addressing these problems will also enhance the long-term viability of conservation banking as an effective tool for mitigating the impacts of development.

Key reforms. Three actions will address these fundamental problems, and many of the challenges that face

TABLE 1. Three major policy changes that address most of the challenges and barriers of conservation banking identified by survey respondents

Site selection and approval challenges	Policy 1. Adopt standards and regulations	Policy 2. Fund adequate program staff	Policy 3. Require regional planning
Lack of agency staff	■	■	
Long and difficult approval process	■	■	■
Upfront and ongoing costs	■	■	
Process uncertainty and risk	■	■	■
Ensuring good site management	■	■	
Determining service area	■		■
Getting agencies to agree	■		■
Determining credit value and schedule	■		■
Selecting sites with good ecological values	■	■	■
Lack of regional conservation plan			■
Conflicts with NCCPs and HCPs	■		■
Assessing market for credits	■		■
Lack of credit market			
Assessing threats to site		■	■
Endowment disagreement	■		
Lack of willing sellers			
Working with landowners without banker		■	
Disagreement on site management	■		
Lack of agency guidance of priority sites	■		■
Negative perception of program		■	■
Gaining access to sites for review	■		
Communications between banks and agencies		■	■
Total	**15**	**10**	**13**
Management challenges			
Lack of agency staff	■	■	
Implementing adaptive management		■	■
Weak monitoring program	■	■	■
Incompatible uses of adjacent lands			■
Controlling invasive vegetation			
Preventing unauthorized use			
Lack of site review guidelines	■		■
Lack of management and monitoring regulations	■		■
Difficulty in accessing endowments			■
Lack of neighbor cooperation for endangered species			
Getting agency support for changes to solve problems	■	■	■
CDFW ownership constrains management options like grazing		■	
Achieving conservation goals		■	■
Managing fire			
Risk of site condemnation for rights of way			
Total	**5**	**6**	**8**

conservation banking: (1) the enactment of state conservation banking standards in statutes and regulations, (2) securing funding for adequate agency staff and (3) establishing a regional approach to planning and monitoring. These reforms are necessary if conservation banking is to achieve its potential for mitigating the negative impacts of development on species of concern.

Establishing legal standards

Wildlife agency personnel and conservation banking practitioners indicated that a high priority for reform was establishing standards for approving new banks, designing and evaluating monitoring programs and reviewing conservation performance. Conservation banking practitioners also highlighted the importance of guidelines or standards being consistent and not changing from year to year once the approval process has begun for a particular site. From the conservation banking practitioner point of view, it is critical that standards do not change after they have invested a year or more on studies and negotiations for easement, endowment and management agreements. Clear and stable standards reduce uncertainty and the length of the approval process — two of the greatest barriers and risks for landowners and conservation bank firms.

Clear standards also assist the agency reviewers and lead to more consistent evaluations of proposed conservation banks. However, wildlife agencies and conservation banking practitioners emphasized that standards must have some flexibility because land use and ecological circumstances are so varied from one region to another and among different natural communities. While most wildlife agencies and conservation banking practitioners agree that standards would improve the program, the latter are reluctant to suggest that those standards be adopted in formal regulations.

However, in January this year, a new state law (SB 1148) established clear guidance for one aspect of the conservation banking program, the application process and timeline. This conservation banking statute is an important first step, and regulations will help to eliminate or reduce many of the major challenges identified by the conservation banking community (fig. 6).

Wildlife agency staffing

The new law may also help to address inadequate staffing by mandating that fees be assessed to cover costs of the program. This increases the likelihood that funding will be provided for dedicated program personnel. Legislatively mandated programs have higher priority for funding and staffing. Additional laws and regulations are still needed to standardize the process for reaching agreement on some of the most contentious elements of banks: regional conservation priorities, credit value and schedule, service area, and monitoring requirements.

Regional planning

The state and federal wildlife agencies should develop regional conservation plans for conservation banking. This would reduce or solve many of the major challenges of the bank selection and approval process and the ongoing management of approved sites (table 1). While conservation banking was originally conceived as a positive alternative to project-by-project mitigation, the creation of stand-alone conservation banks suffers many of the limitations of single project mitigation. Several of the earliest banks were developed in the conservation planning area of a Natural Community Conservation Plan in Southern California to protect coastal sage scrub habitat of the threatened California gnatcatcher among other species. As such, these banks could be evaluated for their regional conservation value and their contribution to the designed reserve network of the regional plans.

California rangelands managed under a conservation bank can provide excellent habitat for burrowing owls. Burrowing owls benefit from several conservation banks in the Central Valley.

Drawbacks of stand-alone banks. More recently approved banks are stand-alone banks. The ecological evaluation of stand-alone banks is based on a biological assessment of the site and site visits. The initial biological assessments of conservation banks, performed early in the site review process, are generally very basic and lack a comprehensive evaluation of the regional ecological context as well as a site's contribution to regional biodiversity and connectivity (Noss et al. 1997). Lacking the regional analyses, sites cannot be compared and ranked, and inferior sites may be approved. This may explain why the ecological value of sites within a region, like the Central Valley, varies widely. In this case, the conservation banking program is not achieving its full potential.

The lack of regional analyses and planning also makes the task of objectively evaluating the conservation value of a proposed bank very difficult. Conservation bankers and agency scientists conduct their own analyses, and this can lead to much disagreement on the conservation value of a site, delaying or stalling the review process. Stand-alone banks may not provide the best ecological value if they are reviewed apart from a regional analysis of conservation priorities or at a more relevant ecological scale (du Toit 2010).

Monitoring. Regional planning and coordination will also improve monitoring of bank performance. Conservation banks must have a monitoring program (USFWS 2003; Wheeler and Strock 1995). There are two problems with establishing a separate monitoring program for each conservation bank. First, the monitoring at the scale of a single bank site, without comparison to regional species or habitat trends, is unable to distinguish the impacts of conservation measures from those of regional environmental changes (du Toit 2010; Noon 2003; Bunn, unpublished). Second, banks have very limited funding for monitoring, and it is not efficient to manage separate monitoring programs for each bank. Allowing landowners or conservation bank firms to pool resources for regional monitoring would be more efficient and would provide better data to assess the impact of conservation measures at the site level versus changes caused by regional factors.

Conservation priorities. Regional planning could pre-identify regional conservation priorities, important reserve areas and corridors, biodiversity hotspots and threats to wildlife resources (Kiesecker et al. 2009). This kind of prior regional analysis would expedite the assessment of credit values, determination of appropriate service area and agreement among regulatory agencies and bankers on the conservation value of a proposed bank site relative to the other potential sites in a region. A portion of the upfront fund commitment for each bank and a portion of the bank management funds should be pooled in a regional endowment to support regional planning and monitoring of conservation banks.

Nationwide, there are now over 120 approved conservation banks covering 100,000 acres. State wildlife departments and the U.S. Fish and Wildlife Service continue to approve more conservation banks each year. Lessons learned from the California Conservation Banking Program can help guide efforts to improve such programs nationwide. If it is to be a successful mechanism for mitigation, conservation banking must achieve conservation goals and be profitable for landowners and banking practitioners. Making conservation banking programs a viable economic option for more landowners will require new policies to establish clear and stable standards, and to fund dedicated agency staff to coordinate the review process for proposed banks and to supervise established banks. Policies requiring regional approaches to prioritize lands and design monitoring programs would both increase the performance of conservation banking and make site selection and approval more efficient. Without program reform, the program is too difficult or risky for most landowners, and many properties with tremendous wildlife value may never be available for conservation banking. The new conservation banking law is an important first step, but does not yet provide guidance on prioritizing sites, nor on addressing regional planning or monitoring.

Moose Peterson

Conservation banks may be one of the best mechanisms for protecting key habitat of San Joaquin kit foxes on private lands.

D. Bunn is Researcher and Project Manager, Wildlife Health Center, School of Veterinary Medicine; M. Lubell is Professor, Department of Environmental Science and Policy; and C.K. Johnson is Associate Professor, Wildlife Health Center, School of Veterinary Medicine, all at UC Davis.

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References

Atkinson AJ, Trenham PC, Fisher RN, et al. 2004. Designing Monitoring Programs in an Adaptive Management Context for Regional Multiple Species Conservation Plans. USGS Western Ecological Research Center.

Bunn D, Mummert A, Hoshovsky M, et al. 2007. California Wildlife: Conservation Challenges, California's Wildlife Action Plan. California Department of Fish and Game.

[CDFW] California Department of Fish and Wildlife. 2012. Conservation Banking. www.dfg.ca.gov/habcon/conplan/mitbank/cmb_genpolicies.html (accessed January 2012).

du Toit JT. 2010. Considerations of scale in biodiversity conservation. Anim Conserv 13:229–36.

Field SA, Tyre AJ, Possingham HP. 2005. Optimizing allocation of monitoring effort under economic and observational constraints. J Wildlife Manage 69(2):473–82.

Kiesecker JM, Copeland H, Pocewicz A, Mckenney B. 2009. Development by design: Blending landscape level planning with mitigation hierarchy. Front Ecol Environ 8:261–6.

Legg C, Nagy L. 2006. Why most conservation monitoring is, but need not be, a waste of time. J Environ Manage 78:194–9.

Lindenmayer DB, Likens GE. 2010. The science and application of ecological monitoring. Biol Conserv 143:1317–28.

Mead DL. 2008. History and theory: The origin and evolution of conservation banking. In: Carroll N, Fox J, Bayon R (eds.). *Conservation & Biodiversity Banking: A Guide to Setting Up and Running Biodiversity Credit Trading Systems*. Sterling, VA: Earthscan.

Noon B. 2003. Conceptual issues in monitoring ecological resources. In: Bush DE, Trexler JC (eds.). *Monitoring Ecosystems, Interdisciplinary Approaches for Evaluating Ecoregional Initiatives*. Washington, DC: Island Press.

Noss RF, O'Connell MA, Murphy DD. 1997. *The Science of Conservation Planning, Habitat Conservation Under the Endangered Species Act*. Washington, DC: Island Press.

Pollack D. 2001. Natural Community Conservation Planning (NCCP), The Origins of an Ambitious Experiment to Protect Ecosystems. California Research Bureau, CRB-01-002.

Ruhl JB, Glen A, Hartman D. 2005. Practical guide to habitat conservation banking law and policy. Nat Resour Environ 20:26.

[USFWS] US Fish and Wildlife Service. 2003. Guidance for the Establishment, Use and Operation of Conservation Banks. Memorandum, May 2.

Wheeler DP, Strock JM. 1995. Official Policy on Conservation Banks. California Resources Agency. http://ceres.ca.gov/wetlands/policies/mitbank.html (accessed December 2010).

For switchgrass cultivated as biofuel in California, invasiveness limited by several steps

by Joseph M. DiTomaso, Jacob N. Barney, J. Jeremiah Mann *and* Guy Kyser

The expected production of biomass-derived liquid fuels in the United States may require cultivation of millions of acres of bioenergy crops, including perennial grasses such as switchgrass. Switchgrass is not native to California and possesses many qualities in common with other perennial grasses that are invasive. To evaluate the potential invasiveness of switchgrass in California, we conducted risk analysis and climate-matching models as well as greenhouse and field evaluations of switchgrass, looking at its environmental tolerance and competitive ability against resident riparian vegetation. We concluded that dryland regions of California are not suitable to vigorous establishment and invasion of switchgrass. However, riparian areas appear to be far more likely to support switchgrass populations. With effective mitigation practices in place throughout the development, growth, harvest, transport and storage processes, it should be possible to minimize or eliminate the movement of seeds and vegetative propagules to sensitive habitats. Consequently, we believe that switchgrass is unlikely to become a significant problem in California, even with widescale production.

Jacob Barney

Some characteristics that make for an outstanding biofuel crop will make the same plant a hardy, hard-to-manage weed if it escapes cultivation. Switchgrass can thrive if it escapes into an ecosystem with an abundant, year-round water supply, so it's best grown far from such areas.

Biomass crops in the United States are projected to yield 136 billion liters of biomass-derived liquid fuels by 2022 (Heaton et al. 2008). The expectation is that this will require cultivation of between 54 and 150 million acres of bioenergy crops. Furthermore, state and federal greenhouse-gas reduction initiatives have incentivized widespread cultivation of biofuel crops. Of the crops under consideration, perennial nonfood grasses are the leading candidates. To be successful in this role, these bioenergy grasses will need to possess many agronomically desirable traits, including broad climatic tolerance, rapid growth rates, high yields, few natural enemies and resistance to periodic or seasonal soil moisture stress (Heaton et al. 2009).

One of the leading candidates among bioenergy grasses is switchgrass (*Panicum virgatum* L.) (Parrish and Fike 2005; Pedroso et al. 2011). Switchgrass is a perennial warm-season (C4) bunchgrass native to most of North America east of the Rocky Mountains, where it was historically a major component of the tallgrass prairie. It was included in the initial screening for biofuel crops in the United States in the 1970s and was determined to be the model bioenergy species by the Department of Energy (McLaughlin and Walsh 1998). This was primarily due to its broad adaptability and genetic variability (Sanderson et al. 2006). Over the past three decades, breeding efforts have developed several cultivars, many of which produce dense stands, tolerate infertile soils and readily regenerate from vegetative fragments (Parrish and Fike 2005). These cultivars are often separated into upland ecotypes (Trailblazer, Cave in Rock, Blackwell and Sunburst) and lowland ecotypes (Alamo and Kanlow) (Pedroso et al. 2011).

Switchgrass is not native to California and was, in fact, included for a brief time on the California Department of Food and Agriculture (CDFA) Noxious Weed List (CINWCC 2007) due to concerns about its potential invasiveness. Although there was one documented report of an escape of switchgrass from cultivation in Orange County, California (Riefner and Boyd 2007), there are no known records of its escaping elsewhere or causing any ecological or economic damage, despite its long-time use as a forage and conservation species (Parrish and Fike 2005). Since its removal from the CDFA Noxious Weed List, it has been the focus of yield trials throughout California (Pedroso et al. 2011). Because of the state's Mediterranean climate, the yield potential is high; however, the crop will require significant water and nitrogen inputs.

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v067n02p96&fulltext=yes

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Invasive and biofuel grasses

In an ideal system, biofuel crops should be cultivated in a highly managed agricultural setting similar to that of most major food crops, such that the crop could not survive outside of cultivation. Under such conditions, the likelihood of escape and invasion into other managed or natural systems would be very small. Unlike biofuel species, most food crops have been selected for high harvestable fruit or grain yield. This nearly always results in a loss of competitive ability, typically accompanied by an increase in the addition of nutrients and often pesticides.

When a biofuel crop is grown for cellulose-based energy, the harvestable product is the entire aboveground biomass. To be economically competitive, such perennial crops should be highly competitive with other plant species, harbor few pests and diseases, grow and establish rapidly, produce large annual yields and have a broad range of environmental tolerance, while also requiring few inputs per unit area of water, nutrients, pesticides and fossil fuels (Raghu et al. 2006). Few species fit these requirements better than rhizomatous perennial grasses, primarily nonnative species (Barney and DiTomaso 2008; DiTomaso et al. 2007). However, these qualities and traits are nearly identical to those found in harmful invasive species (Raghu et al. 2006). For example, species such as johnsongrass (*Sorghum halepense* (L.) Pers.) and kudzu (*Pueraria montana* [Lour.] Merr. var. *lobata* [Willd.] Maesen & S.M. Almeida) were introduced as livestock forage or for horticultural use but have escaped cultivation to become serious weeds in many areas of the United States. In selecting biofuel crops, a balance must be struck between high productivity with minimal inputs, on the one hand, and risk of establishment and survival outside the cultivated environment (DiTomaso et al. 2007) on the other.

Johnsongrass, like switchgrass, was first cultivated as forage, but it subsequently escaped and has become one of the world's most expensive weeds in terms of control costs (Warwick and Black 1983). It is currently listed as a noxious weed in 19 U.S. states. When comparing switchgrass to johnsongrass and to corn, a typical agronomic grass crop, it is clear that switchgrass possesses many growth traits similar to those of weedy johnsongrass and only a few similar to those of corn (table 1). While this is not direct evidence that switchgrass will be a significant invasive or weedy species, it does suggest that the risk may be greater than for more typical agronomic crops.

