Addressing Nitrate in California's Drinking Water

TECHNICAL REPORT 3:

Nitrogen Source Reduction to Protect Groundwater Quality

With a Focus on Tulare Lake Basin and Salinas Valley Groundwater

Report for the State Water Resources Control Board Report to the Legislature

California Nitrate Project,
Implementation of Senate Bill X2 1

Center for Watershed Sciences
University of California, Davis
http://groundwaternitrate.ucdavis.edu

Prepared for the California State Water Resources Control Board

Nitrogen Source Reduction to Protect Groundwater Quality

Technical Report 3

Addressing Nitrate in California's Drinking Water

With a Focus on Tulare Lake Basin and Salinas Valley Groundwater

Report for the State Water Resources Control Board Report to the Legislature

Prepared by:

Kristin N. Dzurella, Josué Medellín-Azuara, Vivian B. Jensen, Aaron M. King, Nicole De La Mora, Anna Fryjoff-Hung, Todd S. Rosenstock, Thomas Harter, Richard Howitt, Allan D. Hollander, Jeannie Darby, Katrina Jessoe, Jay Lund, G. Stuart Pettygrove[1]

Center for Watershed Sciences

University of California, Davis

California Nitrate Project, Implementation of Senate Bill X2 1

Tulare Lake Basin and Salinas Valley Pilot Studies

Prepared for:

California State Water Resources Control Board

July 2012

---

[1] Corresponding author: gspettygrove@ucdavis.edu

Suggested Citation:

Dzurella, K.N., Medellin-Azuara, J., Jensen, V.B., King, A.M., De La Mora, N., Fryjoff-Hung, A., Rosenstock, T.S., Harter, T., Howitt, R., Hollander, A.D., Darby, J., Jessoe, K., Lund, J.R., & Pettygrove, G.S. (2012) Nitrogen Source Reduction to Protect Groundwater Quality. Technical Report 3 in: *Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature*. Center for Watershed Sciences, University of California, Davis.

An electronic copy of this Final Report is available from the following website:

http://groundwaternitrate.ucdavis.edu

Copyright ©2012 The Regents of the University of California

All rights Reserved

The University of California prohibits discrimination or harassment of any person on the basis of race, color, national origin, religion, sex, gender identity, pregnancy (including childbirth, and medical conditions related to pregnancy or childbirth), physical or mental disability, medical condition (cancer-related or genetic characteristics), ancestry, marital status, age, sexual orientation, citizenship, or service in the uniformed services (as defined by the Uniformed Services Employment and Reemployment Rights Act of 1994: service in the uniformed services includes membership, application for membership, performance of service, application for service, or obligation for service in the uniformed services) in any of its programs or activities. University policy also prohibits reprisal or retaliation against any person in any of its programs or activities for making a complaint of discrimination or sexual harassment or for using or participating in the investigation or resolution process of any such complaint. University policy is intended to be consistent with the provisions of applicable State and Federal laws.

Disclaimer: The contents of this document are solely the responsibility of the authors and do not necessarily represent the official views of supporting agencies

For further inquiries, please contact

Thomas Harter, Ph.D.

ThHarter@ucdavis.edu

125 Veihmeyer Hall

University of California

Davis, CA 95616-8628

Phone: 530-752-2709

Contents

Tables

Figures

Acronyms and Abbreviations

BNR	Biological Nutrient Removal
CES	Constant Elasticity of Substitution
CIMIS	California Irrigation Management Information System
CPNB	Marginal cost of improving nitrogen use efficiency as Partial Nutrient Balance
DU	Distribution Uniformity
DWR	California Department of Water Resources
EDR	Electrodialysis Reversal
ET	Evapotranspiration
FP	Food Processor
GRP	Glass Reinforced Plastic pipe
HDPE	High Density Polyethylene pipe
HI	Hazard Index (Center for Watershed Sciences)
MM	Management Measure
NUE	Nutrient Use Efficiency
O & M	Operations and Maintenance
PMP	Positive Mathematical Programming
PNB	Partial Nutrient Balance
POTW	Publically Owned Treatment Works
PVC	Polyvinyl Chloride pipe
RO	Reverse Osmosis
RP	Recommended Practice
SBR	Sequencing Batch Reactor
SSURGO	Soil Survey Geographic Database (NRCS)
SV	Salinas Valley
SWAP	Statewide Agricultural Production Model
TLB	Tulare Lake Basin

Unit Conversions

Metric to US		**US to Metric**	
Mass		*Mass*	
1 gram (g)	0.04 ounces (oz)	1 ounce	28.35 grams
1 kilogram (kg)	2.2 pounds (lb)	1 pound	0.45 kilograms
1 megagram (Mg) (1 tonne)	1.1 short tons	1 short ton (2000 lb)	0.91 megagrams
1 gigagram (Gg) (1000 tonnes)	1102 short tons	1000 short tons	0.91 gigagrams
Distance		*Distance*	
1 centimeter (cm)	0.39 inches (in)	1 inch	2.54 centimeters
1 meter (m)	3.3 feet (ft)	1 foot	0.30 meters
1 meter (m)	1.09 yards (yd)	1 yard	0.91 meters
1 kilometer (km)	0.62 miles (mi)	1 mile	1.61 kilometers
Area		*Area*	
1 square meter (m^2)	10.8 square feet (ft^2)	1 square foot	0.093 square meters
1 square kilometer (km^2)	0.39 square miles (mi^2)	1 square mile	2.59 square kilometers
1 hectare (ha)	2.8 acres (ac)	1 acre	0.40 hectares
Volume		*Volume*	
1 liter (L)	0.26 gallons (gal)	1 gallon	3.79 liters
1 cubic meter (m^3) (1000 L)	35 cubic feet (ft^3)	1 cubic foot	0.03 cubic meters
1 cubic kilometer (km^3)	0.81 million acre-feet (MAF, million ac-ft)	1 million acre-feet	1.23 cubic kilometers
Farm Products		*Farm Products*	
1 kilogram per hectare (kg/ha)	0.89 pounds per acre (lb/ac)	1 pound per acre	1.12 kilograms per hectare
1 tonne per hectare	0.45 short tons per acre	1 short ton per acre	2.24 tonnes per hectare
Flow Rate		*Flow Rate*	
1 cubic meter per day (m^3/day)	0.296 acre-feet per year (ac-ft/yr)	1 acre-foot per year	3.38 cubic meters per day
1 million cubic meters per day (million m^3/day)	264 mega gallons per day (mgd)	1 mega gallon per day (694 gal/min)	0.0038 million cubic meters/day

Nitrate Units

*Unless otherwise noted, nitrate concentration is reported as milligrams/liter as nitrate (mg/L as NO$_3^-$).

To convert from:

Nitrate-N (NO$_3$-N)	→	Nitrate (NO$_3^-$)	multiply by 4.43
Nitrate (NO$_3^-$)	→	Nitrate-N (NO$_3$-N)	multiply by 0.226

Summary

Although reduction of anthropogenic loading of nitrate to groundwater aquifers will not reduce contamination in the short term (due to long travel times), reduction efforts are a critical component of any long term solution to the problem of high nitrate in drinking water. Technologies are available for reducing the transfer of nitrate to groundwater from surface sources. Such technologies involve (1) reducing the amount of nitrogen (N) discharged or applied to the land and (2) controlling the amount of water applied to land which serves as the carrier of nitrate. Many of these source control methods require changes in land management and upgrading of infrastructure.

In this report, we have considered the methods and associated costs for reduction of nitrate leaching losses from the major anthropogenic sources of nitrate loading to groundwater in the two study regions. The sources considered here are irrigated cropland, livestock operations, turfgrass and other urban landscaping, effluent from municipal wastewater treatment plants and food processing plants, sewers, septic systems, and abandoned, dry, and active wells.

Costs for mitigation or abatement vary widely and can sometimes be difficult to estimate. In particular, the amount of nitrate leached from irrigated crop fields (the largest source) is determined by a complex interaction of N cycle processes, soil properties, and farm management decisions; it is therefore virtually impossible to generalize mitigation costs per unit of nitrate load decrease, allowing for only broad estimations.

Reducing Nitrate Leaching Losses from Irrigated Cropland and Livestock Operations

Reduction of nitrate leaching from cropland and livestock and operations can be achieved through changes in farm management that result in improvements in crop nitrogen use efficiency (NUE), and by proper storage and handling of manures and fertilizers. NUE, sometimes referred to as partial nitrogen balance (PNB), refers to the percentage of N applied to cropland (from all sources) that is recovered by the crop and is therefore not lost to the atmosphere or to surface and groundwater.

To determine the actions needed to reduce nitrate leaching losses from crop and livestock operations, we reviewed technical and scientific literature to compile a list of practices that are known or theorized to improve crop NUE. We then convened crop-specific expert panels to review and revise this list of practices. We relied on input from panel members to estimate the current extent of use of each practice within the study area and to help identify the main barriers to expanded adoption.

To establish the proportion of acreage in the study areas that would benefit the most from increased adoption of improved management practices, we conducted a vulnerability assessment. Vulnerability was mapped by use of the UC Nitrate Hazard Index (Wu et al. 2005), which calculates a risk of nitrate leaching based on the crop grown, the irrigation system type in use, and soil characteristics of the field.

Cropland Nitrate Reduction, Findings

NUE can be increased by optimizing the timing and rates of applied fertilizer N, animal manures, and irrigation water to better match crop needs, and to a lesser extent by modification of crop rotations. Improving the storage and handling of manures, livestock facility wastewaters, and fertilizers also plays a role in nitrate leaching reduction. Although crop recovery of N inputs as low as 33% have been reported, a recent U.S. EPA report estimated that with the adoption of best management practices, NUE could increase by up to 25% of current average values (U.S. EPA Science Advisory Board 2011). While improvements in NUE are possible, there exists a practical upper limit of about 80% crop recovery of applied N (Ibid; Raun & Schepers 2008). This limit is due to the unpredictability of rainfall, the difficulty in predicting the rate of mineralization of organic N in the soil, spatial variability in soil properties, and the need to leach salts from the rootzone.

Note that, while it is certain that the mass of nitrate lost by leaching from the crop root zone can be reduced to well below the rate of loss that has resulted in the currently observed nitrate concentrations in affected aquifers, this does not necessarily mean that the concentration of nitrate can be reduced to the MCL, especially where the sole or main source of aquifer recharge is percolate from irrigated crop fields.

To most effectively reduce the mass of nitrate escaping the crop rootzone, a suite of improved practices is generally required, and these must be chosen according to the unique field situation. There is no one set of management practices that will be the most effective in protecting groundwater quality. The applicability and effectiveness of the practices vary according to field specific variables (crop and soil characteristics, as well as underlying hydrology). That being said, the basic principles of improved management are applicable to all operations, and again include optimizing application rates and timing of water, fertilizer, and manure applications to better match crop need, making adjustments to crop rotation strategies, and improving storage and handling of fertilizers and manure. Additionally, it is critical that manure-N be accounted for by reducing inorganic N applications accordingly.

Several of the practices known to reduce nitrate leaching have been adopted in recent years by farmers in the study area, representing a positive change from past practices that have contributed to current groundwater nitrate concentrations. While it is clear that improved management reduces the rate at which nitrate is leached, data are lacking that would allow an estimation of how the rate of leaching has changed as agricultural management has improved and to what degree additional management changes will affect loading rates. Management practices that are not widely used are generally associated with multiple barriers to adoption by farmers. These include higher operating or capital costs, perceived or real risks to crop quality or yield, conflicting farm logistics, and constraints associated with land tenure. Additional significant barriers include inadequate farmer education and insufficient research to adapt practices to local conditions.

Based on soil characteristics of the field, crop species grown, and irrigation system type in use, we estimate that approximately 52% of irrigated cropland in the Salinas Valley and 35% of such land in the Tulare Lake Basin is susceptible to significant nitrate leaching losses. This vulnerability estimate is not indicative of actual nitrate loading to groundwater and does not consider depth to groundwater, the location of land relative to sensitive aquifers, and does not consider farmers' actual management practices. However, we can expect improved management in these areas to have the greatest positive impact on nitrate leaching.

A maximum net benefit modeling approach was used to estimate relative costs of policies aimed at improving NUE. One of the most uncertain input parameters employed in the economic modeling of agricultural nitrate source reductions is the actual cost of improving nitrogen use efficiency. Our modeling results suggest that modest reductions in N fertilizer application rates and increased adoption of related improved practices would increase production costs only slightly (assuming sufficient education in N management techniques). These modest reductions are thus deemed to be economically feasible without significant reductions in total irrigated area. As larger load reduction strategies are undertaken, the model predicts significant production costs increases, reducing net revenues considerably to the point of reducing net irrigated cropland within the study area. Lower value field crops and low NUE crops are especially vulnerable to area reductions, as higher economic returns will be required to cover the increased operating and capital costs associated with increased efficiency. A simulated nitrogen sales tax indicated such a tax could initiate additional grower motivation to adopt practices that contribute to NUE.

Cropland Nitrogen Reduction, Promising Actions

Expanded efforts to promote the adoption of nitrogen efficient practices are clearly needed. The educational barriers that are associated with many of the identified practices highlight the importance of funding research, education, and outreach activities to better assist farmers in applying best management strategies and nutrient management. The University of California Cooperative Extension (UCCE) and USDA Natural Resource Conservation Service (NRCS), for example, play integral roles in delivering quality educational information to both growers and crop advisors. Research should focus on demonstrating the impact of management practices on NUE, and on adaptation of practices to local or site-specific conditions in the crop rotations and soils that present the greatest risk of nitrate leaching. Such adaptive research should document the impact of improved practices on crop N use efficiency as well as on yield and profitability. Guidance in accounting for the nutrient value of manure-N is especially important. Additionally, research on the costs of increasing NUE would greatly benefit the capacity to better estimate the costs of reducing agricultural nitrate loading to groundwater.

Due to the waste discharge regulations imposed on Central Valley dairies in 2007,[2] transfer of significant amounts of manure from these dairies to other farms is increasing. It is not known which crop species and soils are receiving this manure or how the receiving farmers have integrated the manure into their N fertilization practices. We recommend development of adaptive research and education programs that will promote conversion of solid and liquid dairy manure into forms that meet the food safety and production requirements for a wider range of crop species. Providing guidance to non-dairy farms in co-managing conventional N fertilizers and manure-containing materials is necessary to ensure that the nutrient value of the manure is properly accounted for in fertilization activities.