TABLE 1. Agronomic and invasive characteristics of a potential biofuel crop (switchgrass), a phylogenetically related weedy species (johnsongrass) and corn (an agronomic crop related to both)

Agronomic/invasive characteristics	Biofuel crop Switchgrass	Weedy associate Johnsongrass	Agronomic crop Corn
C_4 photosynthesis	+*	+	+
Perennial	+	+	–†
Rapid establishment	–	+	+
Highly competitive	+/–‡	+	–
Drought tolerant	+	+/–	–
Reallocation of nutrients to roots	+	+	–
No major pests or diseases	+	+	–
Prolific viable seed production	+	+	+
Ability to shatter and disperse seeds	+	+	–

Source: Barney and DiTomaso 2010b.
* + = Plant demonstrates the characteristic.
† – = Plant does not demonstrate the characteristic.
‡ +/– = Some ecotypes of the plant demonstrate the characteristic.

Although cultivation of switchgrass and other biofuel crop species may ultimately prove a net benefit to society, the environmental risks associated with their potential escape into natural and managed systems should be assessed before the crops are commercialized and introduced into new regions. A pre-introduction evaluation can be performed in tandem with typical agronomic yield trials. This approach can both quantify ecological risk and assess the suitability and economic performance of the species within a particular region.

To assess the invasive potential of any proposed biofuel species, including

Jacob Barney

Traditional crops are bred to enhance production of food or fiber, but biofuel breeders emphasize hardiness and quick, abundant growth—"weedy" characteristics. Here, researchers grow switchgrass in PVC towers, making it easier for them to monitor root growth and the effects of water stress.

switchgrass in California, we propose a seven-step evaluation protocol (table 2) (Barney et al. 2012a). These evaluations should be performed for all candidate genotypes and cultivars as well as for transformed genotypes of native species because ecological interactions can vary widely within a species. Science-based information generated from risk assessments, biofuel crop ecological studies, niche modeling and other evaluations can guide risk mitigation decisions at appropriate points within biofuel research and development, crop selection and production, harvest and transportation, storage site selection and conversion/refinery practices (DiTomaso et al. 2010).

TABLE 2. Protocol for evaluating the degree of risk that a biofuel crop (including cultivars and genotypes) will become invasive in a region

Evaluating the risk potential of biofuel crops: qualitative and quantitative studies
1. Conduct risk assessment using a science-based protocol to determine invasion potential qualitatively.
2. Determine the potentially invasible range using climate-matching analysis (e.g., CLIMEX) under various assumptions (e.g., drought tolerance) and scenarios (e.g., irrigation).
3. Evaluate environmental tolerance (e.g., soil moisture stress) of crop.
4. Quantify invasibility of susceptible habitats (e.g., riparian areas, rangeland) to introduction of seeds or vegetative fragments.
5. Conduct propagule biology studies: seeds, stem and rhizome fragments.
6. Determine hybridization potential with related native and nonnative taxa.
7. Study competitive interactions with desirable species and related invasive species (for comparison) within the potential habitat where invasion would be expected.

Source: Barney et al. 2012a.

Risk assessment

Risk assessment tools have been used in Australia and New Zealand as an aid in decision making for the proposed introduction of novel species for horticultural, agronomic and other purposes. For potential biofuel species, risk assessment should serve as a basic first step in evaluating their invasive potential, whether the species are exotic, native, novel constructs (e.g., hybrids) or genetically modified.

We performed a risk assessment (Barney and DiTomaso 2008) for switchgrass in California using the Australian model (Pheloung et al. 1999). Our analysis produced an inconclusive result, with an "evaluate further" classification (table 3). The first question in the risk assessment asks whether the species is domesticated. A "yes" response favors acceptance (or reduced risk of invasion), under the assumption that domestication generally reduces the inherent weediness of wild types, which are wild plants not selected for production traits (Pheloung et al. 1999). As previously discussed, this is true for most agronomic and horticultural species, but the opposite is true for biofuel crops because selection (breeding) for favorable biofuel crop characteristics generally enhances "weedy" characteristics (Raghu et al. 2006). When we answered the first question differently, the outcome changed from "evaluate further" to "reject."

TABLE 3. Weed risk assessment (WRA) protocols for switchgrass under the conditions of the target region, for available or proposed cultivars*

Species	Region targeted for production	WRA and alterations	WRA score	Modifications from Australian WRA
Switchgrass	California	Standard WRA	5 (evaluate further)	None
		Domestication parameter altered	10 (reject)	Question 1.01 changed regarding the assumption of domestication on ability to survive in natural areas*.
		Sterile genotypes	1 (accept)	All questions regarding seed production and dispersal changed to reflect a sterile genotype.

Source: Barney and DiTomaso 2008.

* WRA scores "highly domesticated" plants as less weedy than their wild-type progenitors. However, many characteristics desirable in a biofuel feedstock are the same as those found in aggressive invaders.

We further evaluated switchgrass as a hypothetically sterile cultivar. In this case, the weed risk assessment yielded an acceptably low risk that it would become invasive. This suggests that seed production may be key to the potential invasiveness of switchgrass. However, a lack of seed production does not guarantee a low risk of invasion, considering that the giant reed (*Arundo donax* L.), which is sterile, is highly invasive in California. The invasiveness of giant reed is due to its ability to regenerate from stem nodes after the stem is detached from the rhizome as a result of flooding or control efforts.

The environmental risks associated with their potential escape into natural and managed systems should be assessed before the crops are commercialized.

Despite the invasive potential that our analysis shows for switchgrass in California, there are no documented cases of the species escaping in agricultural or natural systems. This, however, may be a function of the limited number of opportunities for introduction of switchgrass propagules (seeds, rhizomes and stem nodes) outside of intentional planting areas. It is also important, therefore, to conduct studies that will quantify switchgrass performance in various ecological settings in order to mitigate the risk of propagule escape and establishment.

Climate-matching analysis

The natural distribution of a species is largely controlled by climate factors, with precipitation and temperature playing the dominant roles (Sutherst 2003). Bioclimatic envelopes, or climate matches, can provide both an estimate of range suitability for the biofuel crop species outside cultivation and the agronomic potential of the biofuel crop in the target region (Barney and DiTomaso 2011). There are numerous methods for estimating the bioclimatic envelope, including CLIMEX, Maxent, GARP, BIOCLIM, classification and regression tree, and simple logistic regression. CLIMEX has been used to model the distribution of biocontrol agents (Poutsma et al. 2008), poikilothermic (cold-blooded) animals (Sutherst et al. 2007) and many invasive plant species (Holt and Boose 2000; Kriticos et al. 2005; Pattison and Mack 2008). The strength of CLIMEX for invasive species applications is that the model can be based on the historical range (e.g., from herbarium data) and supplemented with empirically derived biological and physiological data (Sutherst et al. 1999).

We performed a CLIMEX analysis of switchgrass using the plant's native range as a basis in building the model and then supplementing it with environmental tolerance data from greenhouse studies (discussed below). In a global model of potential suitability, the potential cultivatable range of switchgrass was very broad, both with and without irrigation inputs (Barney and DiTomaso 2010b, 2011; see fig. 1). Subsequent analysis of potential suitable habitat in the western United States (fig. 2A) indicated that much of the region is unsuitable for switchgrass, likely because of the very dry summers of arid and Mediterranean climatic regions (Barney et al. 2012a). However, when adequate yearlong soil moisture was available (i.e., with summer irrigation or a permanent water source), the suitable range of switchgrass increased dramatically throughout much of the western United States (fig. 2B). This could indicate that the successful cultivation of switchgrass would depend upon summer irrigation, while any escape from cultivation and invasion into natural areas would likely be confined to riparian or wetland areas with a permanent water source. Riparian systems are the most heavily invaded habitats in the Central Valley of California, as they possess the primary limiting resource of soil moisture (Levine 2000). Furthermore, riparian areas often border production fields, and traversing them would be unavoidable during biofuel biomass transport.

The CLIMEX model does not forecast yield potential, but it does demonstrate that some regions of California are suitable for establishment and persistence of switchgrass. In support of our suitability prediction in California, Pedroso et al. (2011) evaluated the agronomic potential of switchgrass in four regions of the state. This evaluation showed high productivity in both study locations in the Central Valley, which was considered a highly suitable region based on our bioclimatic index (fig. 2B). Switchgrass grown in the Imperial Valley (El Centro), near the margin of highly suitable climatic conditions in our analysis, also produced high yields. In contrast, yields and survival of switchgrass were lowest in the most northern, cooler, mountainous region of Tulelake, near the Oregon border in northeastern California. Our model also predicted that this region of the state would be poorly suited to switchgrass establishment, even with irrigation.

Environmental tolerance

Each biofuel species should be evaluated for various physiological and environmental tolerances. This information can be used to identify the ecosystems that are most susceptible to invasion and can also be integrated into risk analysis and bioclimatic and agronomic models to estimate, and subsequently mitigate, the likelihood of invasion (Barney and DiTomaso 2008). Based on results from our CLIMEX analysis of switchgrass in the western United States, water availability should be the major limiting factor for switchgrass naturalization. To test this, we conducted a greenhouse study to evaluate switchgrass's tolerance of soil moisture stress at various levels of water availability, ranging from moisture deficit

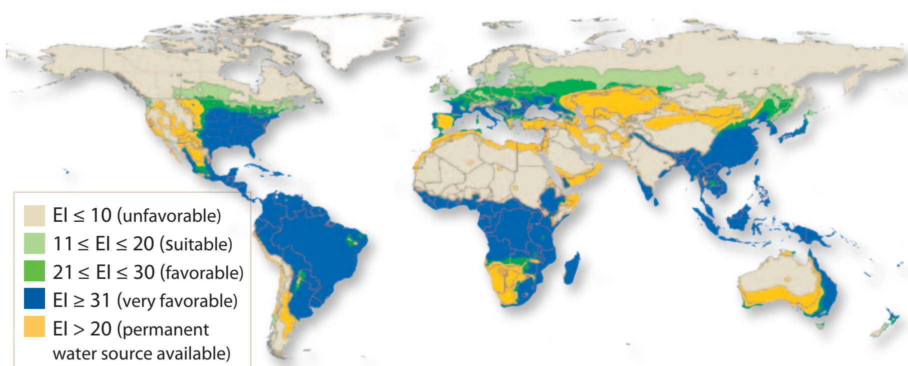


Fig. 1. Global CLIMEX climate-matching results for switchgrass. The colors represent the CLIMEX ecoclimatic index (EI), where cream (EI ≤ 10) is "unfavorable," light green (11 ≤ EI ≤ 20) is "suitable," dark green (21 ≤ EI ≤ 30) is "favorable," and blue (EI ≥ 31) is "very favorable." The yellow regions are those with an EI > 20 when a permanent water source is available (Barney and DiTomaso 2011).

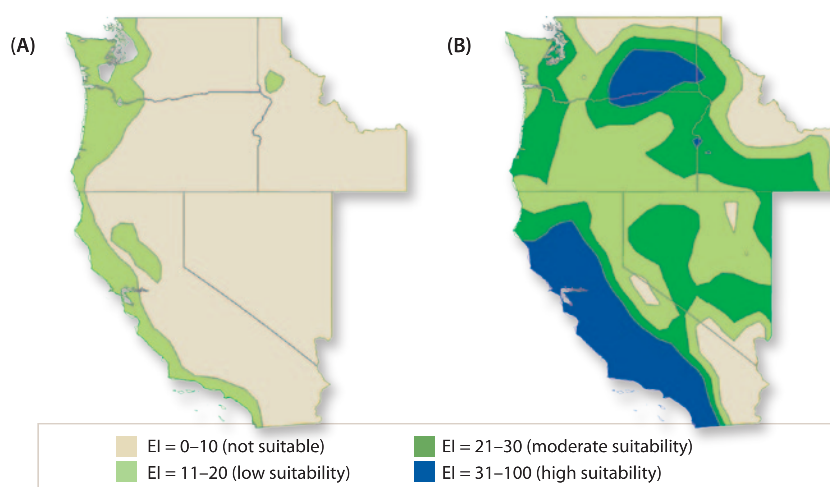


Fig. 2. CLIMEX climate-matching results for switchgrass based on climate preferences estimated for (A) the nonnative range of the western United States and for (B) the nonnative range of the western United States assuming yearlong access to water (e.g., land along a stream or land that is irrigated). The colors represent CLIMEX ecoclimatic index values (EI; 0–100), where higher numbers represent a more suitable environment (see figure legend) (Barney and DiTomaso 2011).

to flooded, and we also assessed the germination, establishment, performance and reproductive potential of four common ecotypes, both upland and lowland (Barney et al. 2009).

Our results showed that cultivars of switchgrass performed well in both well-watered control and flooded conditions. Although switchgrass survived extended periods without water, individual plants in drought treatments were shorter, with lower measurements for leaf area and specific leaf area, and they produced fewer tillers and less biomass (fig. 3). As expected, lowland types outperformed upland types in the flood treatment and also displayed higher fitness under most conditions, which likely explains why they are the target of germplasm improvement for biofuel cultivation (Parrish and Fike 2005).

We concluded that switchgrass, particularly lowland ecotypes, has the ability to germinate, establish and flower in low moisture and even more so in flooded conditions. The evidence further supports the climate-matching data and indicates that soil moisture is the limiting factor in the establishment and growth of switchgrass in regions of the western United States. While tolerance to a range of soil moisture conditions may increase the cultivatable range of switchgrass, it also suggests that the species is not likely to be very competitive in natural areas exposed to prolonged drought, as is common in much of California.

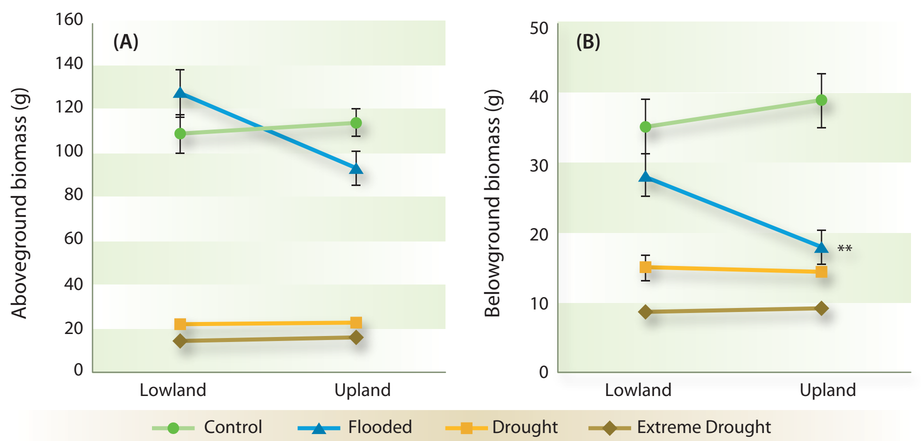


Fig. 3. Aboveground biomass (A) and belowground biomass (B) for lowland and upland switchgrass under control, flooded, drought (5–10% soil moisture) and extreme drought (< 5% soil moisture) soil moisture treatments. Lines followed by double asterisk (**) indicate significant difference ($p < 0.05$) between upland and lowland cultivars for that treatment (Barney et al. 2009).

In another study, we grew switchgrass in outdoor mesocosms (3-meter-tall tubing) under irrigated and rainfed (dry) conditions and assessed the spatial distribution and abundance of roots using minirhizotron images and whole-root-system sampling (Mann et al. 2012). Although plants survived extended periods of drought, their shoot and root biomass, root length density, numbers of culms and culm height were greatly reduced under dry conditions. These data support the results of the greenhouse study (fig. 3). The rainfed treatment reduced switchgrass whole-plant biomass by 83%, culm production by 67% and root length density by 67% from the levels of irrigated plants. However, switchgrass grew roots continuously into regions of available soil moisture as surface soil layers grew increasingly dry (fig. 4). This study suggests that switchgrass is able to tolerate drought by mining deep soil moisture. A deep-rooting habit and continuous root growth from regions of water depletion to moister regions are strategies used for drought avoidance by plants exposed to periodic water stress (Lambers et al. 2008).

It is important to note that while switchgrass survived dry, rainfed conditions, its performance was significantly reduced. This level of performance would be unacceptable for agronomic production and would also reduce the ability of switchgrass to establish and compete with resident vegetation in drier natural areas.

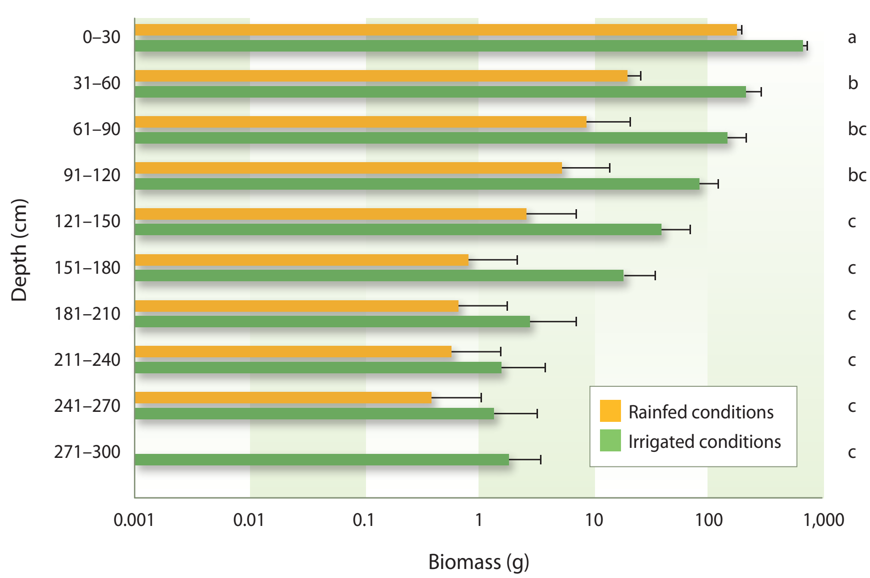


Fig. 4. Distribution of switchgrass belowground biomass (means + standard deviations) in rainfed and irrigated conditions. Note the logarithmic scale of the x-axis. Letters indicate significant differences (at 95% confidence level) between depths averaged over both treatments (Mann et al. 2012).

Invasibility and competitiveness

The results of our climate-matching analyses as well as the biological and physiological studies allowed us to identify habitats that were most susceptible to invasion by switchgrass. From our previous work, we knew that riparian corridors (e.g., streams, irrigation canals) and perhaps even rice production fields are the regions most likely to be susceptible to switchgrass invasion in California. In subsequent work (Barney et al. 2012b), we confirmed these findings by introducing switchgrass propagules into a riparian

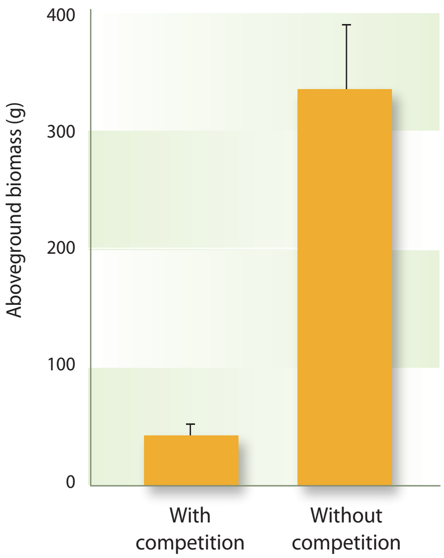


Fig. 5. Switchgrass (*Panicum virgatum* = PAVI) (means ± standard error) aboveground biomass in lowland habitats along Putah Creek. Treatments include switchgrass (PAVI) with competition (PAVI + Comp) and without competition (PAVI – Comp) from resident herbaceous vegetation (Barney et al. 2012b).

habitat under controlled conditions and evaluating their colonization, survival and establishment potential under varying levels of soil moisture availability and competition. The results supported our greenhouse and mesocosm studies, again demonstrating that while switchgrass can survive under drought conditions, its performance on upland sites away from streams was very poor compared to that of switchgrass plants adjacent to the stream. This confirms our conclusion that riparian regions of the state are the areas most potentially susceptible to switchgrass invasion, while dryland regions of California have very low susceptibility to invasion. Of equal importance, switchgrass grown without competition in the first year in the wet habitat produced about six times more tillers than switchgrass growing in an intact resident plant community with competition, and the tillers were twice as tall and yielded eight times the aboveground biomass (fig. 5). This further indicates that, even in a suitable habitat, switchgrass is not highly competitive with other vegetation.

Propagule biology

The probability of establishment of an invasive population is directly proportional to the propagule pressure from outside sources (Barney and DiTomaso 2008). In the case of switchgrass, outside sources will be production fields, harvest and transportation equipment and biomass storage sites. Our initial risk assessment for the invasive potential of switchgrass in California determined that seed production and dispersal were the means of the greatest threat that it would become invasive (Barney and DiTomaso 2008). To aid in their efficient conversion into energy, cellulosic biofuel species are typically harvested after senescence in the field, usually in late fall. In our seed biology experiments, we showed that switchgrass germinates and survives under conditions that range from 10% soil moisture to submersion in water (Barney et al. 2009). From these experiments, we estimate that an average switchgrass field would produce between 300 and 900 million seeds per hectare. Using a conservative estimate of 300 million seeds per hectare and 60% dormancy, approximately 120 million seeds per hectare would be capable of germinating, given adequate soil moisture conditions (Barney et al. 2009). This tells us that mitigation practices will be needed to reduce the risk of seeds spreading to sensitive ecosystems. Mitigation practices could include the planting of sterile cultivars, cleaning equipment before moving it to other areas and using closed transport systems and storage facilities.

Hybridization potential

As with genetically modified food and feed crops, screening for possible cross-hybridization with related and desirable species should be obligatory to reduce the chance of genetic contamination or creation of novel hybrids (DiTomaso et al. 2007). In California, there are five native species and five introduced species within the genus *Panicum* (Baldwin 2012). To date, there is no evidence of hybridization between switchgrass and any other *Panicum* species, regardless of its native origin. Thus, the likelihood that switchgrass would either contaminate the gene pool of native *Panicum* species or enhance the weediness of nonnative *Panicum* species through hybrid vigor seems very small.

Mitigation recommendations

In August 2009, the U.S. Invasive Species Advisory Committee (ISAC), a group of nonfederal experts and stakeholders chartered under the Federal Advisory Committee Act of 1972, adopted nine recommendations for the federal government's biofuel programs (table 4). The recommendations comprehensively address biofuel production and use, as well as the necessity of agency and private sector stakeholder cooperation for effective implementation of the recommendations (DiTomaso et al. 2010).

Initially, all federal agencies with authority relevant to biofuel production should be identified, their likely responsibilities on the invasiveness issue determined, and their ability to minimize the risk of biofuel escape and invasion strengthened as necessary. To reduce the risk of escape, the biofuel crops that are promoted should not be currently invasive or should pose a low risk of becoming invasive in the target region. In addition, biofuel crops should be propagated in production sites that are least likely to impact sensitive habitat or create disturbances that would facilitate

TABLE 4. The Invasive Species Advisory Committee's* recommendations for U.S. biofuel programs, 2009

1. Review/strengthen existing authorities.
2. Reduce escape risks.
3. Determine the most appropriate areas for cultivation.
4. Identify plant traits that contribute to or reduce the incidence of invasiveness.
5. Prevent dispersal.
6. Establish eradication protocols for rotational systems or abandoned populations.
7. Develop and implement early detection and rapid response (EDRR) plans and rapid response funding.
8. Minimize harvest disturbance.
9. Engage stakeholders.

Source: DiTomaso et al. 2010.

* A subcommittee to the National Invasive Species Council whose members are nonfederal experts and stakeholders reporting to the Secretaries and Administrators of 13 federal departments and agencies.

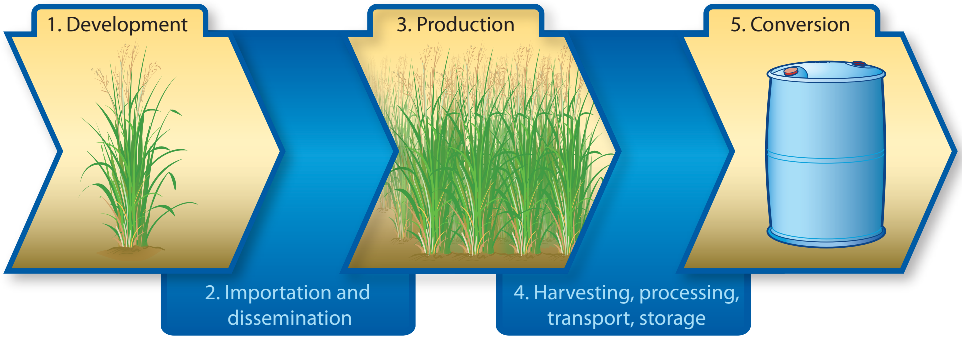


Fig. 6. Simplified biofuel supply chain showing (1) crop development, (2) crop importation and dissemination, (3) crop production, (4) feedstock harvesting, processing, transport, and storage, and (5) feedstock conversion. Black arrows indicate links where propagule or feedstock movement is involved (Barney and DiTomaso 2010b).

invasion. Most importantly, effective mitigation protocols need to be developed to prevent dispersal of plant propagules from sites of production, transportation corridors, storage areas and processing facilities. Minimizing harvest disturbance can also reduce the potential for dispersal and off-site movement of propagules. Prior to widescale planting, multi-year eradication protocols should be developed that are based on integrated pest management (IPM) strategies. Such practices should be readily available, and appropriate information should be distributed with the purchase of biofuel crop seeds. These control methods are not only critical for preventing the dispersal of biofuel crops from abandoned production sites, they are a necessary component of an effective early detection and rapid response (EDRR) system for biofuel crop populations that do escape active management. Throughout this entire process (fig. 6), all stakeholder groups should be engaged, from biofuel development to conversion.

In prior publications, we have identified five mitigation points along the biofuel supply chain, or biofuel pathway, in the seed-to-fuel lifecycle of switchgrass or any other biofuel crop (Barney and DiTomaso 2010b):

Breeding or selection programs can target the development of cultivar traits that reduce the risk of escape and invasion. For example, (1) sterile switchgrass cultivars can decrease the likelihood that the plant will escape from production fields. In contrast, (2) enhancement of other environmental traits such as seedling vigor or tolerance to drought or salt may increase the risk of escape from cultivation and invasion into surrounding environments.

(3) Within the production process, growers can reduce the risk of propagule dispersal by cultivating plants away from known dispersal corridors (e.g., streams) or by creating buffers between production areas and transportation corridors. In addition, (4) routine scouting of field margins and bordering habitat for switchgrass escapes, followed by (5) prescriptive management of escaped populations, can help prevent invasion into sensitive habitats.

Seeds present the greatest risk for invasion. Although it may not be economically possible to do so, harvesting before flowering or seed set would reduce the likelihood of propagule production. In addition, the cleaning of planting and harvesting equipment prior to movement from one field to another will help to prevent switchgrass seed dispersal.

Transportation of biomass from grower fields to refineries and storage locations creates another potential opportunity for switchgrass seed dispersal. To mitigate against this, refineries should organize with growers to coordinate efficient harvest and transport practices that minimize propagule loads to outside environments. When applicable,

Switchgrass invasive potential in California

Based on our evaluation of the potential invasiveness of switchgrass in California, we conclude that dryland regions of California have very high resistance to switchgrass establishment and invasion. However, riparian areas (i.e., streams, irrigation canals, rivers, lakes and ponds) are capable of supporting the establishment of switchgrass. Our data also indicate that the agronomic production of switchgrass in the western United States will require irrigation during the dry season. Most vegetation in the Central Valley of California germinates following late fall or early winter rains to maximize usage of the limited precipitation. Switchgrass, however, germinates or emerges primarily in late spring, toward the end of the rainy season, not long before the rapid drying of the surface soils in summer. These conditions are not conducive to switchgrass establishment and probably account for the poor survival and growth of seedlings in our studies (Barney et al. 2012b). In addition, our climate-matching analysis indicates that the limiting abiotic factor in the northern range of switchgrass in California is cold temperature (Barney and DiTomaso 2010a, 2011). While this may be the current situation, genetic improvement and climate change may expand, contract or shift suitable regions.

Naturalization will be further limited by the competitiveness of resident plant communities (Barney et al. 2012b). However, switchgrass may be able to establish following disturbance in high-resource sites where resident vegetation is removed or damaged, and it may become more competitive following establishment.

Having considered all aspects of our invasive analysis, we conclude that while switchgrass is not without risk of invasion in riparian or wetland areas, it is unlikely to become a significant problem, particularly when mitigation practices are employed to minimize propagule movement. If this crop is developed, grown, harvested, transported and stored responsibly, the ecological risk should be acceptably low and in balance with the need for sustainable energy production.

transport from fields should be done with closed trucks or shipping containers.

While switchgrass biomass refineries will presumably operate year-round, stored plant biomass will likely be harvested once, or at most twice, a year—mostly from midsummer through late fall. This means that the biomass will be baled and stored for most of the year either on grower property or, more likely, on refinery property near the conversion facility. These storage sites may serve as seed reservoirs if not managed properly.

J.M. DiTomaso is Cooperative Extension Weed Specialist, UC Davis; J.N. Barney is Assistant Professor, Department of Plant Pathology, Physiology, and Weed Science, Virginia Tech.; J.J. Mann was Graduate Student, Department of Plant Sciences, UC Davis; and G. Kyser is Specialist, Department of Plant Sciences, UC Davis.

Jacob Barney

Researchers are assessing a number of plants for their potential as biofuels, hoping to find crops that will produce well in a variety of different growing environments. *Here,* PVC towers planted with giant miscanthus grow alongside towers planted with switchgrass to see which does better in this setting.

References

Baldwin BG (ed.). 2012. *The Jepson Manual: Vascular Plants of California* (2nd ed.). Berkeley, California: UC Press. 1,568 p.

Barney JN, DiTomaso JM. 2008. Non-native species and bioenergy: Are we cultivating the next invader? BioScience 58:64–70.

Barney JN, DiTomaso JM. 2010a. Bioclimatic predictions of habitat suitability for the biofuel switchgrass in North America under current and future climate scenarios. Biomass Bioenerg 34:124–33.

Barney JN, DiTomaso JM. 2010b. Invasive species biology, ecology, management and risk assessment: Evaluating and mitigating the invasion risk of biofuel crops. In: Mascia P, Scheffran J, Thomas S, Widlholm J (eds.). *Plant Biotechnology for Sustainable Production of Energy and Co-products, Biotechnology in Agriculture and Forestry 66*. Berlin, Heidelberg: Springer Publ. Co. p 263–84.

Barney JN, DiTomaso JM. 2011. Global climate niche estimates for bioenergy crops and invasive species of agronomic origin: Potential problems and opportunities. PLOS ONE 6(3):e17222. doi:10.1371/journal.pone.0017222.

Barney JN, Mann JJ, Kyser GB, et al. 2009. Tolerance of switchgrass to extreme soil moisture stress: Ecological implications. Plant Sci 177:724–32.

Barney JN, Mann JJ, Kyser GB, DiTomaso JM. 2012a. Mitigating the invasive risk potential of biofuel crops. In: Harker KN (ed.). *The Politics of Weeds.* Topics in Canadian Weed Science 7. Pinawa, Manitoba: Canadian Weed Science Society.

Barney JN, Mann JJ, Kyser GB, DiTomaso JM. 2012b. Assessing habitat susceptibility and resistance to invasion by the bioenergy crops switchgrass and *Miscanthus* x *giganteus* in California. Biomass Bioenerg 40:143–54.

CINWCC. 2007. California Interagency Noxious Weed Coordinating Committee. New CDFA plant pest ratings list released. Noxious Times 8(4):7–9.

DiTomaso JM, Barney JN, Fox AM. 2007. Biofuel feedstocks: The risk of future invasions. Council for Agricultural Science and Technology (CAST) Commentary. QTA2007-1 November 2007. 8 p.

DiTomaso JM, Reaser JK, Dionigi CP, et al. 2010. Biofuel vs. bioinvasion: Seeding policy priorities. Environ Sci Technol 44:6906–10.

Heaton EA, Dohleman FG, Long SP. 2008. Meeting US biofuel goals with less land: The potential of giant miscanthus. Global Change Biol 14:2000–14.