---

[2] The General Order for Waste Discharge from Existing Dairies in the San Joaquin Valley, see http://www.waterboards.ca.gov/centralvalley/water_issues/dairies/dairy_program_regs_requirements/index.shtml

Supporting the development of crop-specific N-accounting methods that allow growers to evaluate their success in achieving high crop nitrogen use efficiency would be beneficial. An example of such a "nitrogen mass balance metric" is the ratio of the amount of N, from all sources, applied to a crop to the amount of N removed in the harvested crop. This serves in lieu of direct estimates of nitrate to the groundwater, which is extremely difficult to monitor at the individual farm or farm field scale.

Finally, additional promising actions include reviewing and further developing methods for identifying cropland areas that are at an increased risk or significantly vulnerable to nitrate leaching. Several methods have been used or are under consideration for doing this in California; some attention should be given to methods that can be used at the farm and county scale for on-farm applied research and technology transfer (outreach) activities. Such a method should include consideration of the spatial soil characteristics, as well as probable monitoring requirements.

Reducing Nitrate Leaching from Turfgrass in Urban Areas

Nitrate leaching from urban turfgrass including golf courses, is often negligible due to the dense plant canopy and perennial growth habit of turf, which results in continuous plant N uptake over a large portion of the year. Fertilizer N applied beyond plant need is often still taken up and utilized by the turf, increasing vegetative growth. However, poor management can lead to a discontinuous canopy and weed presence, wherein nitrate leaching risk increases, especially if growing on permeable soils, if over-irrigated, or if fertilized at high rates during dormant periods.   The best strategy to reduce leaching from turfgrass is to simply follow recommended guidelines for the rate and timing of fertilizer application along with proper water management techniques. The University of California Cooperative Extension (UCCE) and UC Integrated Pest Management (UCIPM) program publish such guidelines. The practice of keeping fertilization rates and timing concordant with plant need has the added benefit to professional turfgrass managers of requiring less frequent mowing and a reduction of the volume of clippings requiring disposal. The knowledge and willingness of homeowners and groundskeepers to apply university and industry guidelines is primarily dependent upon funding for outreach efforts.

Reducing Nitrate Leaching from Municipal Wastewater Treatment and Food Processing Plants

Discharges from municipal wastewater treatment and food processing facilities, while not as regionally significant a source of groundwater nitrate as agriculture, do have locally important impacts to groundwater quality. Implementation of N control options for these sources is feasible and could be an important part of a multi-pronged approach.

Cropland application of wastewater treatment and food processing effluents can both reduce direct groundwater contamination as well as reduce the total fertilizer application requirements of such fields as the water and nutrients are effectively treated and recycled. Such wastes should be managed in an agronomic manner, such that the nutrients (especially nitrogen) present in the wastes, are included in the overall nitrogen management plan for the receiving crops. Appropriate agronomic application practices should be used (especially with respect to application rate and timing). Biological and chemical treatment of these effluents can further reduce their impact on groundwater contamination. Which treatment option to employ depends upon the unique characteristics and limitations of the treatment plants. Costs of biological treatment options likewise vary widely; estimated capital costs for nutrient removal from all wastewater (FPs and WWTPs) for facilities categorized as “at-risk” range from $70 to $266 million depending on if the project is a retrofit or an expansion (associated operations and maintenance costs range from $3.2 - $20 million).

Optimizing wastewater treatment plant and food processing plant operations is another important consideration; limiting nitrogen and total discharge volume through in-plant process modifications may be sufficient for some facilities. Groundwater monitoring is required for many facilities, but the data are largely unavailable since they are not in a digital format. To improve monitoring, enforcement, and abatement efforts related to these facilities, groundwater data need to be more centrally managed and organized digitally.

Reducing Nitrate Contributions from Leaking Sewer Pipes and Septic Systems

Retrofitting of septic system components and sewer pipes represents the main avenue of diminishing loading from these sources. To reduce risks to human health, it is important to replace aging sewer system infrastructure and to ensure proper maintenance; necessary infrastructure upgrades will also reduce N leaching from leaking pipes. Our investigation of pipe-replacement costs indicate that the selection of pipe material is the cost determining factor, ranging from $7 - $55 per linear foot.

Loading from septic systems, a locally significant N source, can be reduced significantly by two approaches. Source separation technology, in which urine (representing approximately 80% of the total N in human waste) is removed from the waste stream and reused as a fertilizer, can be expected to reduce nitrate loading to onsite wastewater treatment systems by about 50%. Costs include separating toilets ($300 - $1100), dual plumbing systems ($2000 - $15,000), as well as storage tank costs, maintenance, pumping, heating, and transport costs (where applicable). The other option, post-septic tank biological nitrification and denitrification treatment, reduces N concentrations below levels achieved via source separation technology, but does not result in a reusable resource. Wood chip bioreactors have been shown to reduce influent nitrate by 74 – 91%, with costs ranging from $10,000 - $20,000 to retrofit existing septic systems.

Reducing Nitrate Transfer and Loading from Wells

Local or state programs and funding to identify and properly destroy abandoned and dry wells is needed to avoid their behaving as nitrate transfer conduits. However, it is also clear that many well owners may not be able to afford the high costs of retrofitting long-screened wells to seal contaminated groundwater horizons. As such we advocate that enforcement of proper well-construction standards for future wells may be more feasible and that expenditures on retrofitting of existing wells should be selected based on individual contamination risks.

1 Introduction

This report provides an assessment of the currently available technologies and management approaches for minimizing nitrate leaching from irrigated croplands and livestock facilities, turfgrass and other urban landscaping, wastewater treatment plants, food processing plants, sewers, septic systems, and wells. The assessment includes descriptions of the management measures, technologies and infrastructure upgrades that are available for reducing the load from these sources, and, where possible, their costs. Additionally, for cropland, barriers to expanded adoption by farmers of improved management practices are described.

Among the sources of nitrate analyzed in this report, irrigated cropland and livestock operations have the largest footprint and account for a much greater proportion of N in the environment than other sources (see Technical Report 2, Viers et al. 2012). Croplands represent a nonpoint N source, and in many instances there is a long delay – years to decades – between the initial escape of nitrate from the crop rootzone or other land surface, and the appearance of nitrate in drinking water wells. In Section 2 of this report, we provide a detailed overview (and a concise summary in Section 2.4) of management measures that are known to reduce the level of nitrate leaching to groundwater from crop fields. The report includes an estimate of the proportion of irrigated crop acreage within the study areas for which mitigation measures are likely to have the largest impact. This vulnerability estimate is based on soil properties, crop species, and irrigation system type, and does not consider underlying hydrology or whether farmers may have already adopted improved management measures and technologies.

Livestock, especially dairies, contribute significantly to the overall nitrate load in the Tulare Lake Basin (TLB). Because the animal waste is applied to croplands as a fertilizer and soil amendment, manure management is considered in tandem with inorganic N management in Section 2 of this report, along with proper storage and handling prior to cropland application. Regulations aimed at reducing nitrate discharges to groundwater were imposed on all dairies in the Central Valley in 2007 (Central Valley Regional Water Quality Control Board 2007). The regulations include animal housing, manure storage facilities, and dairy farm crop fields that receive manure. Croplands not associated with dairies (whether receiving manure or not) are not currently regulated for nitrate discharges to groundwater.

In Section 3, the cost of mitigation measures for irrigated crop production is evaluated by use of an agro-economic model. The model is based on the assumption that technologies are available to farmers that individually or in combination can be used to make modest improvements in crop nitrogen use efficiency. Very general assumptions are made about the likely management and equipment costs of such measures and the offsetting savings due to lower fertilizer use. Section 4 provides a brief overview of ornamental landscaping and turfgrass management options that minimize leaching losses from these areas.

Section 5 outlines nitrate loading from urban and domestic wastewater, sewers, and septic systems, all of which tend to have less regional impact but important local consequences. We discuss the infrastructure upgrades and improved technical standards necessary to reduce loading from these sources. Costs and overall feasibility are included for each option, which tend to vary widely. In section 6, we examine how to reduce the contributions to aquifer nitrate contamination from wells, and the financial feasibility of the options available to address this source.

Finally, the Conclusions in Section 7 summarize the findings and promising actions concerning reduction of nitrate leaching from all of the above sources, as outlined in this report.

2 Reducing Agricultural Nitrate Loading

Prepared by:

Kristin N. Dzurella, G. Stuart Pettygrove, Anna Fryjoff-Hung, Allan D. Hollander

Acknowledgments

The authors would like to thank Dr. Todd Rosenstock for the use of his literature repository and Ria DeBiase for her assistance in literature screening. We are grateful for the review, clarifications and input provided by Dr. Timothy Hartz and Dr. John Letey. We are especially appreciative of the expert panel participants listed here for their very helpful advice and for their review of the agricultural management practices contained in this report. These individuals (and their employers) are not responsible for and may not agree with all of the report's findings, conclusions, and recommendations, which are solely the responsibility of the authors. This work was funded by the State Water Resources Control Board under agreement number 09-122-250.

Salinas Valley Vegetable Crop Panel:
Tim Borel
Michael Cahn
Eric Overeem
Richard Smith
Larry Tokiwa
Joel Wiley

Tulare Lake Basin Vegetable Crop Panel:
Joe Fabry
Bret Ferguson
Ceil Howe III
Gary Jorgensen
Michelle LeStrange
Dick Newton
Kurt Quade
Scott Stoddard

Forage Crops Receiving Manure Panel:
Tom Barcellos
Jamie Bledsoe
Carol Frate
Armando Leal
Shannon Mueller
Ben Nydam
Blake Wilbur

Tree Fruit and Nut Panel:
Keith Backman
Robert H. Beede
Tom Coleman
Kevin Day
Alan Scroggs
Jim White

Field/Agronomic Crop Panel:
Vern Crawford
John Diener
Nick Groenenberg
Clay Houchin
Michael Larkin
Blake Sanden
Greg Wegis
Steve Wright

2.1 Introduction

Crop production represents the largest source of groundwater nitrate in the study areas, while also playing an important role in recycling waste from urban areas, food processing, and most importantly, animal production. Livestock waste (especially dairy manure), a key source of the agricultural nitrate footprint, is primarily disposed of by application to croplands as a fertilizer and soil amendment. For this reason, manure is considered within the context of crop production, in addition to proper handling and storage prior to land application in this report.

A highly important industry, both economically and socially, crop production in California requires inputs of irrigation water and nitrogen. Nitrogen use efficiency (NUE) is dependent upon the management of both of these inputs. NUE, sometimes referred to as partial nitrogen balance (PNB), refers to the percentage of N applied to cropland (from all sources) that is recovered by the crop and therefore is not lost to the atmosphere or to surface and groundwater. As such, high NUE reduces losses to leaching while reducing unnecessary costs to the producer. Due to unavoidable N losses, complete crop recovery of all applied inputs is impossible to sustain. Our approach in this report is to identify and describe practices and technologies that are potentially available to growers for achieving high crop N use efficiencies, and for reducing, but not eliminating, nitrate leaching to the groundwater from cropped land. Although NUE as low as 33% crop recovery of N inputs has been reported, a recent U.S. EPA report estimated that with the adoption of best management practices, NUE could increase by up to 25% of current average values (U.S. EPA Science Advisory Board 2011).

In California’s semi-arid climate, avoiding accumulation of salt in the crop rootzone requires some movement of water downward past the crop roots to leach the plant-toxic salts. Winter rains contribute to fulfilling this need but in low-rainfall years and in areas of reduced precipitation, such as the San Joaquin Valley, irrigation volumes applied must include water in excess of the evapotranspiration requirement (ET). With the leaching salt, any soluble nitrate present will likewise travel downward with the water, and once beyond the rootzone where it will no longer be available for plant uptake, the majority will make its way to groundwater. Efficient and uniformly distributed irrigation water is therefore a critical component of NUE, although ideal efficiency and uniformity are not possible due to spatial variability in soils (texture, water holding capacity, permeability, etc.) and the practical limits of the various irrigation systems available to growers.

The second component of maximizing NUE is to provide a plant-available form of N only at times and amounts required by the crop. Avoiding a large surplus of N in the soil at times of low crop demand or in excess of plant growth requirements is paramount to reduced leaching. While it is not possible to produce crops while maintaining zero soil nitrate and thus it is not possible to achieve zero leaching of nitrate, management measures are available that can contribute to optimization of NUE. Crop nitrogen and irrigation system design and management techniques that can help maximize crop N recovery (thereby limiting leaching losses) are well known. A selection of these practices is described in Section 2.3 of this report. Not all practices are appropriate or practically feasible for all farms and tandem use of a suite of practices is often required to significantly affect NUE.

Due to the typically long delay between the initial escape of the nitrate from the crop root zone and its appearance in groundwater, and the nature of croplands as a non-point source, it is not possible to provide quantitative estimates of the degree of reduction in loading that would result from adoption of any particular practice or combinations of practices. This is, in part, due to lack of survey data on the current use of many recommended practices and a lack of definitive information on how management practices have changed over time. Additionally, it is very difficult to relate increased adoption of a practice (such as nitrate soil testing) to a quantitative reduction in nitrate leaching, and the studies that do so are sparse and variable. Again, depending on the unique field situation (i.e., soil characteristics, crop type, and irrigation system, etc.), the effect a practice has on nitrate leaching will vary. It is clear that to significantly reduce leaching, adoption of a suite of improved management practices is the most effective and that the choice of which bundle of practices to adopt will always be field specific.

A detailed presentation of farm management practices follows the Methodology in Section 2.3. After introduction of an individual management measure, recommended practices to achieve the measure follow. Individual practices are briefly described, including an outline of how they contribute to crop NUE and estimation of the current use within the study area, and conclude with a discussion of the barriers to their expanded adoption.

A summary of the management measures and recommended practices follows in Section 2.4 emphasizing their current extent of use in the study areas while highlighting the barriers to increased adoption. In Section 2.5, examples of improved practice bundles that could be feasibly undertaken for specific crops, given specific barriers, are provided.

In Section 2.6, we illustrate the lack of a one-size-fits-all approach to farm management options, and how the selection of the appropriate suite of management practices will be highly variable and can only be attended to on a case by case basis. We provide a visualization of this variability within the study areas, and broadly identify the areas in which increased adoption of improved management practices may have the most effect. This was carried out by assessing the vulnerability of the study area fields to nitrate leaching using a Nitrate Hazard Index (Wu et al. 2005), based on each field’s specific combination of crop, soil, and irrigation system choice. As such, the areas identified as especially vulnerable are the areas in which improved management practices will have the largest effect on groundwater aquifers.

2.2 Methods

2.2.1 Approach to Identifying Potential Nitrate Reduction Strategies

Crop production practices with the potential to maximize plant N recovery and reduce nitrate loading to groundwater were identified and refined via literature review and expert panel input and consensus. The 1998 UCANR publication "Nitrogen and Water Management for Cool-Season Vegetables" written in response to the Coastal Zone Management Act, provided a starting point for identifying these practices. The literature review[3] and expert panels (see below) provided the opportunity to significantly expand and revise the listed management practices. Case studies show unequivocally that nitrate leachate reductions are possible with the adoption of improved farm management strategies (Gheysari et al. 2009). However, such studies do not cover the range of crop, soil, and irrigation system combinations represented in California's diverse agricultural landscape. To address this greater diversity, five expert panels were convened to discuss and refine the draft list of practices and to provide insight into the current state of farm management practices specific to the two study areas.

2.2.1.1 Expert Panels

The following five expert panels met to review and refine the draft list of suggested practices, estimate their current extent of use and identify the barriers to increased adoption:

1. Salinas Valley cool-season vegetable and strawberries
2. Woody perennials (vineyards, tree fruits, and nuts)
3. Agronomic/field crops not receiving dairy manure
4. Forage/silage crops receiving dairy manure
5. Tulare Lake Basin vegetables and other truck crops.

Panels were set up as 6 – 10 person roundtable discussions, including the project leader and support staff, two UC Cooperative Extension farm advisors, two to three growers, and two to three crop management professionals or other industry personnel (most of the latter being Certified Crop Advisors). UCCE advisors were chosen based on their expertise and experience with the specified crop group's nitrogen and water management regimes within the study areas. The 10 UCCE farm advisors recommended growers and allied industry members with extensive knowledge of, and experience with, the crops and management practices in the study areas. To promote frank discussion, panel meetings were not open to the public and all members agreed to maintain confidentiality.

Each participant was provided with a project background statement and was asked to complete a detailed survey covering the draft list of practices. The survey asked panel members to rate each practice for mitigative potential and its current extent of use within the crop group and study area basin.

---

[3] Dr. Todd Rosenstock, of the California Nitrogen Assessment project, provided us a large repository of literature that we used in conjunction with our own.

A numerical summary of the results of these questionnaires was distributed at each panel meeting and was used to guide discussion and identify areas of consensus and disagreement. For practices identified as having high mitigative potential, panel members were asked to identify the main constraints or barriers to expanded adoption.

2.2.2 Crop Management Practice Scenarios

Managing nitrate leaching generally requires a tandem application of various mitigating practices (Power et al. 2001). Selection of suitable management practice suites will depend on the unique farm situation, requiring site-specific consideration of field variables such as crop and crop rotation practices, irrigation and management constraints, and soil and climate characteristics (Tilman et al. 2002; Fixen 2011).

Although some general farm management measures are important and generally applicable for all farm operations in terms of reducing the potential for nitrate leaching (e.g., improving irrigation efficiency), the specific practices used to implement these goals will change depending on the unique situation. For example, for grain production, converting to drip irrigation is not economically feasible; however, it may be possible to improve uniformity of existing surface gravity or sprinkler systems. In contrast, for production of many vegetables, irrigation with sprinklers beyond initial establishment may increase susceptibility to disease due to wetting of foliage and conversion to drip irrigation may be financially more feasible.

Examples of practice “bundles” that might be adopted to improve nitrogen use efficiency are presented as possible management change scenarios restrictive to a unique set of conditions. Six crops were selected to serve as these examples. These crops represent the major crop categories important to the two study areas (cool season vegetables, valley vegetables, field crops, silage crops, and permanent crops). For each selected crop or crop rotation, a bundle of feasible management practices was chosen based on literature reviews specific to that crop and expert panel input. For each scenario, potential barriers to adoption (e.g., high costs) are described.

2.2.3 Leaching Vulnerability Assessment

It is unlikely that any one set of farming practices would be effective in improving crop nitrogen use efficiency on all crop acres in the study area. It is also unlikely that mitigative measures are even needed on all cropped acres. For example, deep-rooted crop species grown on less permeable soils will be less likely to generate nitrate leaching when farmed with typical methods. In contrast, crops such as spinach, a shallow rooted species often grown on permeable loams, with a peak N uptake at the time of harvest, is more likely to generate nitrate leaching. In this situation more intense employment of effective management techniques will be justified.

We used a Nitrate Hazard Index (HI) developed in 2005 by the UC Water Resources Center to identify, at the scale of individual fields, the nitrate leaching risk based solely on soil, crop species, and irrigation system type (Wu et al. 2005). Crop and irrigation types were identified using the most recent DWR land use maps for the five counties (Monterey 1997, Tulare 1999, Fresno 2000, Kings 2003, Kern 2006), and the Soil Survey Geographic (SSURGO) database (USDA NRCS). The HI was used to evaluate the area (at the time of the DWR surveys) where utilization of improved practices may have the most impact on nitrate leaching and where improved nitrogen and water use efficiency need special attention. The most important caveat to consider is that the DWR surveys represent only a “snapshot in time,” that is, a one-time survey (generally in the summer) carried out as far back as 1997. As such, the overall pattern of risk is not reflective of current cropping systems, current irrigation system type, annual crop rotations, or associated irrigation system rotations. For example, drip irrigated vegetable fields may be rotated with similar vegetables in the winter months, or with furrow irrigated wheat; these rotational factors affect overall risk and cannot be spatially analyzed.

Spatially, agricultural nitrogen inputs do not correlate well with groundwater nitrate concentrations (U.S. Geological Survey 1999). Farm management practices heavily influence the fate of applied N, but equally important are the innate soil attributes, crop characteristics, and method of water delivery. Consideration of these three field-specific components can then provide guidance on the suitability of various management practices to the unique farm situation and indicate how much attention to reduced nitrate leaching strategies is warranted.

2.2.3.1 Nitrate Groundwater Pollution Hazard Index

In 1994, the California State Water Resources Control Board (State Water Board) appointed a Nutrient Technical Advisory Committee (TAC) to assess water quality problems associated with agriculture and make suggestions for addressing such issues (Irrigated Agriculture Technical Advisory Committee 1994; Wu et al. 2005). A hazard indexing methodology was conceptualized in which growers could identify field nitrate leaching vulnerabilities based on the soil characteristics, the crop grown, and the irrigation system utilized. An index or ranking method, such as this, allows for a way to quickly and easily determine risk severity and identify the major factors contributing to this risk, without requiring the large data set needed for more involved indexing methods (see for example Delgado et al. 2008) or modeling-based vulnerability assessments. The TAC suggested that growers with fields that scored high, in terms of nitrate leaching risk, should then be required to complete nutrient management plans.

The UC Center for Water Resources proceeded with this work, developing the matrix-based (overlay and index method) Nitrate Groundwater Pollution Hazard Index (HI) for irrigated agriculture (Wu et al. 2005) and making it available online to the public.[4] This online tool borrowed and built upon the conceptual framework of the TAC, assigning soil series, crop types, and irrigation systems individual leaching risk values through consideration of multiple factors by expert collaboration. Index values proposed for soils, crops, and irrigation systems were then subjected to external review by experts.

According to this HI system, soils are allocated a scale rating of 1 (low risk of nitrate leaching) to 5 (high risk) based on denitrification potential and water infiltration and transmission rates. NRCS soil series

---

[4] http://ucanr.org/sites/wrc/Programs/Water_Quality/Nitrate_Groundwater_Pollution_Hazard_Index/

descriptions were utilized by the developers of the HI to compile these values, with attention focused on the soil's drainage and permeability characteristics including typical pedon texture, restrictive layers, and evidence of mottles, (indicators of poor aeration). Additionally considered are color changes, depth to restrictive layers, degree of hardness, and organic matter content. For example, the Hanford series is a deep and well drained sandy loam with low organic matter content, moderately rapid permeability, and a lack of mottles or restrictive layer and is thus rated 5 (i.e., of the highest risk). The Cropley series on the other hand, is given a rating of 2; although moderately well drained, it has a clay to clay loam texture, light mottles with iron deposits, and a slow permeability. Note that the online HI allows users to include deep ripping as an option, which results in a decrease in the soil HI component. Deep ripping is a form of deep tillage that can improve drainage of soils having hardpan layers. It is commonly used to prepare land for planting of trees or vines. We could not assign this component in our analysis, although it is an available option in the online tool. In most situations, the addition of this factor does not move the overall hazard rating from one of low risk to high.

Soil series were extracted from a statewide layer produced by the local USDA-NRCS office that amalgamated the county-level SSURGO soils maps and assigned the dominant soil series by proportion to each map polygon. These polygons were then filtered by selecting only those that intersected irrigated agriculture. For any soil series of high area not found in the online HI tool, soil properties described in NRCS soil surveys were compared to the criterion described in Wu et al. (2005), and HI values assigned by a soil scientist. Fields of undefined soil series of very small area within the study area were excluded from the analysis.

The crops and irrigation components of the HI each range from 1 (low risk) to 4 (high risk). Crop rating is based on rooting depth, overall N requirements, how closely peak demand for N coincides with harvest, the ratios of N uptake and harvest removal to suggested N application rates, denitrification inherent to the crop, and, for permanent crops (trees and vines), whether leaf material is typically removed (i.e., if N stored in dropped leaves is available for subsequent crops). For example, lettuce, a shallow rooted annual that demands high N levels particularly just prior to harvest, is rated a 4 and considered high risk. Conversely, vineyards are considered a low risk crop and rated 1, due to their deep roots and generally low N requirements, among other factors.

In the case of irrigation systems, TAC suggestions were followed by the HI developers (with an updated scale from 1 to 4) wherein fertigation; environmental influence on water delivery; and the level of water application control and precision afforded the manager are considered. In all cases it was assumed that the system would be operating at maximum potential, in that application uniformity is not decreased by poorly maintained or faulty systems. Per the developers of the HI (Wu et al. 2005), fertigated drip and microirrigation are given a rating of 1 (2 without fertigation, a rare case), sprinklers without fertigation are rated a 3 (2 with fertigation, also rare), and all methods of surface irrigation are assigned a rating of 4.

In our irrigation analysis however, we deviated from these values slightly. An important caveat is that most drip irrigated annuals are germinated under sprinklers, a higher risk system due to the effects wind and design flaws can have on uniformity. Fields are especially vulnerable to leaching during crop establishment due to the need to keep the seed bed (or transplant area) evenly moist at all times (to avoid risk of plant failure) via frequent irrigation events, coupled with the scarcity of plant roots to utilize any soil nitrate present at this time. The HI online tool does not differentiate mixed irrigation systems and designates fields pre-irrigated and germinated via sprinkler as the same risk as season-long micro- irrigation, as used for tree crops (HI 1). For our assessment however, we rated drip irrigated annual crops, which are germinated with sprinklers, to have an HI of 2. Based on feedback from experts, we considered an HI of 1 to be too low, ignoring the high risk of excessive pre-plant and germination sprinkler irrigation during times of low plant need. For example, Vázquez et al. (2005) showed that the greatest leaching losses occurred during crop establishment in drip irrigated tomatoes. For the spatial assessment it was necessary to assume that all drip irrigated annual fields were sprinkler established and designating the irrigation component value of 2. Similarly the spatial assessment required assumptions that all micro-irrigated crops are fertigated, while also assuming no fertigation for crops sprinkler irrigated through harvest.

The composite HI values, ranging from 1 to 80 (lowest to high risk) were produced by multiplying all three factor values (soil, crop, and irrigation) using an index matrix as shown in Figure 1. The authors of the HI proposed that fields identified as having an overall index below 20 are of low concern and that average management practices are usually adequate. As such, although continued vigilance is necessary for all fields, attention to optimizing NUE via good management practices is best focused in areas with greater risk for leaching. Any value over 20 is indicated as being cause for such concern, where adoption of more stringent management practices is paramount. The authors of the HI caution that comparing an HI value of 40 with 60, for example, is not especially useful, and that anything over 20 should be of equally high concern. More importantly, the HI can guide management improvement options by identifying the factors that contribute most to the high value. For example, if carrots (HI 2) are being grown on the high risk Hanford series (HI 5) and sprinkler irrigated (HI 3), it is clear that reducing risk on this field will need to be focused on tight irrigation management to optimize the system and match the rapid soil drainage characteristics. On the other hand, a high risk crop, such as broccoli, might be grown on a low risk soil with drip irrigation after being established with sprinklers. In this case, the high N levels required and the relatively high residuals left after harvest contribute the most to the risk value and incorporating a cover crop to scavenge residual N may represent a good choice for reducing risk in such a situation. For

	Soil					
Crop	1	2	3	4	5	Irrigation
1	1	2	3	4	5	1
1	2	4	6	8	10	2
1	3	6	9	12	15	3
1	4	8	12	16	20	4
2	2	4	6	8	10	1
2	4	8	12	16	20	2
2	6	12	18	24	30	3
2	8	16	24	32	40	4
3	3	6	9	12	15	1
3	6	12	18	24	30	2
3	9	18	27	36	45	3
3	12	24	36	48	60	4
4	4	8	12	16	20	1
4	8	16	24	32	40	2
4	12	24	36	48	60	3
4	16	32	48	64	80	4

Figure 1. The UC Nitrate Hazard Index multiplicative matrix with highly vulnerable situations highlighted in yellow (adapted from We et al. 2005)

the spatial analysis, the overall HI map was created by intersecting the soil HI polygon layer with the DWR polygon layer containing both crop and irrigation HI information.

There are important assumptions and caveats associated with the overall HI results. DWR surveys represent a single period in the year. Although information regarding double cropping is provided with most of these reports, it is only possible to spatially assign a single crop per field per layer, meaning that the resulting map is a “snapshot” in time. DWR surveys are repeated approximately every seven years, and the year of the most recent report for each county varied (Tulare 1999, Fresno 2000, Kings 2003, Kern 2006). Similarly, the time of year during which these surveys were carried out varied, but generally are confined to the summer months of June through September. Therefore, our evaluation of HI is skewed toward summer crop representation where, for example, cool season crops and winter fallow periods cannot be visualized simultaneously with the crops grown during the summer surveys. Likewise, irrigation system choice has evolved rapidly over the past 10-20 years, notably the increased adoption of drip and microsprinkler systems, reduction of surface gravity irrigated vegetable and permanent crops, and changes in impact sprinkler methods.