Heaton EA, Dohleman FG, Long SP. 2009. Seasonal nitrogen dynamics of *Miscanthus* × *giganteus* and *Panicum virgatum*. Global Change Biol Bioenerg 1:297–307.

Holt JS, Boose AB. 2000. Potential for spread of *Abutilon theophrasti* in California. Weed Sci 48:43–52.

Kriticos D, Yonow T, McFadyen RE. 2005. The potential distribution of *Chromolaena odorata* (Siam weed) in relation to climate. Weed Res 45:246–54.

Lambers H, Chapin III FS, Pons TL (eds.). 2008. *Plant Physiological Ecology* (2nd ed.). New York: Springer.

Levine JM. 2000. Species diversity and biological invasions: Relating local process to community pattern. Science 288:852–4.

Mann JJ, Barney JN, Kyser GB, DiTomaso JM. 2012. Root system dynamics of *Miscanthus* × *giganteus* and *Panicum virgatum* in response to rainfed and irrigated conditions in California. BioEnerg Res In press. doi:10.1007/s12155-012-9287-y.

McLaughlin SB, Walsh ME. 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass Bioenerg 14:317–24.

Parrish DJ, Fike JH. 2005. The biology and agronomy of switchgrass for biofuels. Crit Rev Plant Sci 24:423–59.

Pattison RR, Mack RN. 2008. Potential distribution of the invasive tree *Triadica sebifera* (Euphorbiaceae) in the United States: Evaluating CLIMEX predictions with field trials. Global Change Biol 14:813–26.

Pedroso GM, DeBen C, Hutmacher RB, et al. 2011. Switchgrass is a promising, high-yielding crop for California biofuel. Calif Agr 65(3):168–73.

Pheloung PC, Williams PA, Halloy SR. 1999. A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. J Environ Manage 57:239–51.

Poutsma J, Loomans AJM, Aukema B, Heijerman T. 2008. Predicting the potential geographical distribution of the harlequin ladybird, *Harmonia axyridis*, using the CLIMEX model. BioControl 53:103–25.

Raghu S, Anderson RC, Daehler CC, et al. 2006. Adding biofuels to the invasive species fire? Science 313:1742.

Riefner RE, Boyd S. 2007. New records of wetland and riparian plants in Southern California, with recommendations and additions to the national list of plant species that occur in wetlands. J Bot Res Inst Texas 1:719–40.

Sanderson MA, Adler PR, Boateng AA, et al. 2006. Switchgrass for biomass feedstock in the USA. Can J Plant Sci 86:1315–25.

Sutherst RW. 2003. Prediction of species geographical ranges. J Biogeogr 30:805–16.

Sutherst RW, Maywald GF, Bourne AS. 2007. Including species interactions in risk assessments for global change. Global Change Biol 13:1843–59.

Sutherst RW, Maywald GF, Yonow T, Stevens PM. 1999. *CLIMEX: Predicting the Effects of Climate on Plants and Animals.* Victoria, Australia: CSIRO Publ.

Warwick SI, Black LD. 1983. The biology of Canadian weeds—*Sorghum halepense* (L.) Pers. Can J Plant Sci 63:997–1014.

RESEARCH ARTICLE

Buffers between grazing sheep and leafy crops augment food safety

by Bruce R. Hoar, Edward R. Atwill, Lesa Carlton, Jorge Celis, Jennifer Carabez *and* Tran Nguyen

The presence of livestock in or near fresh-market vegetable fields has raised concerns about the potential for contaminating produce with pathogenic bacteria. To develop buffer zones for grazing near production of leafy greens, we assessed the prevalence of* Escherichia coli *O157:H7 and* Salmonella *species in sheep that were grazed on alfalfa fields during the winter in California's Imperial Valley. We found* E. coli *O157:H7 in 1.8% of fecal samples and 0.4% of soil samples, and* Salmonella *in 0.8% of fecal samples and 0.4% of soil samples. Our results indicate that sheep grazing on alfalfa in the Imperial Valley have a low prevalence of these pathogens in their feces and that these bacteria are rarely found in soil from fields with grazing sheep. The California Leafy Green Products Handler Marketing Agreement guideline of 30 feet between grazing lands or domestic animals and the crop edge is adequate to minimize potential contamination of nearby crops.

Bruce Hoar

Wherever sheep graze, they always leave something behind — as on this alfalfa field, where their droppings become fertilizer for subsequent crops. But if the animals range too close to a field where food crops are grown, there's a potential for contamination with disease-causing bacteria.

California ranks second in the nation for sheep production, yielding 325,000 lambs, more than 3 million pounds of wool, and $50 million annually (CDFA 2007). The sheep industry relies heavily on grazing crop, vineyard and orchard fields throughout California as a source of inexpensive feed. In addition, ruminants play an important role in sustainable agricultural systems. Sheep are particularly useful in converting vast renewable resources including rangeland and pasture forage as well as crop residues into edible food (Oltjen and Beckett 1996). Moreover, the manure produced by the sheep serves as an organic fertilizer that improves soil structure and contributes to plant nutrition.

The sheep production system employed in Imperial County, California, involves intensive grazing for short time periods. Bands of approximately 1,500 sheep are typically left in a 40-acre field until the forage is grazed close, which usually takes 4 to 7 days. Then the sheep are moved to another field. If the next field is located only 2 to 3 miles away, this is often accomplished by herding the flock along public roads.

Sheep grazing is seasonal in the Imperial Valley. Typically, sheep arrive from throughout the western United States in October and rotate between fields of alfalfa or bermudagrass until approximately mid- to late March, when they are sent to a feedlot or directly to slaughter. Market prices for sheep and alfalfa and other factors (such as transport cost) affect the use of this grazing system.

Rotating vegetables and alfalfa

The Imperial Valley has long been recognized as the "winter salad bowl" for the United States. With over 100,000 acres of fresh-market vegetable production that is valued at $500 million and distributed nationwide, the valley's agricultural industry has a tremendous impact on the local economy as well as on the nationwide food supply (CDFA 2007). To produce fresh-market vegetables successfully, growers must rotate these crops with others that provide a suitable economic return while reducing pest pressure in the subsequent vegetable crop. Alfalfa is the standard rotation with vegetable crops in Imperial County.

Leafy greens and bacteria

Integrating crop and animal agriculture, however, can have detrimental consequences. Crop contamination with *Escherichia coli* O157:H7 (which in humans can cause severe acute hemorrhagic diarrhea, and in a small proportion of cases can lead to hemolytic uremic syndrome

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v067n02p104&fulltext=yes
doi: 10.3733/ca.v067n02p104

and possibly kidney failure) has been documented through application of raw manure, use of irrigation water contaminated with animal or human feces (Solomon et al. 2002) and deposition of feces by livestock and wild animals (Cieslak et al. 1993; Jay et al. 2007). Recent outbreaks of human disease caused by *E. coli* O157:H7 in California have been associated with consumption of raw spinach (CDC 2006; Jay et al. 2007) and lettuce (Brandl 2008; Cooley et al. 2007). These have raised concerns that sheep and other ruminants may elevate levels of pathogens within the soil, which then have the potential of being transmitted to produce fields via aerosols (CDC 2006; Cieslak et al. 1993; Cooley et al. 2007; Jay et al. 2007).

The California Leafy Green Products Handler Marketing Agreement (LGMA) of January 2012 lists sheep as one of the five mammalian species that are "animals of significant risk" and states that any intrusion by such animals requires a detailed food safety assessment prior to harvest (LGMA 2012). Buffer zones between the crop production fields and livestock operations are important in order to prevent the potential transmission of pathogens from animals to crops.

Due to food safety concerns, essentially all of California's leafy greens are produced and marketed under the California Leafy Green Products Handler Marketing Agreement (LGMA 2012). The participating companies have committed themselves to selling products grown in compliance with LGMA food safety practices, including having a complete food safety compliance program, performing environmental assessments, testing and record-keeping for water use and soil amendments, to name a few.

The LGMA recognizes the need for further research to validate or adjust these guidelines based on scientific evidence. One area identified by LGMA as needing additional research relates to setback distances, or buffer zones, between livestock and crops. The LGMA suggests a buffer of 400 feet between the edge of a crop and a concentrated animal-feeding operation, and a buffer of 30 feet for grazing lands or domestic animals. However, they also acknowledge a lack of science on which to base this recommendation (LGMA 2012). There is a paucity of information related to appropriate combinations of time and distance between livestock operations and crop systems, particularly with regard to how long pathogens survive in animal feces, soil and aerosols, and how pathogens move via wind, water or flies.

Leafy greens and sheep

While considerable attention has been paid to the prevalence of foodborne pathogens in cattle, less is known about the epidemiology of *E. coli* O157:H7 in grazing sheep. Much as in cattle, prevalence of this organism in sheep varies considerably, with levels as low as 0.2% reported in some studies (Battisti et al. 2006) and as high as 68% in others (Sidjabat-Tambunan and Bensink 1997). There are approximately 650,000 sheep and lambs in California and as many as 150,000 in the Imperial Valley seasonally, making it essential to understand the ecology of important human pathogens associated with sheep. Therefore, the primary objective of this research project was to develop data that can be used to accurately define buffer zones appropriate for grazing of sheep near production of leafy greens.

Measuring fecal bacteria

Fecal and soil samples were collected from alfalfa fields where bands of sheep were grazing or had recently grazed. These bands consisted of 1,200 to 1,800 head of approximately 6- to 10-month-old lambs from numerous locations throughout the western United States. Typically, a 160-acre block of alfalfa is broken into four 40-acre plots, and each plot is grazed for approximately 7 days. These blocks are separated from other crops by either an irrigation ditch or a roadway. Each field that was sampled for this study was stocked with sheep only once during the winter grazing season. For each collection, 40 samples of fresh feces (minimum 0.35 ounce or 10 grams) and 40 samples of soil (minimum 0.35 ounce or 10 grams) were placed into individual containers, which were immediately placed on ice. Samples were shipped overnight by courier and processed within 24 hours of collection. Data were recorded and related to management of the sheep and the alfalfa field, including number of days sheep were present on the current field, age and source of sheep, and number of days since last irrigation event. Most bands of sheep were sampled once, but four bands were sampled twice, and two bands were sampled three times.

Standard microbiological techniques were used to enumerate commensal *E. coli* (those generally regarded as non-pathogenic) (APHA 2012) and to identify two potential pathogens, *E. coli* O157:H7 (Kilonzo et al. 2011) and *Salmonella* species (US EPA 2011). We determined mean coliform bacteria concentration in feces and soil by dispersing 0.035 ounce (1.0 gram) of feces or soil in 1.32 fluid ounces (39 milliliters) of phosphate buffered solution (PBS) using a rotational mixer for 5 minutes. The feces- or soil-PBS solution was then serially diluted (102, 103, 104, 105, 106). The *E. coli* concentration in the diluted feces- or soil-PBS solution was determined by direct membrane filtration and culturing onto CHROMagar EC (Chromagar Microbiology, Paris, France) at 112.1°F (44.5°C) for 24 hours (APHA 2012).

Integrated livestock and crop operations are beneficial to producers of both products.

Jorge Celis

Placed downwind from grazing livestock, a portable microbial air monitoring station keeps track of airborne bacteria.

***Above,* one side of an Imperial Valley road is a leafy green vegetable crop; the other, an alfalfa field. As many as 150,000 sheep graze on Imperial Valley alfalfa from October to March. During this period, sheep are moved to a new field every 4 to 7 days, and at times herded along public roads.**

Fecal and soil samples were enriched for *Salmonella* species using US EPA Method 1682 (US EPA 2011). *Escherichia coli* O157 samples were enriched in tryptic soy broth (TSB), exposed to an immunomagnetic separation step and then cultured on cefixime potassium tellurite sorbitol MacConkey (CT SMAC) and Rainbow agar containing novobiocin and tellurite (NT Rainbow) as previously described (Cooley et al. 2007; Kilonzo et al. 2011). *E. coli* O157:H7 colonies identified were further analyzed by real-time PCR (RT-PCR) to detect presence of virulence genes. Pulsed-field gel electrophoresis was performed on *E. coli* O157:H7 isolates with the standard PulseNet procedure by using XbaI restriction enzyme (Kilonzo et al. 2011; Ribot et al. 2006).

Air samples were collected from the edge of the field where the sheep were grazing. The prevailing wind direction was used to determine which side of the field was sampled. Samples were collected from the downwind side of the field in duplicate or triplicate at the following distances from the field edge: 6.6, 16.4, 32.8, 65.6, 164.0 and 328.1 feet (2, 5, 10, 20, 50 and 100 meters). A sample was also obtained from an upwind location to serve as a control. The microbial air monitoring system MAS-100Eco (Merck) was used to test total levels of all forms of bacteria. The MAS-100 aspirates air at the rate of 26.4 gallons (100 liters) of air per minute, and after initial tests we determined that a sampling time of 10 minutes was appropriate given the low concentrations of bacteria in the air. Specific agar (Chromocult) was used to enumerate colonies, and the number was converted to colony-forming units per cubic meter of air (Chinivasagam et al. 2009). Air samples were obtained at the same time and on the same day as the fecal and soil collections. Air samples were collected on five additional occasions as well.

Meteorological data (wind speed, temperature, relative humidity, rainfall) were recovered daily from the closest California Irrigation Management Information System (CIMIS) weather station (CIMIS 2012). Data were entered into, and graphs were prepared from, a commercially available spreadsheet program (Excel 2010, Microsoft Corporation, Redmond, WA). Statistical analysis (chi-square tests for homogeneity, one-way analysis of variance) was performed using a software program (Egret for Windows, version 2.0.1, Cytel Software Corporation, Cambridge, MA).

TABLE 1. Prevalence (number of positive samples divided by number of total samples) of *E. coli* O157:H7 and *Salmonella* species in sheep feces and soil from alfalfa fields with grazing sheep, Imperial Valley, 2011*

	Feces		Soil	
Date	*E. coli* O157:H7	*Salmonella*	*E. coli* O157:H7	*Salmonella*
Feb 2	0	0.025	0	0
Feb 11	0	0	0	0
Feb 14	0	0	0	0
Feb 17	0	0	0	0
Feb 24	0	0	0	0.075
Mar 2	0	0.075	0	0
Mar 15	0.025	0	0	0
Oct 25	0.025	0.025	0.050	0
Nov 1	0	0	0	0
Nov 4	0	0	0	0
Nov 8	0.050	0	0	0
Nov 15	0	0	0.025	0
Nov 18	0	0	0	0
Nov 29	0.050	0	0	0
Dec 2	0.100	0	0	0
Dec 5	0.025	0	0	0
Dec 9	0.050	0	0	0
Dec 15	0	0.025	0	0

* On each date, 40 fecal samples and 40 soil samples were collected.

Pathogenic bacteria from sheep

Since sheep are present only seasonally in the Imperial Valley, samples were collected from February 2011 to March 2011 and again from October 2011 to

December 2011. Total precipitation during these two time periods was 1.82 inches (4.62 centimeters); average air temperature was 57.5°F (14.2°C) and average wind speed was 4.3 mph (6.9 kilometers per hour). Ten-year averages during the period of October to March are 1.1 inches (2.9 centimeters) rainfall, 61.1°F (16.2°C) average air temperature and 4.5 mph (7.3 kilometers per hour) average wind speed (CIMIS 2012).

A total of 1,440 samples (720 fecal and 720 soil) were collected throughout the project.

***E. coli* O157:H7.** These pathogenic coliform bacteria were found in 13 of the fecal samples (1.8%) and in 3 of the soil samples (0.4%) (table 1). *E. coli* O157:H7 was found in feces in 7 of 18 sample collections, and in soil in 2 of 18 sample collections. The highest prevalence of *E. coli* O157:H7 in feces at any one sample collection was 10% (4 positive out of 40 samples).

There were no statistically significant differences in the proportion of positive samples on any of the collection dates; however, there were more positive fecal samples collected from October to December (12 of 440) than from January to March (1 of 280) (p value = 0.02). No significant associations between prevalence and management factors such as duration of grazing, irrigation events or source of sheep were detected. There was also no association between duration of sheep grazing and presence of bacteria in the soil.

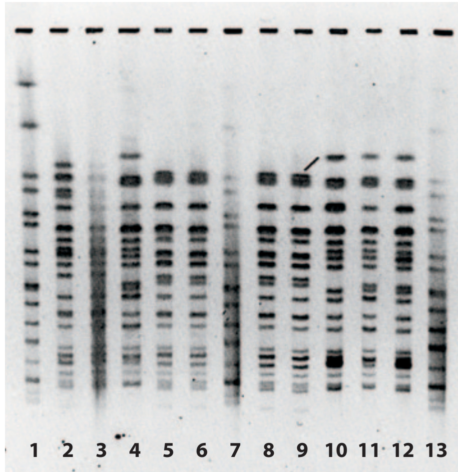


Fig. 1. Pulsed-field gel electrophoresis of *E. coli* O157:H7 isolates from sheep feces and soil with grazing sheep, Imperial Valley, 2011. Lanes 1, 7 and 13 are control isolates. Lanes 2 and 3 are from Oct. 25, 2011, lane 4 from Nov. 8, 2011, lanes 5, 6, 8, and 9 from Dec. 2, 2011, lane 10 from Dec. 5, 2011, and lanes 11 and 12 from Dec. 9, 2011. Samples collected from different days have different patterns, indicating the presence of different *E. coli* O157:H7 genotypes.

Pulsed-field gel electrophoresis (PFGE) was performed to determine genetic relatedness of isolates on several of the recovered *E. coli* O157:H7 samples (fig. 1). In general, isolates from the same date and same group of sheep shared a PFGE pattern, while isolates from other groups of sheep sampled on different dates had unique patterns. This indicates that different bands of sheep likely carry unique strains of *E. coli* O157:H7, a factor that could be useful in determining bacterial sources in the event of a disease outbreak.

Salmonella species. These potentially pathogenic bacteria were detected in 6 fecal samples (0.8%) and 3 soil samples (0.4%). All positive soil samples were obtained on the same sampling date, while positive fecal samples were obtained from three sampling dates. Interestingly, a significant precipitation event (over 2.5 centimeters, 1 inch, within a 2-day period) occurred a few days before the *Salmonella* positive soil samples were collected (table 1). We speculate that the additional moisture likely affected the ability of the bacteria to survive and therefore be recovered from the soil.

The mean commensal *E. coli* and coliform bacteria concentration in feces and soil was also measured. The overall mean coliform count from feces over the entire project was 1.05×10^7 colony-forming

Jorge Celis

In the corner of an alfalfa field, grazing sheep cluster near a water trough. Investigators analyzed soil and fecal samples from fields intensively grazed by bands of sheep; each consisted of 1,200 to 1,800 head of approximately 6- to 10-month-old lambs, from various locations in the western United States.

TABLE 2. Mean number of colony-forming units of bacteria per cubic meter of air at various distances from edge of fields with grazing sheep, Imperial Valley, 2011

Date	Upwind (control)	Downwind distance from field edge: 2 meters	5 meters	10 meters	20 meters	50 meters	100 meters
Feb 1	0.67	1.67	0.67	1.00	2.00	NA*	NA
Feb 11	1.00	0	0	0.67	0	0.33	0
Feb 14	0	11.67	0	0	0	1.67	0
Feb 17	0.33	0.33	1.00	0.33	0	0.33	0.67
Feb 24	0.67	0	1.33	0.33	0.67	0	0.33
Mar 2	0	0	0.67	0	0	0.33	0.33
Mar 15	0	0.33	0	0	0	0	0
Oct 21	0	16.50	2.00	0	3.00	0	1.00
Oct 24	1.00	1.00	0	0	0	0	0
Oct 27	0	0	0	0	1.00	1.00	0.50
Nov 1	0	0	0	0	0	0.50	0
Nov 8	0	0	0	0	0	0	0
Nov 14	0	0	0	1.00	3.00	0	0
Nov 18	0	0	0	0	1.00	0	0
Nov 23	0	0	0	0	0	1.00	0
Dec 1	0	7.00	4.00	5.00	4.50	NA	NA
Dec 6	0	0	0	0	0	0	0
Dec 9	0	0	0	0	0	0	0
Dec 20	0	0	0	1.00	0	0	0
Mean	**0.19**	**2.03**	**0.51**	**0.49**	**0.80**	**0.30**	**0.17**

* Samples not collected due to proximity of structures.

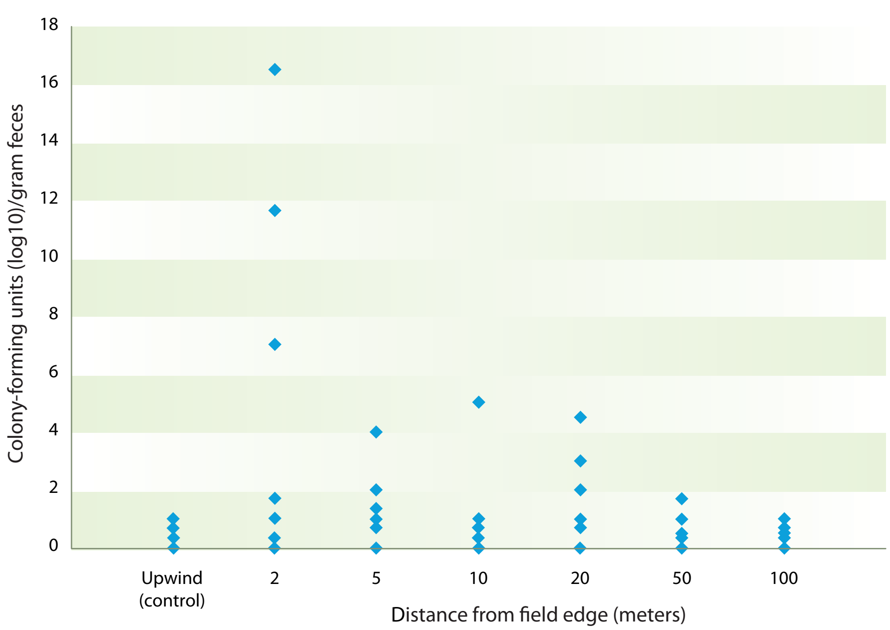


Fig. 2. Mean number of colony-forming units of bacteria per cubic meter of air from samples obtained at various distances from the edge of fields with grazing sheep, Imperial Valley, 2011. Each data point shown represents a bacteria level measured on one or more sampling dates from February 1 to December 20, 2011. (Specific data by date are listed in table 2.)

units per gram of feces, while mean commensal bacteria count from soil was 3.5×10^3 colony-forming units per gram of soil. This compares well to the mean coliform counts of approximately 6×10^6 found by other researchers (Taylor et al. 2012). Air sampling revealed that few bacteria were being dispersed through the air. The maximum number of colony-forming units was 16.5 per cubic meter of air obtained from a sample collected on October 21, 2011. The mean number of colony-forming units was greatest at a distance of 2 meters from the alfalfa field edge; however, a one-way analysis of variance demonstrated that there was no statistically significant difference at any distance measured, nor was there significant correlation between distance and bacterial count. Using linear regression, it was determined that there were no significant correlations between fecal or soil *E. coli* counts and aerosol bacterial counts at any of the distances measured (table 2, fig. 2).

Feces and soil are low risk

We detected *E. coli* O157:H7 in 1.8% of fecal samples and 0.4% of soil samples, and *Salmonella* species in 0.8% of fecal samples and 0.4% of soil samples. These results indicate that fresh sheep feces present minimal risk for leafy greens producers. Soil where sheep have been actively grazing is even lower risk. The positive soil samples were observed to be associated with recent (within 5 to 7 days) rainfall events. However, this observation requires further study, as positive soil samples were obtained in only 3 sample collections.

The finding of any human pathogens in fresh sheep feces warrants the LGMA recommendation of a food safety assessment following known intrusion by sheep. The PFGE patterns indicate that unique strains of *E. coli* O157:H7 exist in populations of sheep, and this information can be useful if investigations of the source of contamination of leafy greens are necessary.

Airborne transmission of bacteria was also assessed in this project. The greatest number of airborne bacteria (from all sources including feces) recovered from the edge of a field where sheep were grazing was at a distance of 2 meters (table 2, fig. 2). However, the difference compared to the number of bacteria at any other distance was not significant. We did not speciate the bacteria found. Given the low prevalence of pathogenic bacteria in feces and soil, we were not able to detect these pathogens in air samples. (Although we did not speciate bacteria from airborne samples, their gross morphology—or appearance on the agar plates—did not match that of pathogenic bacteria.) Future studies that compare the genotypes of bacteria recovered by air sampling with bacteria from the sheep would be worthwhile to improve understanding of the possibility of airborne transmission.

Based on our findings, we believe that the LGMA-recommended buffer distance of 30 feet (9 meters) between grazing livestock and crops is justified, and is more than adequate to ensure protection from potential contamination.

B.R. Hoar is a Livestock and Food Safety Epidemiologist and E.R. Atwill is Professor and Director, both at the Western Institute for Food Safety and Security, School of Veterinary Medicine, UC Davis; L. Carlton is Executive Director, California Wool Growers Association; J. Celis is Research Assistant, ANR Desert Research and Extension Center; J. Carabez is Research Assistant, and T. Nguyen is Research Assistant, both at the School of Veterinary Medicine, UC Davis.

Bruce Hoar

***Above,* portable electric fencing restricts movement of grazing livestock. Based on low prevalence of pathogenic bacteria in soil and fecal samples, scientists concluded that a buffer distance of 30 feet between grazing sheep and the edge of a food crop was adequate to prevent contamination.**

References

APHA. 2012. Membrane filter technique for fecal coliforms. In: *Standard Methods for the Examination of Water and Wastewater*. Washington, DC: American Public Health Association (APHA).

Battisti A, Lovari S, Franco A, et al. 2006. Prevalence of *Escherichia coli* O157 in lambs at slaughter in Rome, central Italy. Epidemiol Infect 134:415–9.

Brandl MT. 2008. Plant lesions promote the rapid multiplication of *Escherichia coli* O157:H7 on postharvest lettuce. Appl Environ Microbiol 74:5285–9.

[CDC] Centers for Disease Control and Prevention. 2006. Ongoing multistate outbreak of *Escherichia coli* serotype O157:H7 infections associated with consumption of fresh spinach—United States, September 2006. Morb Mortal Wkly Rep 55:1045–6.

[CDFA] California Department of Food and Agriculture. 2007. California Agricultural Resource Directory. www.cdfa.ca.gov/statistics/ (accessed April 24, 2010).

Chinivasagam HN, Tran T, Maddock L, et al. 2009. The aerobiology of the environment around mechanically ventilated broiler sheds. J Appl Microbiol 108:1657–67.

Cieslak PR, Barrett TJ, Griffin PM, et al. 1993. *Escherichia coli* O157:H7 infection from a manured garden. Lancet 342:367.

[CIMIS] California Irrigation Management Information System. 2012. wwwcimis.water.ca.gov/cimis/welcome.jsp (accessed January 4, 2012).

Cooley M, Carychao D, Crawford-Miksza L, et al. 2007. Incidence and tracking of *Escherichia coli* O157:H7 in a major produce production region in California. PLOS One 2:e1159.

Jay MT, Cooley M, Carychao D, et al. 2007. *Escherichia coli* O157:H7 in feral swine near spinach fields and cattle, central California coast. Emerg Infect Dis 13:1908–11.

Kilonzo C, Atwill ER, Mandrell M, et al. 2011. Prevalence and molecular characterization of *Escherichia coli* O157:H7 by multiple-locus variable-number tandem repeat analysis and pulsed-field gel electrophoresis in three sheep farming operations in California. J Food Prot 74:1413–21.

[LGMA] California Leafy Green Products Handler Marketing Agreement. 2012. LGMA Accepted Food Safety Practices 08/31/2012. http://lgma.ca.gov/sites/default/files/08.31.12%20CALGMA%20GAPs%20-%20metrics.pdf (accessed March 19, 2013).

Oltjen JW, Beckett JL. 1996. Role of ruminant livestock in sustainable agricultural systems. J Anim Sci 74:1406–9.

Ribot EM, Fair MA, Gautom R, et al. 2006. Standardization of pulsed-field gel electrophoresis protocols for the subtyping of *Escherichia coli* O157:H7, *Salmonella*, and *Shigella* for PulseNet. Foodborne Pathog Dis 3:59–67.

Sidjabat-Tambunan H, Bensink JC. 1997. Verotoxin-producing *Escherichia coli* from the faeces of sheep, calves and pigs. Aust Vet J 75:292–3.

Solomon EB, Yaron S, Matthews KR. 2002. Transmission of *Escherichia coli* O157:H7 from contaminated manure and irrigation water to lettuce plant tissue and its subsequent internalization. Appl Environ Microbiol 68:397–400.

Taylor JB, Dungan RS, Lewis GS. 2012. Sodium chlorate reduces the presence of *Escherichia coli* in feces of lambs and ewes managed in shed-lambing systems. J Anim Sci 90:381–6.

[US EPA] US Environmental Protection Agency. 2011. Method 1682: *Salmonella* in Sewage Sludge (Biosolids) by Modified Semisolid Rappaport-Vassiliadis (MSRV) Medium. http://water.epa.gov/scitech/methods/cwa/bioindicators/upload/2008_11_25_methods_method_biological_1682.pdf (accessed October 1, 2011).

Stinkwort is rapidly expanding its range in California

by Rachel Brownsey, Guy B. Kyser *and* Joseph M. DiTomaso

Stinkwort (**Dittrichia graveolens*****) is a Mediterranean native that has become a weed in areas of Europe as well as in Australia. This strongly aromatic weed was first reported in California in 1984 in Santa Clara County, and it had spread to 36 of the 58 California counties by 2012. Stinkwort is not palatable to animals, and can be poisonous to livestock and cause contact allergic dermatitis in humans. In California, this weed is found primarily along roadsides. However, the biology of this annual plant suggests that it could also invade open riparian areas and overgrazed rangelands. Stinkwort has an unusual life cycle among annual plants: Unlike most summer or late-season winter annuals, stinkwort flowers and produces seeds from September to December. Such basic biological information is critical to developing timely and effective control strategies for this rapidly expanding weed.***

Joseph DiTomaso

Stinkwort is related to fleabanes and goldenasters and grows to about 2.5 feet tall. In California, this rapidly invading weed most often occurs in disturbed and wasteland sites.

Dittrichia graveolens (L.) Grueter, commonly known as stinkwort, is a member of the Asteraceae, or sunflower, family. This plant is native to the Mediterranean region of Europe, occurring as far east as Turkey, Afghanistan and Pakistan (Brullo and de Marco 2000; Qaiser and Abid 2005). Stinkwort is an erect, fall-flowering annual that can grow about 2.5 feet tall. Its foliage has sticky glandular hairs covered in resin. The resin emits a strong aromatic odor that resembles the smell of tarweeds. The flowerheads are 0.2 to 0.3 inch (5 to 7 millimeters) in diameter and consist of short yellow ray flowers on the outer edge and yellow to reddish disk flowers in the center. Stinkwort is closely related to fleabanes, horseweed (*Erigeron*; formerly *Conyza*), goldenasters and telegraphweed (*Heterotheca*), but it also closely resembles the tarweeds (*Centromadia* spp., *Hemizonia* spp. and *Holocarpha* spp.). From a distance, stinkwort can resemble Russian-thistle (*Salsola tragus* L.), also called tumbleweed. Because it is fairly unattractive and nondescript in appearance, stinkwort initially passed unnoticed by many botanists and weed managers, and it was not included in the 1993 edition of *The Jepson Manual* of California flora (Hickman 1993).

In its native range and some introduced regions, stinkwort inhabits riparian woodlands, margins of tidal marshes, vernal pools and alluvial floodplains, although it has not yet invaded these wildland areas in California. In California and other introduced areas of the world, stinkwort is most often found in disturbed places, such as overgrazed rangelands, roadsides, pastures, wastelands, vineyard edges, gravel mines, levees, washes and mining sites, although in California it is seldom found in rangelands or pastures (DiTomaso and Healy 2007; Higueras et al. 2003). Stinkwort grows best on well-drained, sandy or gravelly soils and thrives in areas with hot, dry summers but can also do well along the margins of wetlands. In addition, this plant tolerates a variety of soil types and survives under a range of soil conditions, temperatures and precipitation regimes (Preston 1997). When adequate moisture is available, stinkwort can even survive on serpentine or saline soils. In Europe, this plant was shown to tolerate and to possibly hyperaccumulate heavy metals, including mercury, zinc and copper (Higueras et al. 2003; Shallari et al. 1998).