Similarly, crop production trends have changed since some of these surveys took place. For example, sugarbeets in the TLB are heavily overestimated in the DWR data (over 7,000 hectares reported, but near zero coverage currently remaining) due to the closure of one the last remaining processing facility in the state since the time of the surveys. These fields have likely been converted to higher risk species, given that sugarbeets are one of the few species with an HI rating of 1, and thus driving overall HI values up. Likewise, strawberry acreage in the Salinas Valley (SV) has increased substantially since the 1997 Monterey County survey date, due to strong financial incentives. In general, it is important to keep in mind when reviewing our results, that the agricultural landscape is very dynamic and has changed since these summer surveys were carried out between 1999 and 2006.

To simplify the crop HI map, some crops produced on very small acreages were grouped with crops of different HI values, but this was rare and restricted to very low acreage species. For example, olive trees, which are rated 1, were placed in the “orchard” category, where nearly all other tree crops are rated 2. In this case the olives represent only 2% of the total orchard area and thus, this and other similar crops were kept within the orchard group, rated HI 2 for the purposes of mapping (HI 1 figs and apricots, HI 3 grapefruit and kiwis, were also categorized with other HI 2 orchard species). Nearly all field, grain, and hay crops are rated HI 2, and the small area of dry beans and sudangrass (both rated HI 1) were kept in this category, while a separate category was created for the high acreage, HI 1 alfalfa, as well as HI 3 corn. Note that these groupings were only used to construct the *crop* HI analysis and map (Figure 6) and the actual (ungrouped) crop HI values were used to calculate the overall composite HI of each field, as displayed in the *overall* HI map (Figure 9). Vegetables were separated into those with HI values of 3 versus those of highest risk (HI 4). A small category was designated for lower risk vegetables consisting of carrots (HI 2) and the now extinct sugarbeet (HI 1) area.[5] Certain irrigated fields of very low

---

[5] Also included in this mixed HI 1-2 category were sweet potato, bush berry, and rice fields which collectively represent less than 0.01% of the study area acreage.

acreage that do not fit into any crop HI designation were not included in the HI analysis. These include turf farms, pasture, eucalyptus and Christmas tree plantations, and nursery operations.

For the four San Joaquin Valley counties, the DWR crop reports also include spatial irrigation system type for the same land parcels and years. The DWR surveys of individual fields for Monterey County did not include irrigation data. Although it is not realistic to assume that the same irrigation type is used for any one crop species, by choosing the method used for a majority of each crop, a spatial analysis could be performed for the Salinas Valley. To develop irrigation system type for individual fields, we relied on (a) expert panel estimates of the percent of crops irrigated by each method, and (b) the most recent county Ground Water Summary Report (MCWRA 2011), which summarizes irrigation methods used in portions of the Salinas Valley. Based on these sources of information, we assigned all field and grain crops to surface irrigation, and all tree crops (reported to be >70% citrus and >15% walnuts) and vines (nearly all winegrapes) to microsprinkler irrigation.   Although drip irrigation is common in SV vegetables, the degree of uncertainty is wide. It is estimated that 50 – 70% of the vegetables (including strawberries) are currently drip irrigated, with the bulk of the rest furrow irrigated or sprinkler irrigated throughout the season. However, because there is no way of distributing such percent estimates for drip irrigation spatially, for purposes of our analysis, we assigned drip irrigation to all vegetable and strawberry acres in the Salinas Valley. This important caveat implies an underestimation of the area with high risk potential (HI>20) in the SV.

Note also that irrigation system choice has evolved rapidly over the past 10-20 years, notably the increased adoption of drip and microsprinkler systems, reduction of surface gravity irrigated vegetable and permanent crops, and changes in impact sprinkler methods. While the area of drip irrigated vegetables in the SV is overestimated in our analysis, there is some underestimation in the TLB, due to the much higher use of microirrigation in vegetables and permanent crops since the original surveys were carried out.

2.3 Management Measures (MM) and Recommended Practices (RP) for Reducing Movement of Nitrate to Groundwater from Crop Operations

While the complete elimination of agricultural nitrate loading to groundwater is not possible, adoption of improved farming management practices can help to mitigate this concern (Esser et al. 2002; Gheysari et al. 2009). The practices provided below hold some promise of contributing to the goal of reducing agricultural nitrate leaching losses and maximizing crop recovery of N inputs.

Management measures (MMs) described herein represent technologies or processes for reducing nitrate leaching to groundwater. Note that this report does not cover greenhouse and nursery production practices (refer instead to Newman 2008). After exploring the literature and conferring with members of the expert panels, a total of 10 of these measures with mitigative potential were identified. A total of 50 recommended practices (RPs) for achieving these management measure goals are reviewed in depth. All measures and practices fall into one of four categories:

1) Design and operate irrigation and drainage systems to reduce deep percolation
2) Manage crop plants to capture more N and decrease deep percolation
3) Manage N fertilizer and manure to increase crop N use efficiency
4) Improve storage and handling of fertilizers and manure to decrease off-target discharge[6]

For each category, a narrative description of the associated management measures and their accompanying practices follows. Practice descriptions refer to the literature in terms of mitigative potential and summarize panel findings, including an assessment of the extent of current use and, if promising in terms of mitigation, discussion of what barriers may be preventing more widespread adoption of the practice, follows. Although cost savings can often be realized with more efficient use of nitrogen and water, the barriers considered here include:

- Real or perceived risks to crop yield or quality
- Capital costs (infrastructure, equipment)
- Operating cost (labor, management, training needs, energy, physical inputs, etc.)
- Ranch logistics barriers
- Land tenure constraints
- Grower education, training, or demonstrations needed to speed technology transfer
- Insufficient adaptation of technology to local conditions

---

[6] Note that besides these categories, poor stand uniformity and N use efficiency can be affected by various factors including salinity, pests and diseases, non-N deficiencies, and soil chemical problems. Addressing these concerns is a common practice among growers but is clearly a critical component of maximizing crop N recovery.

The expanded narrative of the mitigative management measures follows the outline presented in Table 1 below. A suite of improved management practices, adopted in tandem, will usually be the most effective approach. Note that the mitigative potential of a practice will vary between individual fields depending on site-specific soil, irrigation and crop variables (Tilman et al. 2002; Fixen 2011). Thus, while the most effective suite of specific practices will be field specific, each of the four basic principles and management measures (depending on irrigation type) are universally applicable to irrigated fields. See Section 2.4 for a condensed review of the use and barriers of each practice specific to the study area.

Table 1. Agricultural management measures that can increase nitrogen use efficiency and decrease nitrate leaching to groundwater, including the number of described practices used to achieve each measure.

Basic Component	Management Measure	Number of Recommended Practices Described
Design and operate irrigation and drainage systems to decrease deep percolation	MM 1. Perform irrigation system evaluation and monitoring	3
	MM 2. Improve Irrigation scheduling	4
	MM 3. Improve surface gravity system design and operation	6
	MM 4. Improve sprinkler system design and operation	5
	MM 5. Improve micro-irrigation system design and operation	2
	MM 6. Make other irrigation infrastructure improvements	2
Manage crop plants to capture more N and decrease deep percolation	MM 7. Modify crop rotation	4
Manage N fertilizer and manure to increase crop N use efficiency	MM 8. Improve rate, timing, placement of N fertilizers	9
	MM 9. Improve rate, timing, placement of animal manure applications	6
Improve storage and handling of fertilizer materials and manure to decrease off-target discharges	MM 10. Avoid fertilizer material and manure spills during transport, storage and application	9
		Total: 50

2.3.1 Design and Operate Irrigation and Drainage Systems to Decrease Deep Percolation

Retention of soluble N within the root zone, where it is available for plant uptake, is achieved in part by good irrigation management. The amount of nitrate lost to leaching is related to the volume of water that percolates below the root zone, which in turn is related to the irrigation system performance (Letey et al. 1977; Allaire-Leung et al. 2001). Scheduling irrigation events such that the volume of applied water matches the crop water requirement (evapotranspiration or ET), and delivering water uniformly to the field, are both critical to increasing N use efficiency and reducing nitrate leaching. Non-uniform irrigation forces farmers to over-irrigate some parts of the field in order to ensure adequate delivery to the parts of the field receiving the least water.

For example, Pang et al. (1997) modeled expected nitrate leaching under various irrigation and fertilization regimes. Their models show that as irrigation uniformity decreases, leaching increases exponentially, even under lower and less optimal N application rates than would be encountered on functioning farms. Furthermore, N application rates that provided good yield under efficient irrigation were modeled to be too low under situations of inefficient irrigation uniformity, wherein excess water application in some areas of the field resulted in decreased yields as the water flushed the available N too quickly beyond the rootzone.

It is important to note that some extra water beyond ET must be applied for rootzone salinity control. This is particularly true in regions with very low rainfall (such as the southern San Joaquin Valley) and with very tightly managed irrigation systems, such as drip irrigation. In such situations, farmers must apply extra water specifically to move salt out of the root zone, inevitably leading to some nitrate leaching along with the salts. As discussed in Section 2.3.3, aiming for reduced soil N levels at times of low crop demand, when intentionally irrigating to leach salts, or during the winter rainy season can help to minimize the concern of concurrent nitrate leaching during salt management activities (Hanson & May 2011).

Maximizing distribution uniformity is complicated by the spatial variability of soil texture and permeability within a field or operation, as soil drainage characteristics affect retention and loss of available N within and beyond the rootzone (Letey et al. 1977; Goldhamer & Peterson 1984; Williams & Kissel 1991; Hanson et al.; 1998; Khosla et al. 2002). Such attributes are generally not easily alterable by the manager. In some situations however, it can be economically worthwhile to attempt manipulation of natural soil variability. Panel members brought up several examples of such manipulations. Draining of the marshy soils in Northwestern Monterey County increases aeration and, in turn, plant productivity; the installation of subsurface drains in such soils has proven to have beneficial economic consequences in terms of yield and diversification of potential crop palettes. Note that although the tile drains dramatically reduce levels of nitrate entering the groundwater, the drain effluent is then flushed into surface waters. Impacts of this diversion on surface water quality and the ecosystems associated with the Salinas River, Elkhorn Slough, and the Monterey Bay are cause of major environmental concern (see Section 2.3.1, MM 6 for further discussion of tile drains).

Another example of manipulation of soil variability is in row crops within the TLB. Many fields with highly variable alluvial sand deposits have had such sand spits removed and the fields regraded, allowing for more uniform drainage and water retention characteristics, and leading to increased water and nitrogen use efficiency. In both basins, it is not uncommon for field boundaries to have been reconfigured over the years to follow natural soil series boundaries more closely. Deep ripping, where underlying hardpans within the soil profile are broken up, is another example of a profitable practice aimed in part at increased water use efficiency, but especially at plant productivity, via changes to the soil rather than manipulations of water delivery systems, water application rates, or timing.

A variety of different irrigation system types (i.e., surface, sprinkler, and micro systems) and subtypes exist (e.g., basin, furrow, etc.), all with their own inherent maximum efficiencies and uniformities, assuming equal levels of management optimization. Determining which irrigation system is most suitable is guided by the crop type, soil type, water quality and availability, topography, and technological and economic considerations. Regarding water application, although perfect efficiency and perfect uniformity are not possible, their maximization can be attended to within the constraints of the existing system or by choosing to utilize systems that have, when operated correctly, higher efficiency thresholds.

Panel members estimated that the bulk of deciduous fresh market tree fruit as well as a very high proportion of field crops, such as grain and cotton, remain surface irrigated in the study area. Carrots, baby greens, and a still somewhat large proportion of onions and garlic were thought to be sprinkler irrigated throughout their lifecycle. The majority of the remaining direct seeded vegetables tend to be sprinkler irrigated during the early establishment period after which they are switched to drip or, to a lesser degree, surface irrigation for the remainder of their life cycles. Crop value and other economic concerns are the primary drivers behind the decision to install drip or microsprinkler irrigation systems. In recent years, a large proportion of acreage in processing tomatoes, leafy vegetables, strawberries, vineyards (especially winegrapes), citrus, and tree nuts have been converted from furrow or basin irrigation to drip and microsprinkler irrigation methods. In the SJV there is growing, yet still small, interest in mechanized sprinkler systems (center pivot and linear move) for some crops (see RP 3.6 for more information).

MM 1: Perform Irrigation System Evaluation and Monitoring

To meet the crop water requirement while minimizing deep percolation, the volume of water applied must be measured and application uniformity must be evaluated. Scheduling irrigation events to match the crop water requirement is difficult if the amount of water applied is not known or if water is applied to fields non-uniformly. Although slow or uneven water advance rate (in surface gravity irrigation systems), plugged lines or malfunctioning sprinkler heads provide visible cues to the need for maintenance, other symptoms of gradual efficiency decline can be slow to reveal themselves without periodic system evaluation. Over time, gradual loss of efficiency equates to potentially high levels of unnecessary nitrate leaching.

RP 1.1 Conduct irrigation system performance evaluation

Evaluation of system performance includes measurement of the volume of water applied to a field and the degree of uniformity of the application. Where water is inexpensive or where crop value is low, growers are less likely to carry out such evaluations. Where water is expensive, they are more likely to do so. This practice alone does not necessarily lead a land owner or grower to make system improvements or to reduce deep percolation losses, but it does make it possible to identify the magnitude of inefficiencies and the potential for improvement.

Irrigation system evaluation is standard practice on some farms; but for others it is rarely or never done Panel members indicated that the practice of performance evaluations varies widely, with some operations maintaining peak performance as part of their standard operational procedures and others more or less oblivious to their system's inefficiencies. Consensus was that there indeed exists room for improvement in this arena, although several barriers preclude enhanced adoption.

Barriers to expanded use of this practice include the following: In surface gravity and sprinkler systems, evaluation is usually time consuming and complicated and therefore more appropriately carried out by consultants. Growers who receive their water supply from district canals or who produce relatively low value field crops may view performance assessment data as having little value, because they cannot easily change the amount of water applied, or they cannot afford to make the changes that would improve performance. Performance evaluation of drip and microsprinkler systems is generally undertaken more often by growers, as the functioning of these systems is more dependent upon regular maintenance.

Often irrigation system complexity, e.g., multiple sources (several wells and surface waters) feeding single fields on varying days with varying levels of soil type uniformity, presents a barrier in that understanding all individual components and their interactions within the system requires more expertise than is present on-farm. Educational and consultant costs can be prohibitive. The time and labor involved with performing and analyzing results often lacks economic incentive unless an obvious problem forces action. In the past, DWR and the USDA-NRCS, in cooperation with UC Cooperative Extension and/or local water management agencies, operated so-called Mobile Laboratories, which provided irrigation system evaluation and advice, free of charge, to individual growers. Funding and expanding and marketing such programs certainly holds promise to improve wise-use of farm water resources.

RP 1.2 Install and use flow meters or other measuring devices to track water volume applied to each field at each irrigation

Knowledge of the volume of water applied is the crucial first step in minimizing excess water applications and reducing leaching risk (Mosley & Fleming 2009). Although nominal pump capacity multiplied by operating time can provide an estimate of how much water is applied to a specific field, the actual rate at which water moves through the irrigation piping system may not equal the rate at which the pump is rated due to, e.g., total pressure head, impeller obstructions, etc. Thus, totalizing flow meters are considered the better method. Tracking water applications can identify potential problems associated with excess irrigation before they cause economic and environmental problems. Where water is expensive, flow meters are a financially sound investment. Knowledge of water flow and pressure are especially crucial in drip irrigation systems.

In the TLB, some crop consultants maintain records of irrigation water applications for their clients. Additionally, the water district and how they allot and price their water can influence use of flow meters. For those that do track their water flow with such devices, panel members indicated that it was primarily used more often as an accounting technique rather than one of long-term monitoring and irrigation management.

Barriers to the use of flow meters include equipment and installation costs. Also, there are technical limitations to flow metering. Inaccurate readings can result from pipes not being full at the time of reading, the influence of check valves and pipe turns, user errors in reading and use, or a faulty mechanism within the meter itself. Additionally, lack of understanding of water budget data and the complexity of evaluation (e.g., when fields are irrigated from multiple sources) can limit the usefulness of flow meters.

RP 1.3 Conduct pump performance tests

In non-pressurized (surface gravity) systems, deteriorating pump performance contributes to irrigation inefficiency. Pump performance tests are more important for these surface systems than for pressurized systems such as drip and sprinkler, where flow volume is controlled to some degree by emitter or nozzle characteristics. Although pump inefficiency will not affect water delivery rate in pressurized systems, it can lead to higher pumping cost. Salvaging the money lost to poor pump performance is thus an incentive for this practice.

Costs of these tests can sometimes present a barrier, although not in the case of those portions of the southern Central Valley serviced by Southern California Edison, which offers pump performance tests free of charge. The Center for Irrigation Technology at California State University Fresno, in collaboration with Pacific Gas & Electric, also offers reduced cost pump performance testing, education, and partial repair incentive rebates through the Advanced Pumping Efficiency Program (formerly the Agricultural Pumping Efficiency Program). When free or low cost, these tests are often preferred by growers over the more costly installation of flow meters. The availability of the Advanced Pumping Efficiency Program appears not to be well known, and the growers who do not know about this free and reduced cost testing are less likely to conduct pump performance tests.

MM 2: Improve Irrigation Scheduling

Scheduling irrigation timing and amounts to coincide with actual water needs, rather than by calendar date, is an important component of any good water management program. Synchronizing water and nutrient applications with crop needs reduces nitrate leaching (Meisinger & Delgado 2002; Gehl et al. 2005; Gheysari et al. 2009). To be effective, such scheduling does not only consist of evaluating current soil and crop water status, but also must include anticipating and forecasting future water needs (Martin et. al. 1991). Frequency will depend on the crop needs and their rooting depth, soil water holding capacity and drainage characteristics, and the specific irrigation system. Weather- and plant-based scheduling and soil moisture guidance can be used in tandem or independently to guide choices of when and how much water to apply. All have advantages and disadvantages and tandem use will enhance the overall predictive capacity. Optimal frequency of water application will be dictated by weather, crop characteristics, soil water holding capacity, and availability of water to the farmer. Good irrigation scheduling is important for all crops and soils, although it is especially critical when growing crops on sandy soils and with shallow rooted species.

In spite of years of effort by public agencies and universities to educate growers on the concepts of water budgeting and crop water use, calendar scheduling is still common, particularly in field and forage crops. This is due, in part, to tradition or lack of understanding, but in many instances, ranch logistics, labor, and water availability constrain the farmer's ability to adjust irrigation schedules. Inexpensive water in some areas and a lack of penalty for over-irrigating also promote poor scheduling, while expensive water districts are home to some of the study area's most efficient and conscientious irrigators. Growers who do not track their water use are often simply unaware water is being wasted. Panel members stressed the necessity of continuing education and that farmer access to irrigation specialists is critical to seeing a reduction in the typical dominance of calendar scheduling. NRCS and UCCE outreach has increased grower awareness and knowledge of the importance of good scheduling and the tools available to guide timing decisions, but continued outreach and intensity will be required to see increased use of advanced scheduling techniques.

RP 2.1 Use weather-based irrigation scheduling

Weather-based scheduling is based on crop evapotranspiration (ET) estimates calculated from recent weather data and normal-weather forecasts. The "reference ET" is then adjusted with a crop species specific factor that accounts for plant geometry. In California, a network of weather-stations, known as the California Irrigation Management Information System (CIMIS), provides crop ET estimations in real time via the internet to help growers schedule their water applications. Use of CIMIS technology is proven to increase water use efficiency (Hartz et al. 1994). In a SV lettuce trial, use of CIMIS during the germination and establishment phase led to a reduction in total water applied and reduced nitrate leaching losses (Smith & Cahn 2011).

Note that where the groundwater is shallow, CIMIS is generally not appropriate, as the method assumes that soil water changes between irrigations is equal to crop ET. This is not the case in shallow groundwater areas due to crops extracting some of their water from the perched groundwater (Hanson & Ayars 2002). Otherwise, irrigating to crop ET should be sufficient to meet salinity leaching fraction requirements. The occasional exception comes up in drip irrigated fields when winter and spring rainfall is low, where sprinkler irrigation may be needed to reduce salts during stand establishment (Hanson & May 2011).

Panel member commentary indicated that the use of CIMIS and weather-based scheduling was limited according to crop, crop management needs, user education, irrigation system type, and water district delivery constraints. Vegetable and tree fruit and nut producers tend to utilize ET data fairly regularly, whereas calendar scheduling remains common in field crop production. Although real-time ET/CIMIS data provides the most precise guidance, historical ET and weather data is more often utilized by growers. Historical data are readily available and do not require active access to CIMIS and adaptation for the specific crop from the reference ET using established crop coefficients.

Specific crops react to irrigation events in ways that complicate scheduling, requiring managerial attention beyond expected ET. For example, tree fruit yield and quality will be compromised without sufficient irrigation during their ripening process, driving growers to want to overcompensate, whereas nut crops are generally more tolerant of deficit irrigation in the late season. Ranch logistics can also present as a barrier, for example, needing to access the field to spray or cultivate can trump an optimized irrigation schedule. Labor schedules can also complicate irrigation scheduling, especially in surface irrigated systems.

Calculating crop coefficients demands specific knowledge that follows a learning curve, thus educational requirements were also cited by panel members as a possible barrier to increased use. For some crops, more research is required to determine their specific coefficients and corresponding ET. Water district delivery schedules often complicate the ability of growers to optimize their irrigation schedule. A tendency is to over-irrigate in the spring when ditch water is abundant, with poorer supply during the dry summer leading to deficit irrigation in some crops. Forage, silage, grain, and other field crop producers and their advisors agreed that calendar based irrigation scheduling was the more common practice in these crops due to logistics of harvest and field operations and the fact that gravity based systems simply do not allow the manager the option of manipulating how much water is applied in any one run.

In spite of these barriers, increased grower education, especially in terms of water budgeting, could boost utilization of weather-based scheduling techniques, in particular the increased use of real-time ET data. The greatest potential for this happening is in areas where water is expensive, although it is precisely in these areas where growers are already paying very close attention to water use efficiency.

RP 2.2 Use plant-based irrigation scheduling

In general, where weather and soil based scheduling can tell a grower *how much* to irrigate at any given time, plant-based methods can be a superior technique for determining plant water status and therefore are more precise guides to irrigation *timing* (Fulton et al. 2008). At its simplest, plant-based irrigation scheduling consists of the farmer observing plant appearance or condition in the field and identifying the first signs of stress. Stress however, tends to affect productivity before observable physical symptoms appear. In recent years, several ground-based and remote sensing techniques and instruments have become available for use in crop production.

Infrared thermometers detect plant canopy temperature increases when plants reduce their stomatal conductance in response to water stress. This technology has proven to be a useful scheduling tool in some crops and is associated with enhanced crop water use efficiency, and, when irrigations are automated based on such measurements, significant labor reduction (Peters & Evett 2008). The most widely used tissue water status method is the use of pressure chambers, or so called pressure bombs, used to approximate leaf water potential via the inverse relationship this has to the pressure needed to draw sap from a cut leaf stem. Although labor intensive, this method is a relatively commonly employed plant-based scheduling tool in tree crops and some field crops (Hanson & Ayars 2002). Pressure bombs are generally more labor intensive than infrared readings. Note that the reliability of both pressure bomb and infrared temperature techniques are affected by environmental factors such as fog and clouds. For a full overview of all plant-based methods see Jones (2004).

Barriers to plant-based scheduling are similar to those cited for weather-based scheduling, including irrigation system type, water availability and district delivery schedules that are more compatible with calendar scheduling, conflicts with various field operation needs, and other ranch logistics and complexity considerations. Precise technical skill is required of many plant-based scheduling tools and atmospheric differences can cause variability (when using pressure bombs) requiring a large sample pool which increases labor requirements. These tools are used by some tree crop, field, and vegetable producers or their hired irrigation schedulers in the study areas, although of all plant-based techniques, simple visual observation of plant status is the most utilized.

RP 2.3 Use soil moisture content to guide irrigation timing and amount

Tracking soil moisture levels can alert the producer to crop water need sooner than observable wilting and can aid irrigation scheduling. Keeping soil moisture at or within 20% of field capacity is ideal for most crops (Pettygrove et al. 1998). Manually checking soil moisture content with a shovel or soil sampling tube is a traditional farmer method for determining irrigation timing. For annual cropping systems, this is still the most important technique. Various instrumented or automated methods for measuring soil water status exist, including tensiometers, psychrometers, gravimetric (weighing) devices, and neutron probes. Such devices may be used in tandem with ET and plant-based irrigation scheduling methods. These devices are in use by some study area growers.

Although most instruments are relatively straightforward to use, are generally precise, and lend themselves well to automation, a limitation of using soil moisture content to guide irrigation timing is that soil moisture may vary greatly within a field due to heterogeneity of soil texture, crop condition, and water application during the previous irrigation, thus requiring multiple sensors to achieve an acceptable level of accuracy (Jones 2004). Growers may be reluctant to install such devices in row crop fields where they could be damaged by tractors and interfere with harvesting practices. Again, irrigation system, water and pipe availability, and other field requirements will sometimes limit flexibility and stand in the way of scheduling irrigations according to plant need, whether determined via ET, plant status, or soil moisture levels.

RP 2.4 Avoid heavy pre-plant or fallow irrigations

Studies have shown that nitrate leaching is high following fallow period irrigation events (Jackson et al. 1994; Cavero et al. 1999; Jackson 2000; Smith & Cahn 2011). Without adequate plant roots to take up available soil N during these times, any soil N present is potentially lost to leaching. For example, Di & Cameron (2002) report two studies wherein up to 95% of residual N was lost during rainy fallow periods following harvest of the cash crop. However, pre-plant and fallow period irrigations are often required to prepare the seedbed for planting and address salinity concerns (Hanson & Ayars 2002; Hanson & May 2011). Besides germination and salt control requirements, pre-plant irrigation is also sometimes used to encourage deep rooting (e.g., in cotton). Vázquez et al. (2005, 2006) found that the highest leaching losses in tomato fields occurred during the plant establishment phase. Jackson et al. (1994) found that the highest leaching occurred during the germination of the second lettuce crop of the season in the SV, due to the rapid decomposition of the first crop's residues, raising soil N to high levels at a time of little plant uptake. Soil characteristics and weather will influence the ability of farmers to adjust pre-plant irrigation. Note that leaching will not be high, even with heavy irrigations or rain events, if soil N is low during this time. Thus, for crops, soil types, and weather conditions that demand heavier pre-plant or fallow irrigations, focusing on minimizing soil N content during these time periods is critical (see RP's in MM 7, MM 8, and MM 9).

Panel members agreed that annual crop growers are becoming more aware that early establishment water needs are lower than what tradition may have held, although there is a legitimate risk of reduced germination and/or establishment should pre-plant irrigations not be sufficient. This risk was cited as the largest barrier, while emphasis was also given to the role that soil characteristics play in fallow period irrigation needs. Most panel members suggested that there was still room for improvement in reducing fallow period and early establishment water applications, although farmers would likely require more evidence of what is possible before risking crop establishment and yield potential. As such, fueling research and education should help increase adoption of this important management practice.

MM 3: Improve Surface Gravity System Design and Operation

Gravity irrigation systems, in which water flows directly across the soil surface, are traditionally the most utilized crop water irrigation type both in the state and in the study area, although there has been a steady decline in use of these surface systems as growers of some crops convert to drip or sprinkler systems. The comparatively lower capital and operating costs of surface gravity methods of irrigation are attractive to growers, and some crops (especially field and forage crops) and soil types are best served by surface systems in general. In these systems, enough water must be applied to advance the water to the end of the field and this usually limits the capacity for efficiency. The upper end of the field is often subject to deep percolation as the water slowly advances to the opposite field end. Irrigation uniformity is often degraded by long field lengths, uneven slopes, uneven soil compaction or surface roughness in furrow bottoms, and natural variations in soil texture and the soil water intake characteristics (Power et al. 2001).

Surface gravity systems, when operated near peak performance, deliver water at 70-85% efficiency (Hanson 1995). Improving water application efficiency through the practices listed below can reduce nitrate leaching.