Worldwide invasion

While stinkwort is native to the Mediterranean region, including Egypt and other areas of North Africa, this species has also been introduced to several European countries where it is not native. Within the last two decades, this weed has been spreading rapidly along the highways of Central Europe. In summer 2008, stinkwort was detected for the first time in Slovenia and Austria (Frajman and Kaligaric 2009). Outside of

Online: http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v067n02p110&fulltext=yes
doi: 10.3733/ca.v067n02p110

Europe, stinkwort has been reported as an invasive species in Australia (Parsons and Cuthbertson 2001) and South Africa (South African National Biodiversity Institute 2009).

Stinkwort is not considered as a palatable species to animals. In fact, it is reported to cause poisoning in livestock (Philbey and Morton 2000). Although livestock mortality is rare, it appears to be due to enteritis caused by the barbed pappus bristles on the seed, which can puncture the small intestine wall (Philbey and Morton 2000). Stinkwort can also cause contact allergic dermatitis in humans (Thong et al. 2008). However, impacts to wildlife, natural ecosystems and working landscapes have not been broadly characterized. This is likely due to its very recent introduction and expansion in California and to the lack of published information on the species elsewhere in the world.

Rapid spread in California

The first record of *Dittrichia graveolens* in California is a collection made in 1984 near Milpitas in Santa Clara County (HOT Harvey s.n., University of California Jepson Herbarium/JEPS). Although the initial mechanism and time of introduction of stinkwort in the state are not documented, many of the earliest collections were made in the south and east San Francisco Bay Area (Preston 1997). Stinkwort has since spread to numerous counties in California, and many additional herbarium collections have been made throughout the state (Consortium of California Herbaria 2012).

Using the Consortium of California Herbaria records, we determined the rate of stinkwort's spread since the first discovery in Santa Clara County. Based on collection date and location data from herbarium records, this weed invasion appears to have had only a brief lag period and to have expanded at an exponential rate over the past 18 years (fig. 1). This has caused increased concern among resource managers across the state. Although it is still uncommon in many places where it is found, stinkwort has been reported in 36 of the 58 California counties (figs. 1 and 2).

Stinkwort seeds are likely spread by wind, on the fur and feathers of mammals and birds and on motor vehicles and equipment, thus moving along transportation corridors. While the primary expansion has moved radially from the original infestation in Santa Clara County, unconnected populations have also been discovered in San Diego and Riverside counties (fig. 2). This is likely due to either separate introductions or long-distance movement on vehicles.

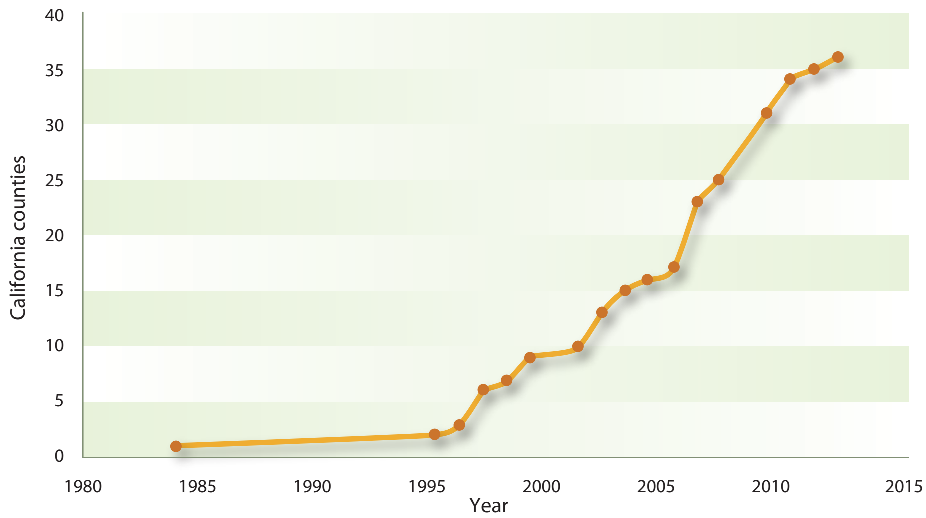


Fig. 1. Approximate rate of spread of *Dittrichia graveolens* in California as represented by the number of California counties where plant collections have been made between 1984 and 2012 (Consortium of California Herbaria 2012).

Unusual life cycle

Stinkwort has very high seed viability, with an average of about 90% of the seeds capable of germination at the time they disperse from the plant. There does not appear to be primary dormancy in the seeds, which is defined as a seed that is dormant at the time it disperses from the plant (Brownsey 2012). These traits, combined with the small seed size, suggest that seed longevity in the soil should be relatively short, perhaps 2 to 3 years. Seeds are capable of germinating at nearly any time of year in the field, but they typically germinate throughout winter and early spring following periods of precipitation. We have shown that germination is limited by soil moisture, rather than soil temperature or low light conditions (Brownsey 2012). When seeds germinate in winter, the plants remain as small rosettes until mid-May. During late spring and summer, they develop into pyramid- or sphere-shaped plants that superficially resemble Russian-thistle.

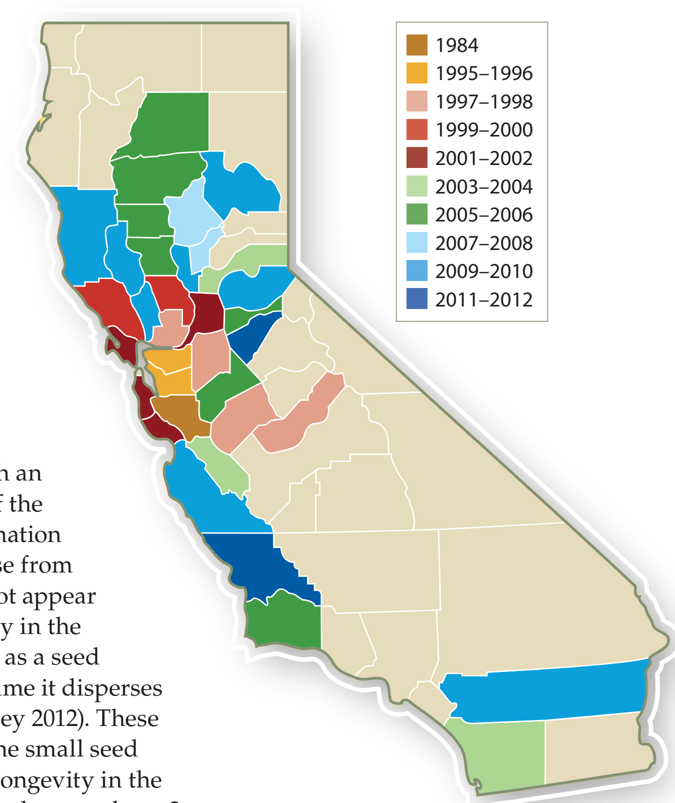


Fig. 2. Chronological spread of stinkwort in California counties from 1984 to 2012.

What makes stinkwort's life cycle rather unusual is that it matures much

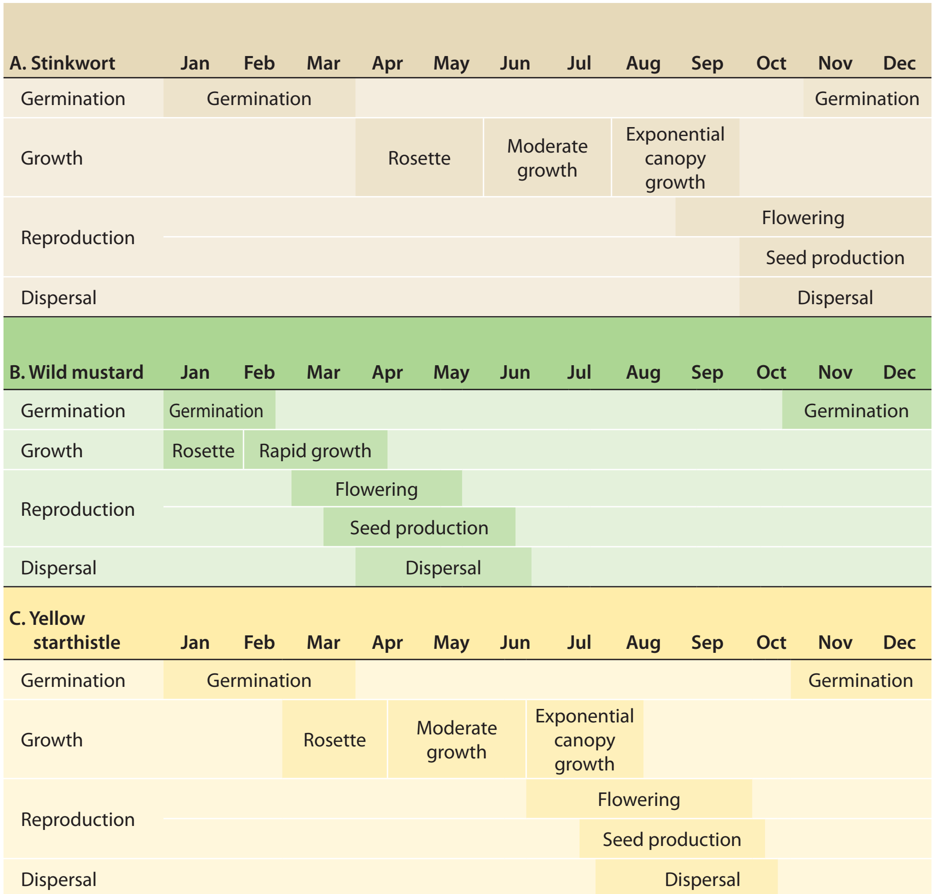
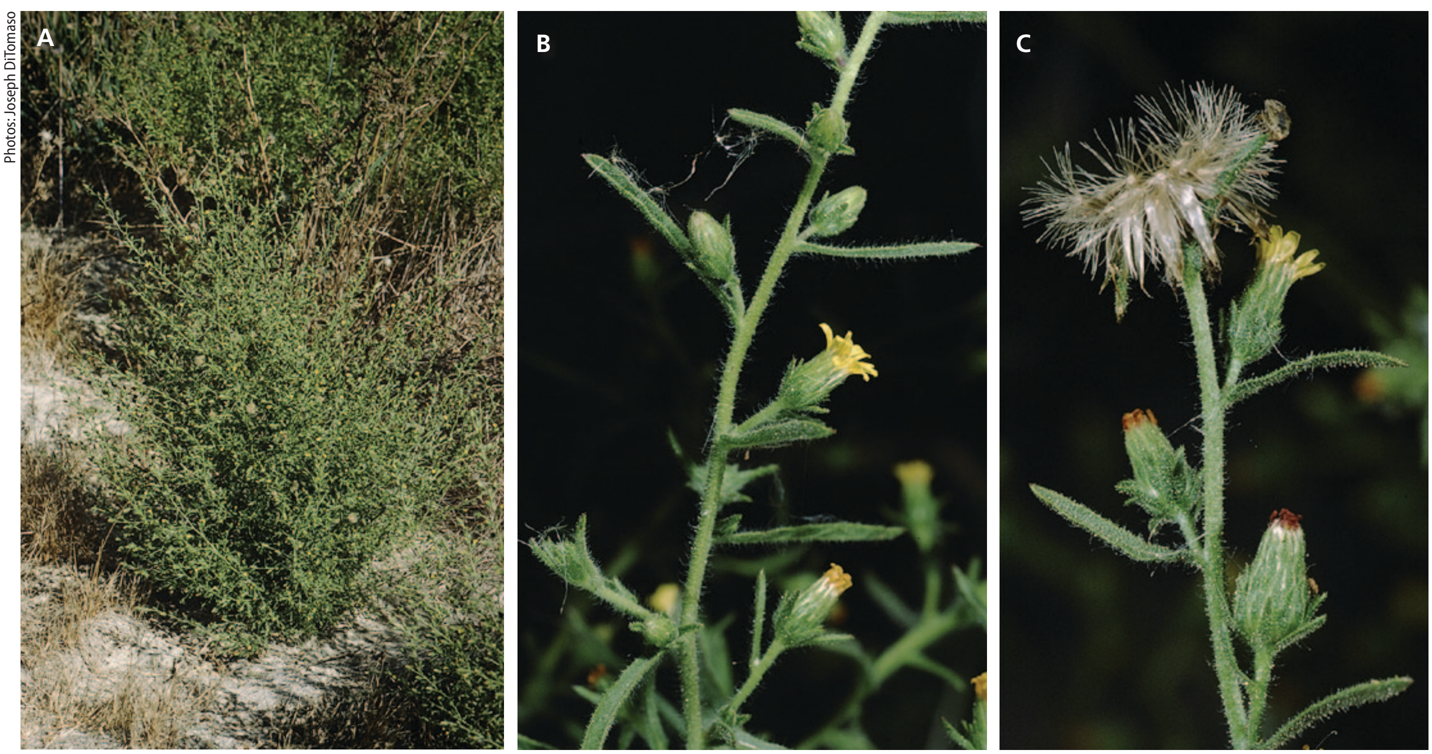


Fig. 3. Life cycle of (A) stinkwort (*Dittrichia graveolens*), a late-season winter annual, compared to the life cycles of (B) wild mustard (*Sinapis arvensis* L.), a typical early-season winter annual, and (C) yellow starthistle (*Centaurea solstitialis* L.), a typical late-season winter annual.

later in the season than most annuals, even other late-season winter annuals (fig. 3). For example, yellow starthistle begins to send up a flowering shoot (bolt, referred to as moderate growth in figure 3C) in April, begins flowering in late June, and — like most late-winter or summer annuals — has completed its life cycle by September or October. In contrast, stinkwort begins to bolt in mid-May (moderate growth in figure 3A), grows most of its branches and leaves between June and September and flowers and produces seeds from September to December. Flowering in stinkwort appears to be controlled by photoperiod (day length), as all plants initiate flowering at the same time regardless of when they germinated (Brownsey 2012).

Aside from the tarweeds, there are few other late-season winter annual species with a similar life cycle in the native California flora. Some other weedy species, such as Russian-thistle, horseweed (*Conyza canadensis* (L.) Cronquist) and yellow starthistle (*Centaurea solstitialis* L.), have similar life history strategies, with only Russian-thistle and horseweed flowering within the same time frame as stinkwort. In contrast to stinkwort, Russian-thistle is a summer annual that germinates in spring.

Photos: Joseph DiTomaso



Stinkwort (A) is a late-season winter annual. The aromatic leaves (B) have sticky hairs covered in resin. Flowering (C) occurs late summer, in response to day length.

Rachel Brownsey

Stinkwort tolerates a variety of soil types and can germinate at almost any time of year. Germination is limited only by soil moisture.

Rachel Brownsey

In an experiment using a minirhizotron camera, stinkwort (left) root growth was tracked over time and compared to the root growth of yellow starthistle and the native virgate tarweed.

Impacts in California

The environmental and economic impacts of stinkwort in California have not been fully realized and are largely unknown. Our greenhouse studies have shown that stinkwort is dramatically suppressed when grown under shaded conditions, even at 50% light (Brownsey 2012). Thus, like yellow starthistle, stinkwort is not expected to be competitive in understory communities of woodland and forest ecosystems. However, stinkwort can form dense infestations along highways and in open disturbed areas. In addition, while the establishment of this weed in undisturbed wildlands and rangelands is currently very limited in California, invasion of such areas over time is likely based on the pattern of spread in Australia.

We are now conducting studies comparing the belowground growth and development of stinkwort with two other common grassland annual species: yellow starthistle and virgate tarweed (*Holocarpha virgata* [A. Gray] D.D. Keck). Yellow starthistle is an invasive winter annual, and virgate tarweed is a native species that, like stinkwort, is a late-season winter annual. The goal is to determine whether stinkwort shares the characteristics of yellow starthistle and virgate tarweed that allow them to compete with shallow-rooted grasses. These characteristics are a rapid rate of root growth and deep soil root penetration.

Initial results indicate that while stinkwort does eventually grow roots as deep as yellow starthistle and virgate tarweed, this occurs several weeks after these other grassland annuals grow their roots. Thus, it may be that stinkwort will not be a significant invasive plant of rangelands, except in years when there is significant late-season rain or when competitive winter annual species are removed by overgrazing. Nevertheless, we have observed stinkwort in open riparian systems, where water is not a limiting factor and a slow-growing shallow root system will not limit its competitive ability. It is possible that this nonnative species may eventually become a problematic weed in these more-open wetland areas.

Current control methods

The challenge in controlling stinkwort is applying the appropriate management

Rachel Brownsey

Stinkwort can grow roots as deep as those of yellow starthistle, though it generally roots more shallowly and grows more slowly.

at the proper time. Although traditional methods of control, including mechanical and chemical techniques, can be effective, determining the most appropriate timing has been difficult. If management actions are not taken before plants begin to produce seeds in the fall, there is a risk that they will help disperse seeds rather than control stinkwort populations. For example, mowing may move seeds on equipment for long distances when conducted too late in the season. Unfortunately, a poor understanding of the biology of this plant and of how to control it effectively have led to unsuccessful management of growing infestations as well as much wasted time and money. However, management tools that prevent seed production for 1 to 2 years have the potential to greatly reduce the soil seedbank and, thus, the population size.

Biological or cultural practices. There are currently two biological or cultural practices that can be employed to limit the ability of stinkwort to invade an area. One is to minimize disturbances such as overgrazing and soil manipulation in natural and rangeland sites. Second, pastures should be managed for dense, competitive stands of desirable perennial or annual grasses that maximize ground cover in spring, when stinkwort seedlings are beginning to establish.

Rachel Brownsey

Seedlings of stinkwort can be controlled by hoeing or pulling, though protective clothing should be worn because the plant can cause dermatitis.

TABLE 1. Effect of postemergence herbicides and mowing on the control of *Dittrichia graveolens*

Treatment	Product trade name	Ounce product/acre	Ounce acid equivalent (a.e.)/acre	Late postemergence treatment* June 24, 2009	
				% cover	Vigor†
Glyphosate	Roundup Pro	16	6	7.3abcd‡	6.8cd
Glyphosate	Roundup Pro	32	12	5.0ab	4.5b
Aminopyralid	Milestone	3.5	0.875	16.3de	9.8d
Aminopyralid	Milestone	7	1.75	15.0cde	9.0d
Aminocyclopyrachlor	—	4	2	10.0bcd	6.5bc
Aminocyclopyrachlor	—	8	4	7.3abcd	6.5bc
Triclopyr amine	Garlon 3A	32	12	3.0ab	8.5cd
Triclopyr amine	Garlon 3A	64	24	0a	0a
Mowing	—	—	—	5.3abc	10.0d
Untreated	—	—	—	23.8e	10.0d

* All late postemergence treatments were made prior to flowering.
† Vigor ratings based on a 0 to 10 scale with 0 = dead plants and 10 = healthy plants.
‡ Numbers in the same column with different letters are significantly different at 5% confidence level.

If management actions are not taken before stinkwort begins to produce seeds in the fall, there is a risk that these actions will help disperse seeds rather than control stinkwort populations.

Mechanical practices. Mechanical control options can take advantage of the stinkwort root system, which is slow growing and initially relatively shallow. Plants may be controlled by hoeing or pulling. However, because stinkwort can cause dermatitis, it is important to wear appropriate protective clothing (long sleeves, long pants, gloves) to minimize exposure to the irritating oils. Once in flower, stinkwort plants should be bagged and removed from the site to prevent seeds from maturing and dispersing after the plants have been cut and left on the soil surface. Mowing can provide partial control when conducted late in the season (table 1). However, buds remaining on branches below the level of the mower may regrow. Mowing a second time can give improved control, especially when conducted after the soil has dried out in mid- to late summer. In contrast, mowing too early, as is done on highways to reduce the threat of grass fires, will favor stinkwort by removing competing annuals while this weed is still small and lower than the mowing blades.

Postemergence herbicides. Postemergence herbicides are applied to small germinated seedlings or young plants. Thus, in contrast to preemergence herbicides that are generally applied to larger areas before seeds germinate, postemergence applications can directly target known infestations visible to the applicator. However, the sticky oils on the foliage, especially on mature plants, make it difficult to control stinkwort with postemergence herbicides. To overcome this, it may be necessary to use ester formulations of postemergence phenoxy-type herbicides (2,4-D, MCPA, triclopyr, etc.). However, these compounds are more volatile compared to salt formulations (commonly used in summer), and some should not be applied when ambient temperatures will reach or exceed 80°F.

In experiments we conducted for the postemergence control of stinkwort, we found that the salt formulation of triclopyr at 24-ounce acid equivalent (a.e.) per acre (2 quarts Garlon 3A per acre) gave the most effective level of control following a postemergence application (table 1). Triclopyr is selective and relatively safe on grasses, but it must be used cautiously around vineyards, as grapevines are extremely sensitive to triclopyr drift. It is also important to note that control with postemergence herbicides is most effective when plants are young, actively growing and not exposed to stresses such as drought. For stinkwort, this is generally just before or at the time of bolting.

Rachel Brownsey

Dense stand of stinkwort in an overgrazed pasture. Stinkwort has spread exponentially in California since its discovery in Santa Clara County in 1984.

Glyphosate (Roundup Pro) at 1 quart product per acre also gave fairly good control, and anecdotal information from other land managers indicates that a rate of 2 quarts product per acre gives control similar to triclopyr at 2 quarts product per acre. Unfortunately, other herbicides, including aminopyralid (Milestone) and aminocyclopyrachlor (one of the active ingredients in herbicide Perspective), did not provide effective late-season postemergence control of stinkwort. As previously discussed, plants also partially recovered from late-season mowing.

Pre- and early postemergence herbicides. Because stinkwort germinates throughout the rainy season, the most effective control options are likely to be broadleaf selective herbicides with both pre- and early postemergence activity, which can control both new germinants and young emerged seedlings. A fairly new group of foliar- and soil-active growth regulator herbicides have proven very effective in winter and spring applications for control of yellow starthistle and other members of the sunflower family (Asteraceae). These herbicides have the ability to control both emerged young plants through foliar activity, as well as germinating seedlings through soil activity. These chemicals include clopyralid (Transline), aminopyralid (Milestone) and aminocyclopyrachlor, and they are generally safe on grasses. In preliminary demonstrations, we found that winter applications of aminocyclopyrachlor and spring applications of Milestone VM+ (aminopyralid plus triclopyr) showed the greatest potential for controlling stinkwort. Early-season application of glyphosate, however, controlled competing vegetation and so allowed late-germinating stinkwort to thrive. Thus, glyphosate is best used later in the season as a postemergence application.

This ongoing research is building our understanding of the life cycle and basic biology of stinkwort, allowing us to make predictions of invasion potential that will help prioritize management activities. This work also lays a foundation for future investigation of specific management methods. If we expect to stop or slow the spread of this newly invasive plant in California, we must quickly develop effective management tools and an informed management approach.

R. Brownsey was Graduate Student, G.B. Kyser is Specialist, and J.M. DiTomaso is Cooperative Extension Weed Specialist, all at Department of Plant Science, UC Davis.

References

Brownsey RN. 2012. Biology of *Dittrichia graveolens* (Stinkwort): Implications for Management. M.Sc. thesis, UC Davis, CA. 107 p.

Brullo S, de Marco G. 2000. Taxonomical revision of the genus *Dittrichia* (Asteraceae). Portugaliae Acta Biologica 19:341–54.

Consortium of California Herbaria. 2012. Specimen Records for *Dittrichia graveolens*. Data provided by the participants of the Consortium of California Herbaria. http://ucjeps.berkeley.edu/consortium/.

DiTomaso JM, Healy EA. 2007. *Weeds of California and Other Western States*. UC ANR Pub 3488, 2 Vols. Oakland, CA. 1808 p.

Frajman B, Kaligaric M. 2009. *Dittrichia graveolens*, a new alien species of the Slovenian flora. Hladnikia 24:35–43.

Hickman JC (ed.). 1993. *The Jepson Manual: Vascular Plants of California*. Berkeley, CA: UC Press.

Higueras P, Oyarzun R, Biester H, et al. 2003. A first insight into mercury distribution and speciation in soils from the Almadén mining district, Spain. J Geochem Explor 80:95–104.

Parsons WT, Cuthbertson EG. 2001. *Noxious Weeds of Australia* (2nd ed.). Collingwood, Australia: CSIRO Publ. 698 p.

Philbey AW, Morton AG. 2000. Pyogranulomatous enteritis in sheep due to penetrating seed heads of *Dittrichia graveolens*. Austr Vet J 28:858–60.

Preston R. 1997. *Dittrichia graveolens* (Asteraceae), new to the California weed flora. Madroño 44:200–3.

Qaiser M, Abid R. 2005. Distribution pattern of *Inula* L. (S. Str.) and its allied genera from Pakistan and Kashmir. Pak J Bot 37(3):551–8.

Shallari S, Schwartz C, Hasko A, et al. 1998. Heavy metals in soils and plants of serpentine and industrial sites of Albania. Sci Tot Environ 209:133–42.

South African National Biodiversity Institute. 2009. (Accessed through the SIBIS portal, sibis.sanbi.org, 2009-06-01.) http://sibis.sanbi.org/faces/SearchSpecies/SearchDetails.jsp?1=1 (accessed July 10, 2012).

Thong HY, Yokota M, Kardassakis D, et al. 2008. Allergic contact dermatitis from *Dittrichia graveolens* (L.) Greuter (stinkwort). Cont Derm 58:51–3.

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

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.

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 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

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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

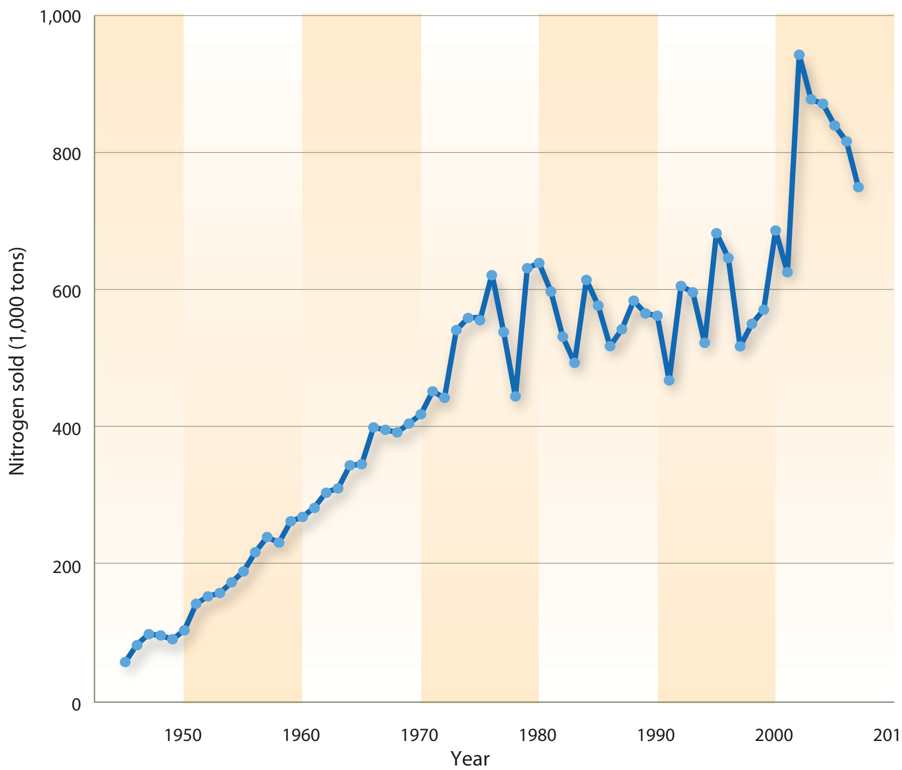


Fig. 1. Statewide sales of nitrogen fertilizer, 1945–2008. Because there is no explanation for the 50% rise in sales from 2001 to 2002, the largest 1-year change since estimates began, there is reason to question the accuracy of data since 2001. Source: California Department of Food and Agriculture.

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*

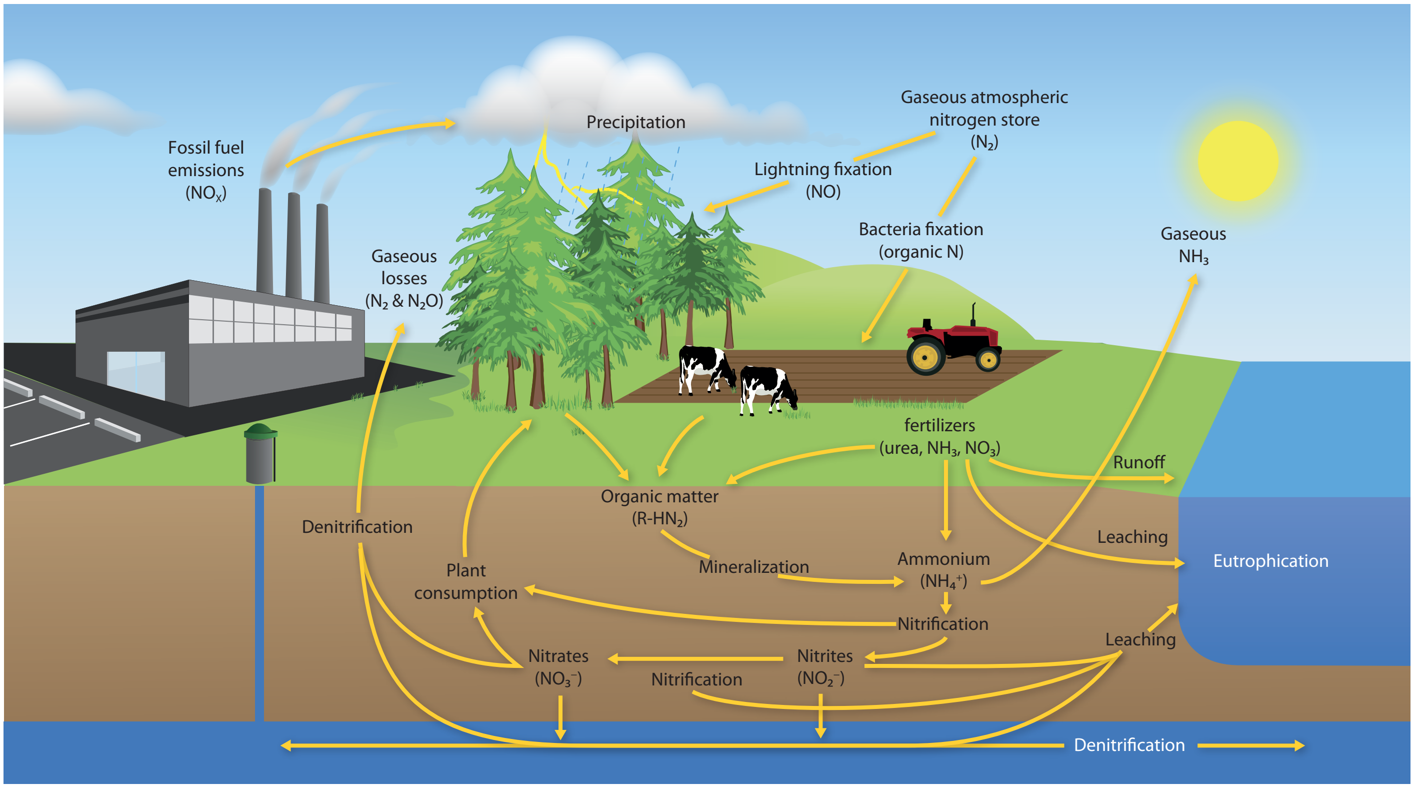


Fig. 2. The nitrogen cycle. Nitrogen in the environment is mobile and readily transformed into various compounds by physical, chemical and biological processes. Arrows indicate major nitrogen-cycling processes, which continuously produce diverse nitrogen compounds in the environment.