RP 3.1 Convert to surge irrigation

In surge irrigation, also known as "bumping", the water is turned on and off as it advances down the furrow. After halting the water flow, water is then run into an alternate set of furrows where it is again turned off before reaching the end of the field. While the new set is watered, the original set of furrows drain. This switching between sets continues until the water has reached the end of the field in both sets. Because the first part of the field has already been wetted prior to the rest of the run, the infiltration is lower in these areas and water advances faster towards the areas that have not yet been saturated. As such, uniformity is increased and the total amount of water required to thoroughly wet the end of the field is decreased by up to 30-80% compared to conventional furrows (those that have not be torpedoed—see RP 3.4) (Coupal & Wilson 1990; Schepers et al. 1995; Power et al. 2001; Rodríguez et al. 2004; Schwankl & Frate 2004). Fertigating while utilizing surge irrigation can also increase N uniformity (Boldt et al. 1994). Advance inflow rates can be further minimized in furrows that have been compacted, as described in RP 3.4 (Yonts et al. 1996).

Although Hanson (1989) argues that the cost of surge irrigation equipment is relatively low and easy to implement on existing systems, panel members felt differently, citing equipment costs, labor costs, and logistics as representative of large barriers that may be difficult to overcome. This technique requires gated pipe and, ideally, automatic valves, both of which are an additional capital cost for farms that are not already equipped as such. Without gated pipe and surge valves, significant additional labor time is required to manually open and close valves. Most dairy grain, silage, and forage production fields do not lend themselves well to utilizing this technique, due to the costs involved, incompatible valves or gates, and bad experiences with malfunctioning equipment (Schwankl & Frate 2004).

RP 3.2 Use high flow rates initially, then cut back to finish off the irrigation

By pushing the water over the surface more quickly during the initial irrigation phase and reducing the subsequent advance rate, otherwise known as cut-back, it is possible to increase uniformity and application efficiency (Evans 1977; Hanson 1989; Mohammed et al. 2006). A constant flow rate from start to finish is the norm and displays reduced uniformity compared to the employment of cut-back methods.

Amongst panel members, the practice was not perceived to have substantial mitigative potential and most agreed that it was not a highly utilized method of irrigating. This is partially due to the expense of the extra labor required to manually operate the valves or the capital cost of automated technologies that would reduce labor costs. Coupal & Wilson (1990) found that this practice may only be economically viable if gated pipe were already in place, although this may depend on the value of the crop and water costs. This practice is usually unsuitable in furrows and provides greater advantage in border check irrigation systems which are commonly used for grain, silage corn, and other forages in the Tulare Lake Basin.

RP 3.3 Reduce irrigation run distances (i.e., field lengths) and decrease set times

Long field lengths are one of the primary reasons why higher efficiency cannot be met by surface irrigation systems. This is due to the minimum water application not being determined by crop needs, but rather by the amount needed to reach the end of the field. For example, if 8 inches of water are needed to reach the field end, but the crop has only used 5 inches of water since the last irrigation, some of the excess water applied (3 inches in our example) is sure to be lost below the rootzone. If the field is long, it could be cut in half where water set times should be reduced to match the reduced time required for the water to reach the of the field. This shorter field length and run-time would increase distribution uniformity and reduce overall water use, thereby increasing efficiency and reducing opportunity for leaching (Schwankl & Frate 2004). For example, Hanson (1989) showed that by splitting a 300 m field in half, subsurface drainage likewise decreased by 50 percent.

This practice removes significant land from production, reducing total farm yield, because it requires a supply ditch or pipe and tailwater ditch, as well as tractor turning areas for each of the shorter field sections. Additionally there is an expense for installation of new pipe. Members of the silage and manure-receiving crop panel agreed that even with the cost barrier, it still may be cheaper than, for example, switching to a mechanized center pivot system. However, overall, it is likely that, until there is a more substantial economic incentive, the practice will remain underutilized due to the loss of farming area and subsequently reduced productivity. Most fruit tree orchards in the TLB and SV vegetable fields are already short in length.

RP 3.4 Increase flow uniformity among furrows (e.g., by compacting furrows)

Improving the surface uniformity among furrows necessarily improves water distribution uniformity. Tractors can pull behind them heavy tubes (torpedoes), wheels, or balls (bolas) for the purpose of smoothing furrow bottoms to achieve a more rapid water advance rate. (Schwankl et al. 1992) showed that torpedoes increased water advance rates by 15 to 30% compared to non-torpedoed furrows. Such compaction practices have been shown to reduce water application and overall leaching risk (Musick et al. 1985; Schwankl & Frate 2004).

Panel members agreed that there is currently moderate use of such equipment amongst growers utilizing furrow irrigation. To see increased adoption, some members suggested that growers would need more convincing that the practice would be worth it in their particular situation in terms of crop, soil, and field length. The practice is not helpful, for example, in cracking clay soils, and is likely unnecessary in short fields. Equipment operating cost and education are the primary barriers, with a need for additional research specific to the study area conditions to bolster the conclusion that any water savings associated with such compacting devices are economically worthwhile to the producer.

RP 3.5 Grade fields as uniformly as possible

To advance water at a uniform rate and to achieve more uniform infiltration across the field, proper grading is essential, with a slope that remains as constant as possible. Poorly graded fields will result in poor distribution uniformity and addressing this issue will lessen leaching risk in surface irrigated fields (Schepers et al. 1995; Mosley & Fleming 2009).

Panel members agreed that with the advent of laser leveling, uniformly graded fields are well represented. Typically fields are graded via land planes for every crop and should then be laser leveled every three years. Growers also noted that further grading-related improvements have been employed by some growers, such as altering the grade slightly towards the end of the field in order to allow water to move faster at the top of the field (where infiltration would otherwise be higher) and slower at the bottom, allowing for a more uniform infiltration.

RP 3.6 Where high uniformity and efficiency are not possible, convert to drip, center pivot, or linear move systems

In some situations, improving surface irrigation systems using the practices listed above will yield only moderate increases in efficiency despite optimal management. This may be due to soil characteristics, incompatibility of the practices with the specific crop grown, or excessive costs. In such cases it may be more economically feasible to consider an alternative irrigation system that offers the possibility of higher system performance. Drip irrigation and mechanized sprinkler systems give the operator greater control over water applications and thus, when managed correctly, can increase irrigation efficiency (Spalding et al. 2001; Hanson & Ayars 2002; Tilman et al. 2002). It is important to keep in mind that if these systems are not properly maintained and managed (including scheduling irrigation timing and amounts to meet crop need) their performance can be less than that of a well running surface system. In other words, nitrate leaching is correlated to the distribution uniformity and efficiency regardless of the specific irrigation system. Nevertheless, the inherently more precise control offered by these systems can translate into significant reductions in deep percolation when managed correctly.

Although converting to any of these technologies will incur significant capital costs, it may work out that such a switch is still more economically worthwhile than staying with a system that performs poorly (Fereres et al. 1982). For example, Hanson et al. (1998) found that in a cracking clay soil, due to preferential flow of water down the soil cracks beyond the rootzone, it was difficult to improve the surface system performance and an alternative system may be needed to reduce deep percolation. Similarly, Goldhamer & Peterson (1984) showed that on a sandy loam soil, cotton irrigated with a linear move sprinkler system yielded slightly better with significantly less deep percolation than a furrow system, and even with higher costs, the net return was slightly higher with the mechanized system. Center pivot systems have been shown to reduce water application by as much as 60-72% as compared to conventional furrow systems (Schepers et al. 1995). Drip irrigation systems can also substantially reduce water application requirements and, in some crops such as tomatoes, consistently increase yields (Hanson et al. 1997, 2001; Hanson & May 2003). Vázquez et al. (2006) showed that water loss was reduced when water is applied with a high frequency, such as is usual in microirrigation systems. A trend towards adopting such technologies in lieu of surface systems has been increasing steadily in the nation, state and study areas (Edinger-Marshall & Letey 1997; Dillon et al.1999; Zoldoske 2002; Orang et al. 2008; MCWRA 2009). Dillon et al. (1999) also found that farmers who adopted more efficient irrigation systems also integrated new, more efficient nutrient management techniques faster than those who had not upgraded their irrigation systems. Additionally, as discussed in MM8, RP 8.3, N fertilizer in microirrigation systems is usually delivered directly in the irrigation water (fertigation), which further enhances NUE by way of the small multiple N doses better matching crop need (see RP 8.3 for more information on split applications) (Vázquez et al. 2006).

The main barrier to switching from a surface system to a more efficient irrigation system is the economic cost-return ratio. For lower value crops, the cost may prove insurmountable unless simultaneously switching to a higher cash crop or adding one to their rotation (Hanson & Ayars 2002). Drip and continuous move systems are not adaptable to all crops (such as grain or hay crops) or may show little advantage. For example, fresh market deciduous tree fruits are grown in small fields where the short-run surface irrigation distribution uniformity can be quite high already and the cost of installing a pressurized system would make little economic sense. Center pivot and linear move systems are not widely used in California, although installation is increasing slowly. Center pivot systems are not favored by some growers due to lost productivity at the corners of the fields and the economic burden associated with the reduced yield that accompanies the reduced effective field size. Additionally, for air quality reasons, dairy farmers in the Central Valley have not been permitted to apply liquid manure through sprinklers. Salinas Valley panel members indicated that the small field and planting block sizes that are common in the region made linear move systems impractical.

Switching to drip irrigation continues to be a favored practice among producers of many high value crops, especially vegetables, nuts, citrus, and winegrapes. Educational barriers often prevent newly installed drip systems from being operated at their maximum efficiency, due to the learning curve involved in managing the much more complicated and labor intense irrigation system. An additional caveat to keep in mind with this improvement is that most annual crops still require sprinkler irrigation during the leaching-vulnerable phase of initial establishment, which can somewhat reduce the positive impact drip has on leaching reduction.

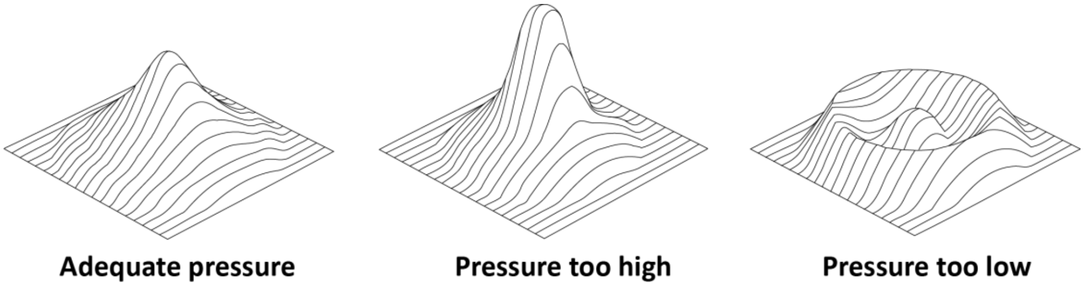
MM 4: Improve Sprinkler System Design and Operation

Optimizing sprinkler systems requires proper design, operation, and maintenance. Irrigation uniformity with sprinkler systems is primarily dependent upon spacing of nozzles along the lateral, lateral spacing along the mainline, proper nozzle maintenance, maintenance of correct pressure within the entire piping system, and wind speed (Hanson et al. 2008). In general, the continuous move center-pivot and linear-move systems offer greater uniformity than hand-move and wheel-line systems when properly maintained (Spalding et al. 2001; Gaudi et al. 2007; Hanson et al. 2008) and investing in such systems offers mitigative potential. Furthermore, better sprinkler distribution uniformity can equate to cost savings to the grower (Chen & Wallender 1984), depending on overall capital investment requirements and level of uniformity prior to change.

RP 4.1 Monitor flow and pressure variation throughout the system

As all sprinkler systems are pressurized, an important managerial requisite is monitoring for variation in pressure. As shown in Figure 2 below, pressure variation can cause water distribution uniformity issues related to inadequate spray breakup (Hanson et al. 2008). Design flaws and insufficient maintenance are the primary causes of pressure and flow problems within the system. Alternatives for addressing pressure problems include adjusting or unclogging contributing heads individually, investing in flow control nozzles, or redesign of the system (e.g., removing heads in excess of what pressure allows) or adjusting pipe gradients (Smajstrla et al. 1997).

The consensus among panel members was that better monitoring of pressure variation is a practical improvement opportunity. The labor costs and expertise required to properly diagnose problems and maintain optimal functioning of sprinkler systems were identified as the main impediments to increased grower attention to these matters. However, panel members agreed that such barriers should not be insurmountable, especially if growers were provided improved access to irrigation specialists, such as NRCS and UCCE staff, or through reinstatement of free or reduced fee irrigation evaluation services, such as the past DWR/NRCS Mobile Laboratories program.



Adequate pressure		**Pressure too high**		**Pressure too low**

Figure 2. Changes in water distribution uniformity from a single sprinkler nozzle when operated at (from left to right) pressures meeting their design specifications, or when pressure is too high or too low (adapted from Trimmer & Hanson 1986).

RP 4.2 Repair leaks and malfunctioning sprinklers, follow manufacturer recommended replacement intervals

Leaks and worn or clogged nozzles contribute significantly to poor system efficiency. These are common occurrences and regular maintenance is required when employing these pressurized systems (Gaudi et al. 2007). Leaks simply waste water and result in high levels of deep percolation on location, as do poorly performing worn or clogged nozzles that can both over- and under-apply water. More often than not, these problems are not necessarily obvious or come on gradually, such that the issues are not identified unless regular system evaluations are made. Panel members agreed that nozzle maintenance is sometimes overlooked by growers and attention could be improved. It was suggested that continued vigilance may require regular reminders during field days and other educational events. Irrigation advisors indicated that a significant portion of operations in the TLB do not follow the suggested nozzle ‘lifespans’ (nozzles should be replaced every 4 years), keeping them in operation beyond optimal performance capacity. Similarly, there is room for additional attention by growers to replacement of impact “spoons” and sprinkler head seals. Extension specialists indicated that growers sometimes avoid regular uniformity evaluations until major problems demand attention. Cost of upgrades and the labor and expertise required to monitor and maintain sprinkler systems were thought to be the main barriers to the needed increased adoption of this practice. Again, programs such as those that have been offered in the past (DWR/NRCS Mobile Laboratories), offering free or low cost irrigation evaluations would allow for earlier detections of gradual declines.

RP 4.3 Operate sprinklers during the least windy periods

Operating sprinklers when it is windy results in non-uniform distribution of water, as shown in Figure 3 below. Panel members agreed that most growers are aware of this problem, but in order to provide water to all fields, they typically must irrigate round the clock, even during windy periods. The Salinas Valley is subject to relatively high winds, making it difficult to optimize sprinkler system performance, although real-time tracking of wind forecasts could allow for some delay in irrigation. Minimizing the distance between laterals can help reduce wind interference of distribution uniformity and the effect of such minimal spacing can be accomplished in hand move systems by alternating lateral locations over successive irrigation sets (see RP 4.4) rather than investing in additional pipe and other necessary equipment.

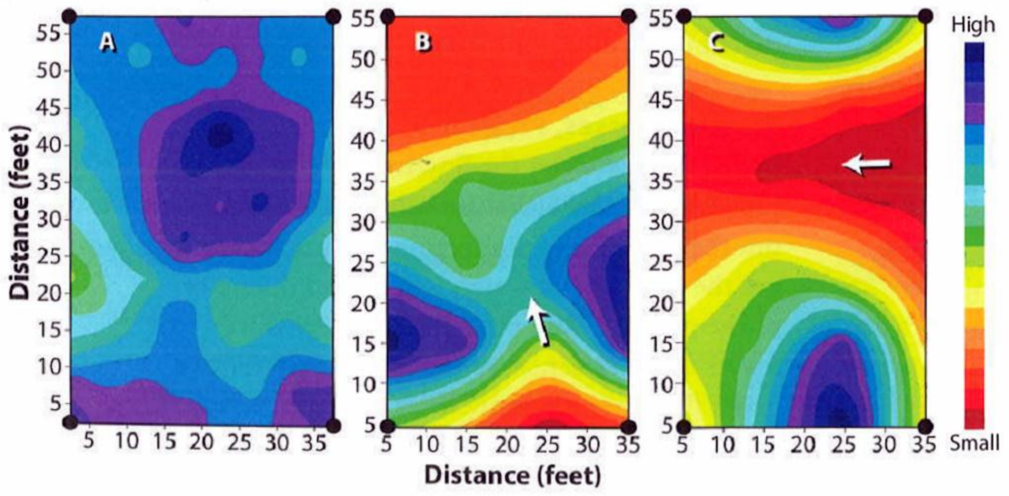


Figure 3. Distribution uniformity of overlapped sprinklers for A) Low wind condition at regular pressure, B) High wind condition with lateral perpendicular to wind direction, C) High wind condition with lateral parallel to wind direction. Black dots represent sprinkler locations and arrows the wind direction (from Hanson et al. 2008, reproduced with permission).

RP 4.4 Reduce distance between lateral lines or alternate lateral line location over successive irrigations

Improvements to water distribution uniformity may be achieved by reducing the distance between lateral lines in cases of high wind or poor pressure. While Sanden et al. (1999) found no statistical difference in distribution uniformity between 33 foot and 48 foot spacing in a Kern County carrot field, they reported that 40 foot spacing demonstrated the most consistent water and nitrogen use efficiencies, especially in high wind situations. Kasapligil (1990) demonstrated that spacing laterals 25-30 feet apart allows for 80% uniformity with 3-8 mph winds. If the capital cost of decreased spacing becomes prohibitive, alternating the lateral locations over successive irrigations and placing them midway between the locations of the previous cycle, will effectively cut the spacing in half, as shown in **Error! Reference source not found.** (Kincaid 1982; Trimmer & Hanson 1986). This is especially useful in ituations of lower pressure and has been shown to be economically beneficial (Chen & Wallender 1984). Panel members indicated that offsetting laterals is practiced by some producers, but not all. Shallow-rooted crops that require frequent water applications are not adaptable to this practice, as it is difficult to keep up with the multiple irrigations required in short time periods. In such cases, simply reducing the distance between solid set lateral lines to 30-40 feet is the best option. Capital costs for additional hardware may be required. Labor and ranch logistical issues may present additional barriers to use of this practice.

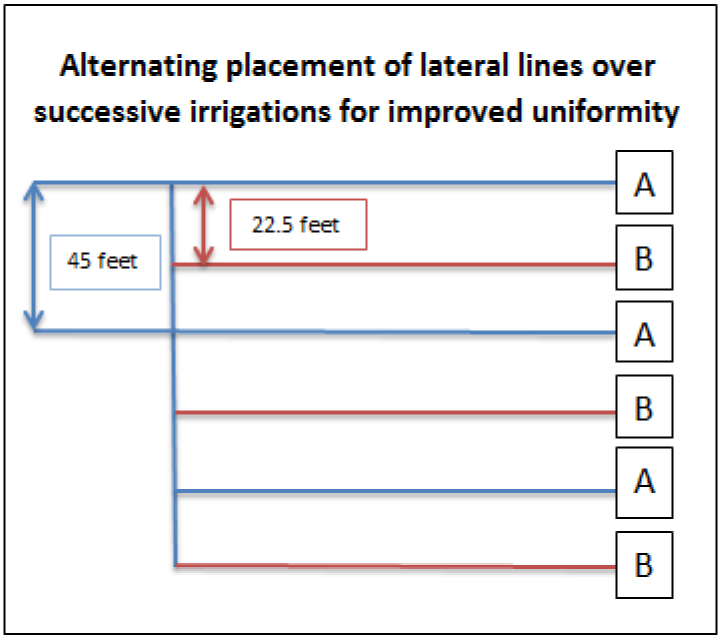


Figure 4. With lateral sprinkler lines set 45 feet apart on the mainline, uniformity can be improved by alternating the location of the laterals for each irrigation set A and B, effectively cutting in half the distance between them, resulting in improved water distribution uniformity.

RP 4.5 When pressure variation is excessive, use flow control or pressure regulating nozzles

As discussed in RP 4.1 and as Figure 2 indicates, pressure variation is a cause for poor distribution uniformity. If pressure variation is difficult to address via re-design and good maintenance and management, installing flow control or pressure regulating nozzles can effectively resolve the issue. When used, regular monitoring of the rubber in these nozzles for degradation and periodic replacement are required to keep the flow control utility functional. Panel members indicated that such equipment is used by some producers, especially in hilly areas where pressure variation is a bigger problem. The main barrier is the equipment and installation costs, although the achieved improvements to uniformity may offset some of these costs via water savings, given good maintenance practices.

MM 5: Improve Drip and Microsprinkler System Design and Operation

Very high application efficiency and uniformity are possible with drip and microsprinkler systems, but poor system design and poor monitoring and maintenance have resulted in lower performance than even some furrow systems (Pettygrove et al. 1998). Burt (2004) found that most of the uniformity problems were due to either pressure differences or to alterations of flow rate among emitters caused by emitter clogging and wear. Pressure variation has been addressed to some extent with the improved pressure compensating emitters that are now more common in today's drip systems, although this does not apply to microsprinkler systems or in cases of poor design. Other farm management activities can also affect drip system performance. Ensuring tractor tires do not compact the soil above soft buried drip tape and being careful when cultivating are both essential to good performance. Panel members also stated that attention to animal populations is important. For example, crows removing orchard emitters, gophers destroying subsurface driplines, or fire ant populations drawn to the localized water source can slowly destroy the tape over time.

Maintenance of drip and microsprinkler systems is complicated by the fact that problems are not as readily visible as in surface gravity and sprinkler systems. Root penetration into buried drip can be slow to reveal itself and close spacing of emitters often allows clogging issues of both surface and buried lines to go unnoticed for some time without vigilance in monitoring. Problems with design such as inappropriate hose lengths, variable distance between emitters, and the installer's failure to follow manufacturer recommendations of emitter to pressure ratios may also not be detected for some time without regular monitoring of efficiency or uniformity. Members of the tree fruit and nut panel indicated that it was not uncommon for 1 gallon-per-hour emitters to be replaced with 2 gallon-per-hour emitters on the same line and system, resulting in inefficiencies. As with other irrigation system types, soil variations within a single field demand growers water according to the least common denominator (that is, the most water demanding soil type). This can result in excess water applications in the areas of higher water holding capacities, increasing potential for nitrate leaching. Design of the system around such variability can help mitigate this concern (see RP 5.3). Soil and crop characteristics also need to be considered when comparing drip emitters, surface drip tape, buried tape, and microsprinklers (Gardenas et al. 2005). In areas of rolling topography for example, pressure compensating emitters are a justified investment.

RP 5.1 Use appropriate lateral hose lengths to improve uniformity

Excessive hose length causes pressure drop and poor uniformity. Generally this is an uncommon problem in that engineering technology and design has improved over time. In cases where the systems have not been updated, reconfiguring the system will present some capital and labor costs, but replacement costs are generally expected with drip systems, and increased water savings usually help to offset such costs. Long lateral hose lengths present less of a problem in steep topography if flowing downward.

RP 5.2 Check for clogging potential and prevent or correct clogging

Mineral-heavy or highly alkaline groundwater can precipitate solids independently or in reaction to fertilizer delivered through the drip system, clogging small emitters and reducing efficiency (Schwankl & Prichard 1990). Calcium carbonate or lime precipitates are common and can be resolved via a number of products on the market that lower pH or otherwise prevent or address the problem. Standard operating procedure should include checking for possible precipitate issues when installing a new system, when switching fertilizer products, or when utilizing a new water source. Biological growth and physical particles can also present clogging issues, especially when irrigating using surface waters prone to hosting microorganism populations. Proper filtration and filter maintenance can address these issues with additional biocide or pH reduction treatments as necessary to control algal or bacterial clogging. Regardless of the reason for clogging, regular flushing should be performed, allowing water to run through the system with open-ended laterals. After fertilization or the use of other chemical additives, lines should be flushed to clean emitters, with maintenance flushing recommended twice a month to keep the system in optimal condition.

Panel members agreed that filtration, chemical treatments, and flushing are common grower practices, although issues regarding proper methodology can still present a problem, as can a lack of proactive management (i.e., only checking the system when problems appear). Distribution uniformity and scheduling methodologies vary widely and optimizing system performance needs more attention by some growers. Panel members noted that treatment options (maintenance products and techniques) have generated “an industry in and of itself,”   but agreed there is some room for increased vigilance by growers on good system maintenance and proper scheduling, again indicating that educational reminders would benefit to this end. Labor and capital costs can also contribute to suboptimal efficiency of drip systems.

MM 6: Make Other Irrigation Infrastructure Improvements

Besides evaluation, scheduling, and irrigation system choices, groundwater protection should be prioritized at the site of water entry (i.e., the well) and exit from the field (i.e., drain and tail water), as discussed below.

RP 6.1 Installation of subsurface drains

Anaerobic conditions generally reduce plant productivity and thus in areas with shallow water tables (some areas on the west side of the southern SJV, some areas in the northern Salinas Valley), it can be economically advantageous (in terms of yields and diversification of potential crop palette) to install subsurface drains to keep the water below the rootzone and to help leach salts. A certain portion of the applied irrigation water and any dissolved nitrogen that percolates with it beyond the rootzone will then flow out of these drains rather than entering the aquifer. The fraction of percolating water that enters these drains versus that which moves directly to the groundwater will be high if the spacing between drains is sufficiently small and the placement of drains is not excessively deep. Depending then on drain design, soil and hydrological characteristics, drains may keep a significant amount of applied nitrate from entering the groundwater (Drury et al. 2009; Schipper et al. 2010a; Woli et al. 2010).

However, the resulting high nitrate and often saline effluent from these drains however, usually acts as a surface water contaminant. The disposal or treatment of this waste then represents a major problem associated with this practice. For example, the drain effluent flushed into northwestern Monterey County surface waters has negative consequences on the ecosystems associated with the Salinas River, Elkhorn Slough, and the Monterey Bay. Technology for treating the effluent on-site via denitrification chambers is currently being researched and developed with some promising results (Schipper et al. 2010). These systems are not yet commercially available in California and it is yet unclear if deeper drain installations (in areas without high water tables that interfere with plant health) might represent a feasible or cost effective means of diverting nitrate from groundwater should treatment systems become commercially available.

The subsurface drains that have been installed in the study area are primarily for the purpose of addressing perched water tables. The drain effluent in Monterey County passes through local sloughs and ultimately into the ocean, creating surface water quality concerns. A few growers in both regions transfer the tile drain water to evaporation ponds, blend it with fresh water and reuse it, although this is not common, and the collection ponds can sometimes pose a risk to wildlife. Until treatment or disposal options are further developed and further research specific to California is conducted, subsurface drain installation will not represent a feasible option for groundwater nitrate leaching reduction.

RP 6.2 Backflow prevention

Farms that practice fertigation are required to protect against backflow of fertilizer into wells. Local, state, and industry guidelines should be heeded when selecting preventative measures. For the most reliable prevention of backflow, multiple devices often are used in some combination. Regularly checking that the device is properly maintained and functioning optimally is critical to ensure fertilizers do not enter the well. While backflow prevention devices are in high use amongst growers, proper maintenance may not be less than optimal. Producers need to keep in mind that, with all devices, there will be pressure loss, which tends to increase as the flow rate increases.

Check valves require a minimum backpressure to completely seal, tending to leak if the minimum pressure is not maintained. Installation of a low pressure drain upstream from the check valves will intercept any leakage that might occur. An inspection port should also be installed upstream from the valve to ensure maintenance of pressure and proper valve seating. Check valves should be installed between the injection point and the well, as well as in the injection pump discharge pipe. Vacuum-relief valves prevent vacuum formation caused by water flowing back down the well column after the pump stops. All of these items should be utilized simultaneously and regularly checked for functionality.

By maintaining an air gap between the water supply and the fertilizer vessel, an actual backflow prevention device may not be required. However, this method is unsuitable for pressurized systems. Alternatively, interlocking circuits can be used, where the irrigation pump and chemical injection pump are wired to shut off whenever the irrigation pump shuts off.

2.3.2 Manage Crop Plants to Capture More Nitrate and Decrease Deep Percolation

Besides managing nutrient and water applications in a way that increases crop N use efficiency, nitrate leaching potential is also affected by other crop and field management decisions, including crop rotation and tillage choices (Tilman et al. 2002). Tillage practices such as deep ripping, chiseling, and slip plowing will increase available rooting depth, allowing plants an increased opportunity to "catch" percolating nitrate. However, depending on soil structure and fertilization method, identical tillage practices can have opposite effects on leaching, reducing it in one situation while increasing it in others (Di & Cameron 2002). Similarly, risks of leaching, greenhouse gas volatilization, surface water contamination, and erosion are all affected differently according to choice of tillage practices (Smith & Cassel 1991). Due to the complex effects of tillage schemes, in this section focus is given to managing crop rotations.