Glossary: Nitrogen in soils

Nitrogen may enter the soil from the atmosphere through rainfall, lightning, and nitrogen fixation by soil organisms; through plant and animal decomposition, or through applied 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 weld-rained, 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^+).

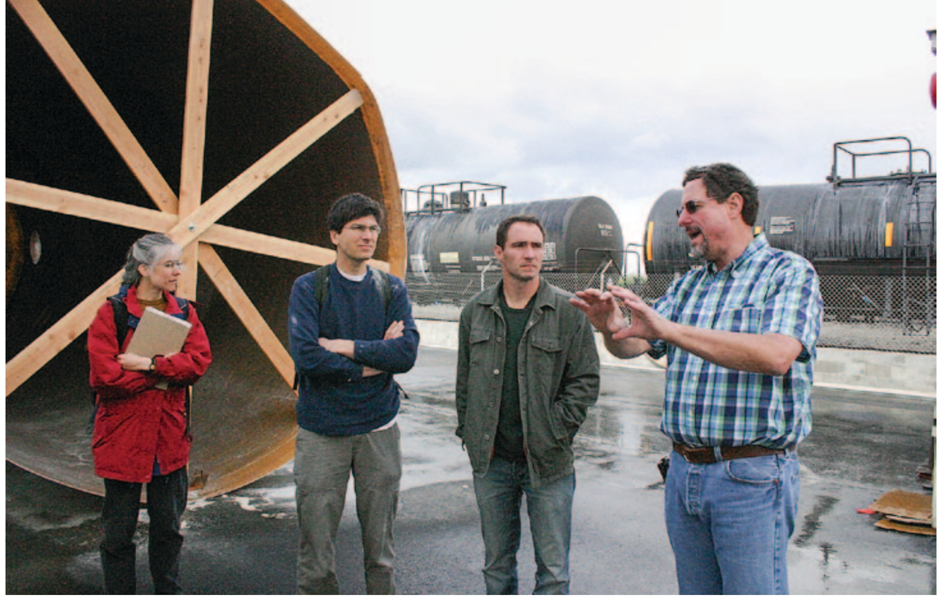
Nitrogen, reactive: Reactive nitrogen is all nitrogen other than dinitrogen gas (N_2).

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* 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.



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.

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

Colin Bishop

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).

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.

Colin Bishop

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.

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

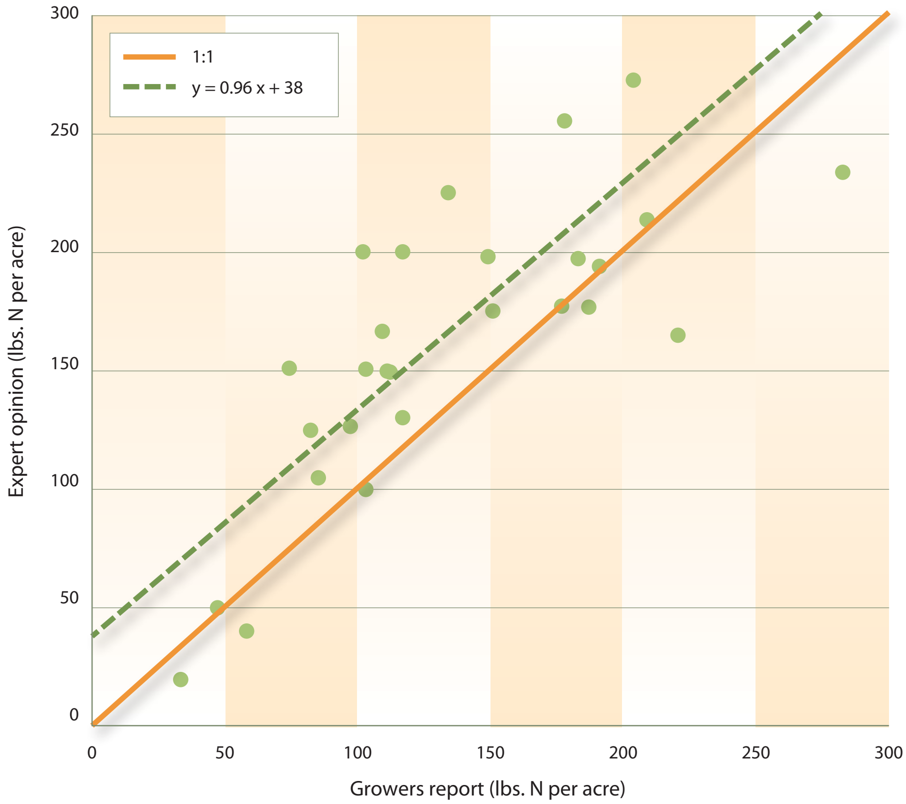


Fig. 3. Relationship between the experts' opinions and growers' reports of nitrogen application rates. Data were available from both sources for only 23 of the 33 commodities. The solid line represents 1:1 agreement, representing the theoretical point (in each case) where expert opinion and grower reports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

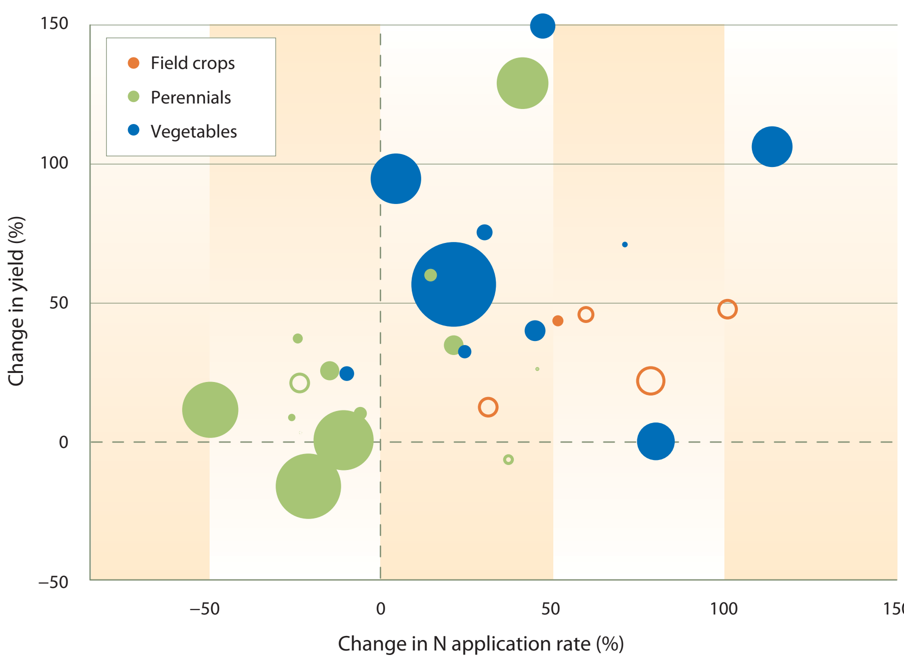


Fig. 4. Changes in nitrogen application rates, yields and cropped area. The size of circle represents the percentage change in the area cultivated for that particular crop between 1973 and 2005; closed circles represent increases in area and open circles represent declines in area.

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	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.

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

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.

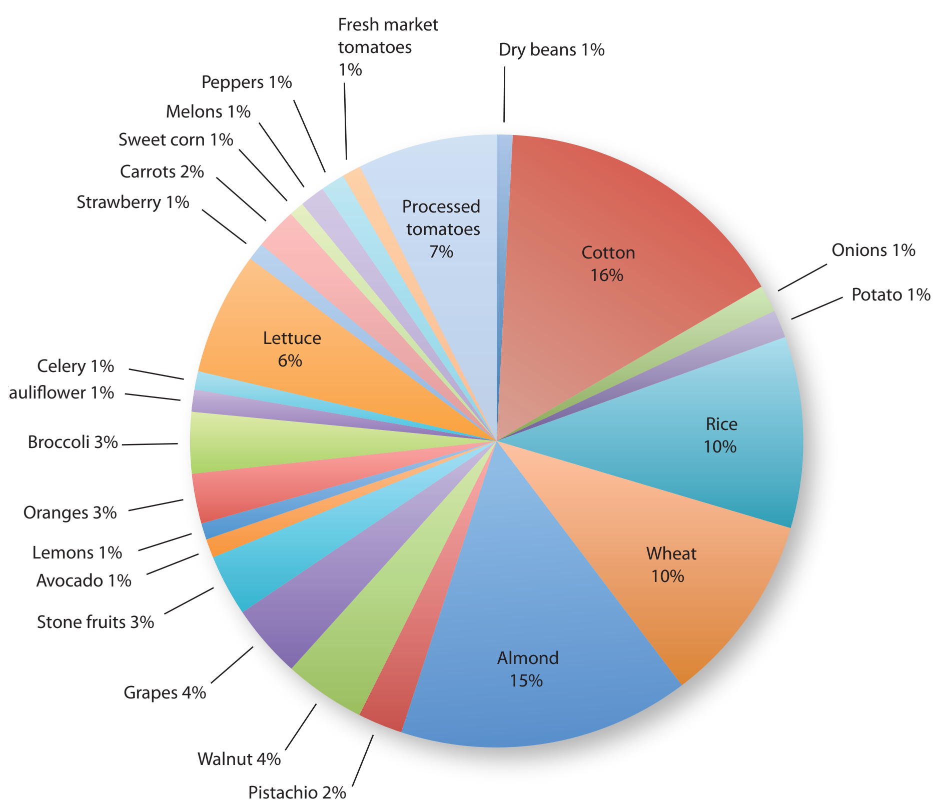


Fig. 5. Relative proportion of nitrogen fertilizer use of the 33 commodities included in the analysis. Stone fruits include peaches, nectarines and dried and fresh plums. Grapes include wine, table and raisin grapes.

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.

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.


Aaron Heinrich

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.

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


Colin Bishop

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.

T.S. Rosenstock and D. Liptzin were Postdoctoral Fellows, Agricultural Sustainability Institute, UC Davis, and are now, respectively, Environmental Impacts Scientist, World Agroforestry Centre and Research Fellow, University of New Hampshire; J. Six was Professor of Agroecology, Department of Plant Sciences, UC Davis, and is now Professor of Sustainable Agroecosystems, ETH-Zurich; and T.P. Tomich is Director, Agricultural Sustainability Institute, UC Davis.

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References

Ash N, Blanco H, Brown C, et al. 2010. Ecosystems and Human Well-Being: A Manual for Assessment Practitioners. Washington, DC: Island Press. p 264.

Broadbent FE, Rauschkolb RS. 1977. Nitrogen fertilization and water pollution. Calif Agri 31 (5):24–25.

Davidson EA, David MB, Galloway JN, et al. 2012. Excess nitrogen in the U.S. environment: Trends, risks, and solutions. Iss Ecology 15:17.

Dillon J, Edinger-Marshall S, Letey J. 1999. Farmers adopt new irrigation and fertilizer techniques: Changes could help growers maintain yields, protect water quality. Calif Agri 53(1): 24–31.

Flint ML. 1991. Integrated Pest Management for Citrus. UC ANR Pub. Oakland, CA.

Galloway JN, Aber JD, JW Erisman, et al. 2003. The nitrogen cascade. BioScience 53(4):341–56.

Gardner JB, Drinkwater LE. 2009. The fate of nitrogen in grain cropping systems: A meta-analysis of 15N field experiments. Ecol Appl 19:2167–84.

Harding R, Embleton TW, Jones WW, et al. 1963. Leaching and gaseous losses of nitrogen from some nontilled California soils. Agron J 55(6):515–8.

Hartley C, van Kessel CV. 2003. Results of the 2003 UC Davis Rice Fertility Management Survey. UC Rice Research Information Program website, www.ucdavis.edu/uccerice/NEWS/FertilityMgtSurvey2003.pdf.

Hoben JP, Gehl R, Millar N, et al. 2011. Nonlinear nitrous oxide (N2O) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. Glob Change Biol 17:1140–52.

Ingels C. 1994. Protecting Groundwater Quality in Citrus Production. UC ANR Pub. Oakland, CA.

Integrated Nitrogen Committee, 2011. Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences, and Management Options. A Report of the EPA Science Advisory Board. Washington, D.C.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, United Kingdom and New York, NY.

Ladha JK, Reddy CK, Padre A, et al. 2011. Role of nitrogen fertilization in sustaining organic matter in cultivated soils. J Environ Qual 40:1–11.

Linquist B, van Groenigen KJ, Adviento-Borbe MA, et al. 2012. An agronomic assessment of greenhouse gas emissions from major cereal crops. Glob Change Biol 18:194–209.

Lopus SE, Santibáñez MP, Beede RH, et al. 2010. Survey examines the adoption of perceived best management practices for almond nutrition. Calif Agri 64(3):149–54.

Millennium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Synthesis. Washington, DC: Island Press.

Miller RJ, Smith RB. 1976. Nitrogen balance in the southern San Joaquin Valley. J Environ Qual 5:274–8.

Peacock WL, Christensen LP, Hirschfelt DJ. 1998. Best Management Practices for Nitrogen Fertilization of Grapevines. Tulare County UCCE, Pub NG4-96.

Proebsting EL. 1948. Nitrogen fertilizer usually beneficial to soils of California. Calif Agri 2(1):10.

Rauschkolb RS, Mikkelsen DS. 1978. Survey of Fertilizer Use in California — 1973. UC Division of Agricultural Sciences Bulletin 1887. p 25.

Strand L. 2006. Integrated Pest Management for Potatoes in the Western United States (2nd ed.). UC ANR Pub 3316. Oakland, CA.

Townsend AR, Howarth RW, Bazzaz FA, et al. 2003. Human health effects of a changing global nitrogen cycle. Front Ecol Environ 1(5):240–6.

[UCD] UC Davis Agricultural and Resource Economics. 2010. Cost and Return Studies. http://coststudies.ucdavis.edu/ (accessed Jan. 5, 2010; verified Feb. 1, 2011).

USDA NASS. 2010a. National Agricultural Statistics Service Surveys: Agricultural Chemical Use Program. www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/index.asp (accessed Jan. 5, 2010; verified Feb. 1, 2011).

USDA. 2010b. National Agricultural Statistics Services Quick Stats. www.nass.usda.gov/Data_and_Statistics/Quick_Stats/index.asp (accessed 10 November 2009; verified 1 Feb. 2011).

Van Groenigen JW, Velthof GL, Oenema O, et al. 2010. Towards an agronomic assessment of N2O emissions: A case study for arable crops. Eur J Soil Sci 61:903–13.

Zhang M, Geng S, Smallwood KS. 2009. Assessing groundwater nitrate contamination for resource and landscape management. Ambio 27(3):170–4.

Zhang M. Unpublished. Bibliography of Studies Citing the PUR Database. http://agis.ucdavis.edu/pur/pdf/2011/PUR-citations.pdf/ (accessed July 26, 2012; verified July 30, 2012).

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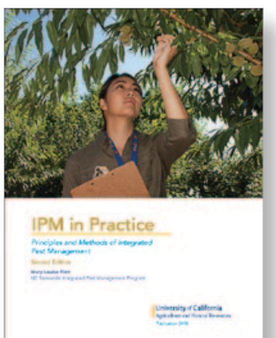

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COMINGUP *in California Agriculture*

Greg Browne

Scientists conducted trials in microplots, *above*, and commercial orchards to test preplant strategies for use against Prunus replant disease.

Alternatives to methyl bromide: Managing replant disease with less soil fumigant

Up to one-third of California's almond and stone fruit acreage is infested with potentially debilitating plant parasitic nematodes, and even more of the land is affected by Prunus replant disease, a poorly understood soil-borne disease complex that suppresses early growth and cumulative yield in replanted almond and peach orchards. Preplant soil fumigation is used widely to control these replant problems, but the fumigant of choice, methyl bromide, has been phased out — and other soil fumigants are increasingly regulated and expensive.

The authors tested and demonstrated alternatives to methyl bromide fumigation for control of Prunus replant disease. They conducted multiple-year replant trials to evaluate costs and benefits of alternative fumigant formulations and application methods. They also examined nonfumigant approaches, including preplant cover crops, use of resistant rootstocks and fallowing. Their results identified valuable components of integrated management methods: Optimized spot and strip soil fumigation, sudangrass rotation and prudent rootstock selection.