MM 7: Modify Crop Rotation

Crop rotation decisions involve choice of crop species, crop sequence, length of fallow periods, and whether cover crops will be grown. Plant species and varieties may differ in rooting depth, rate of N uptake during the season, the amount and quality of residues left in the field following harvest, and other characteristics that influence total soil N and leaching risk. Careful selection of crop rotation schemes, based on knowledge of such traits, can reduce nitrate leaching hazard.

RP 7.1 Grow cover crops

Nitrate leaching potential is substantial on fallow fields during periods of rain, as well as during pre-plant and early establishment irrigations (Cavero et al. 1999; Jackson 2000). In processing tomatoes for example, Vázquez et al. (2006) observed that both water and N losses were highest during their establishment period. Di & Cameron (2002) note two studies reporting that, following harvest of the last crop, up to 95% of residual mineral N can be lost during rainy fallow periods. A cover crop is a non-cash crop[7] grown to improve soil structure and lessen risk of soil erosion or nutrient loss; add organic matter to the soil; and sometimes to help prevent or break a crop disease or insect cycle. By incorporating the prior cash crop's residual N into their biomass, the amount of N ultimately subject to deep percolation is reduced. The subsequent cash crop can then capitalize on cover crop N residuals.

It has been repeatedly shown that growing a cover crop during otherwise fallow periods, or between rows of permanent crops, reduces nitrate leaching and improves overall soil quality (Jackson et al. 1993; Wyland 1996; Brandi-Dohrn et al. 1997; Delgado 1998; Beaudoin et al. 2005; Feaga et al. 2010; Ramos et

---

[7] A broader definition may include crops with a marketable harvest, rotated with the main cash crop. See RP's 7.2, 7.3 and 7.4.

al. 2010). In their covercropping meta-analysis, Tonitto, David, & Drinkwater (2006) reported that use of non-leguminous cover crops reduced leaching by 70% on average and by 40% in legume-based rotations, with the latter simultaneously fixing additional N and in some cases increasing cash crop yields. Using leguminous species, otherwise known as green manures, can add 100-300 kg N per hectare via N-fixation depending on time of year and how quickly their residues decompose (Sheenan 1992). The additional N fixed by leguminous cover crops should be accounted for in the nitrogen budget (see RP 8.8). With any cover crop, one caveat is that if early rainfall is significant, much of the nitrate remaining after the harvest of the main crop can be moved beyond the reach of the cover crop roots depth, or will be in excess of the cover crop's nitrate uptake capacities (Feaga et al. 2010).

A wide variety of crops can be used for this purpose in both annual and perennial systems and much research has been performed regarding which species and species-mixes may provide the best benefit for specific goals or situations. Snapp et al. (2005) reviewed multiple cover cropping studies across specific climates (including California's Mediterranean zone), comparing costs and benefits and evaluating barriers to increased adoption. According to this review the additional benefits of cover cropping (beyond reduction in nitrate leaching) include reduced erosion due to increased water infiltration; improved weed control; increased soil organic matter (leading to improved soil structure, tilth and water holding capacity); improved pest and disease management; and possible yield increases.

Snapp et al. (2005) also outline potential disadvantages of covercropping: harboring of certain cash crop diseases and pests; increased weed problems; problems associated with the residues (temporary decreases in available nutrients while they are broken down); interruption of the planting schedule (delayed planting); along with additional costs for labor, seed, and water. The authors emphasized that the benefits of cover crops tend to be long-term and somewhat cumulative. In addition, making informed decisions regarding the appropriate cover-cropping options for the unique farm situation can require heavy information gathering and experience by trial and error. Specific to the Salinas Valley, Smith & Cahn (2010) additionally point out that the high land rent rates in this area further discourage covercropping, where growing a non-cash crop is economically risky.

Panel members agreed with these literature findings, adding that although growers in the study areas utilize the practice, it was not especially common due to disease hosting concerns, capital and labor costs, delayed planting of the main cash crop, conflicts with tree harvesting methods that require a clean floor, and most especially, the fact that cover crops increase irrigation requirements when water availability is already a concern for their main cash crops. The latter was cited as the largest deterrent to growers incorporating cover crops into their rotations for both study areas. The multiple benefits of cover-cropping were thought to be generally well-known by growers and, despite some of the barriers, most panel members considered it a practice with potential to be more widely utilized should additional local and crop-specific trials occur along with associated educational outreach.

RP 7.2 Include deep-rooted or "nitrogen scavenger" crop species in annual crop rotations

Crops differ in terms of their rooting depth, their total N requirements and uptake curves over the season, the level and nature of the residuals left after harvest, and other characteristics that influence N uptake efficiency and leaching. So-called nitrogen scavenger crops have deep root systems that can capture and recycle N leftover from the previous crop that would otherwise be leached if the ground were left fallow or planted again to a shallower rooted species (Osterli & Meyer 1977; Delgado 1998; Bassil et al. 2002; Delgado et al. 2008). For example, Zhou et al. (2008) showed that when following corn with wheat, the nitrate that has leached below the root zone of the corn is taken up by the deeper-rooted winter wheat that follows it. Unlike the more traditional cover crops (such as vetch), deep rooted N-scavengers are not restricted to the winter months, and using them in a crop rotation scheme usually produces a harvestable crop. Although scavenger crops may require N fertilization, they may also obtain sufficient N from the residuals of the previous crop (Bassil et al. 2002). Examples of such crops include sugarbeets, sorghum, ryegrass and other winter cereals and forages, as well as oilseeds, such as safflower. Alfalfa and other perennials can also be excellent N scavengers (see RP 7.4).

Barriers to incorporating N scavengers into crop rotations are similar to those cited for cover crops, especially the poor economic incentives. Rotation options are also sometimes limited by buyer preferences and requirements. Similarly, growers often do not want to plant crops associated with an uncertain market. For example, in the Tulare Lake Basin, oilseed processing facilities contract with certain growers to meet market demands, leaving non-contracted growers with high economic risk should they grow a crop for which little additional market share exists. There is also very little market for forages in the Salinas Valley, and in the TLB, sugarbeets, although an ideal scavenger and once representing well over 7000 hectares (19,000 acres) of the study area, are no longer grown due to the closure of the last processing facility in the Central Valley. Land tenure, land rent rates, and current price of such crops also need to be considered when developing rotation schemes. Often, crops with high extractive capacity are also of lower economic value, and thus, the high establishment costs present a significant economic barrier to alternative rotation schemes.

RP 7.3 Grow more crops per year (e.g., dairy forage triple crop rotation)

Growing more cash crops per year in annual cropping systems reduces the length of the fallow periods during which there is greater risk of nitrate leaching loss. The third crop should allow for an updated fertilizer application timing regime and ideally would be an N scavenger (see RP 7.2) or one that requires relatively small amounts of additional fertilizer. The best example of this practice is the addition of a late summer sudangrass crop into the more traditional summer silage corn-oats dairy forage double crop. Planted immediately after harvest of the silage corn, the sudangrass can then capture remaining residual soil N, and its presence may allow for manure or dairy lagoon water applications that would otherwise contribute to an ever-increasing soil N content at risk of leaching. As such, the addition of the third forage reduces the risk of nitrate leaching loss later in the winter compared to the more typical double crop.

Some dairy forage crop producers in the TLB are triple cropping in this manner. The main barriers to expanded use of this practice are the cost of the extra field operations and lack of availability of irrigation water. The extra forage produced tends to also be relatively low in feeding value. Additionally, the insertion of sudangrass crop into the rotation in the fall may delay planting of the winter cool-season grass forage (oats, wheat, etc.). With later planting dates, there is an increased risk of early rains preventing entry of planting equipment into the field.

RP 7.4 Include perennial crop rotation (e.g., alfalfa or perennial grasses)

Perennial grasses, clovers, and alfalfa are generally very effective in capturing nitrogen that might be lost in annual cropping systems. Perennial forages, if irrigated, actively take up nutrients and water from the soil over a greater portion of the year than annuals, even where two or three annual crops are grown in sequence during a 12-month period. Legumes in general, and alfalfa especially, have the ability to obtain all needed nitrogen from the air (so-called biological N fixation, BNF) and therefore do not require any N fertilizer applications. However, when nitrogen is available in the soil due to presence of residual manure or fertilizer N, the BNF process stops, and the plants switch to the soil N source. Alfalfa is the most important high protein livestock forage in California and is known as “Queen of the Forages.” Alfalfa is a very deep rooted species and can capture N from the soil at greater depths than corn or cotton. In a corn lysimiter trial, Toth & Fox (1998) demonstrated that nitrate leaching was reduced in fields incorporating alfalfa into the crop rotation. Watts reported that, within a year, alfalfa can remove nearly all nitrate from the soil up to several meters deep and that the crops following alfalfa in the rotation require less fertilizer N to be applied (Power et al. 2001). Pettygrove & Putnam (2009) estimate that the average alfalfa credit is between 50 and 80 pounds of N per acre (56-80 kg N/ha). In their literature review, (Power et al. 2001) found that the residual effects of alfalfa can last up to 5 years, with the caveat that nitrate leaching may not be reduced if the fertilization scheme for the following crop does not adequately account for the legume N credit. Panel members agreed that although many growers were aware of the N credit, they were unsure of how to utilize values in an N budget without fear of yield reduction (see RP 9.8 for more information on N budgeting).

Deep rooted perennial grass is also effective in reducing soil N levels (Dear et al. 2001). Entz et al. (2001) found that perennial grasses extracted higher levels of nitrate than continuous alfalfa in the shallower soil profile (<120cm), with similar extraction levels below this depth. California native perennial grasses can be used between tree and vineyard rows, and because they are summer dormant, offer the added benefit of not requiring additional water application (Ingels et al. 1994). In Central Valley vineyards, perennial clover and native grasses used between grape rows reduces vine vigor (a beneficial effect) and can reduce N fertilizer application needs (King & Berry 2005), although more water use may result (Monteiro & Lopes 2007).

Barriers to utilizing perennial crops in rotations are primarily economic. Perennial forages generally produce much less income than, for example, vegetables or other field crops such as cotton. In some parts of the TLB where water is quite limited, farmers may have enough water to grow tomatoes or cotton, for example, but not enough to produce alfalfa. Dairy producers, who can utilize the harvest for feed, will tend to only grow alfalfa when they know they will be able to produce enough of their other forages. Additionally, alfalfa can be more sensitive to complications associated with manure applications than other silage crops, so it is not as useful for recycling their manure. Harvesting conflicts preclude the use of perennial cover crops in raisin production and some fruit and nut trees due to the need for a “clean” vineyard/orchard floor. In their review, Crews & Peoples (2005) suggest that decreasing N losses from agroecosystems will require increased utilization of perennials, although more research and information dissemination are required.

2.3.3 Manage Nitrogen Fertilizer and Manure to Increase Crop Nitrogen Use Efficiency

Synchronization of fertilizer and manure application rates and timing to match plant requirements is critical to reducing groundwater nitrate contamination from agricultural crop production. Total crop N requirements vary widely among crops as do nutrient uptake patterns throughout the growing season (**Error! Reference source not found.**). The rate, timing, placement and source of fertilizer materials are nder the control of the grower and make up the critical components of matching N supply with demand. Environmental variables, outside of grower control also affect the balance of supply and demand and should be reflected upon, as should crop restrictions on irrigation systems (including fertigation) and requisite cultural practices. These interrelated aspects of N synchrony, although complex, need all be considered simultaneously when managing N applications to increase N use efficiency and better control N leaching.

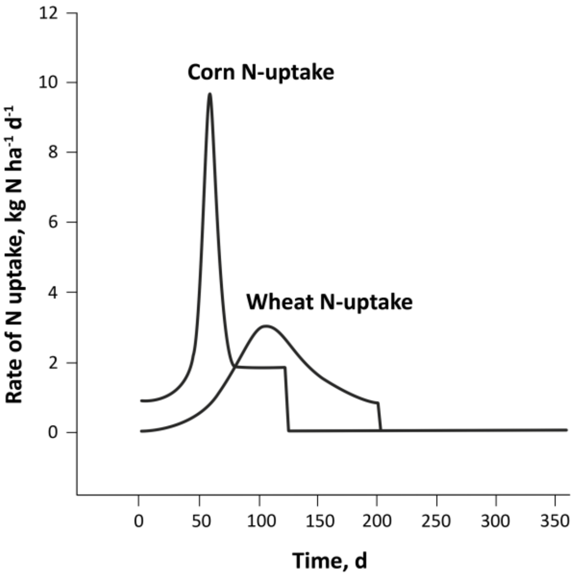


Figure 5. Contrasting N uptake curves for corn and wheat, exemplifying the crop-specific nature of optimizing timing of N applications. (adapted from Pang & Letey 2000, with permission).

MM 8: Improve Rate, Timing, and Placement of Nitrogen Fertilizers

As discussed in the following RPs, applying fertilizer at rates and times consistent with crop needs reduces leaching potential (Di & Cameron 2002; Meisinger & Delgado 2002; Meisinger et al. 2006; Li et al. 2007; Gheysari et al. 2009; Fessehazion et al. 2011). Besides proper rate and timing of fertilizer applications, nitrate leaching is affected by placement and the nitrogen source. Attention to variability in soil characteristics, water infiltration and areas of root proliferation can reduce ill-placed N applications. Banding of fertilizer in row crops (as opposed to broadcast spreading) or with the irrigation water (fertigation) delivers fertilizer to areas of higher root densities, thereby decreasing N leaching risk (Kemper et al. 1975; Lehrsch et al. 2000). Urea-based products are better incorporated below the soil surface than broadcast onto the surface due to risks of volatilization losses. Attention to placement is important in early establishment periods when roots are yet poorly developed and irrigation tends to exceed ET. Nitrogen source (e.g. urea, ammonia, ammonium nitrates, manure, compost) plays a role in gaseous emissions (especially gaseous NH_3) and nitrate leaching, but effects are highly variable according to environmental and management factors and thus debatable. Discussion regarding N source is thus kept minimal in this document, primarily differentiating between organic and synthetic fertilizer sources.

RP 8.1 Adjust nitrogen fertilizer rates based on soil nitrate testing

Applying N rates above plant need increases the risk of nitrate leaching losses. Maintenance of profitable yield plateaus at certain fertilization rates and overfertilizing beyond this point is not uncommon in California (Hartz et al. 1994; Hartz 2006). Soil nitrate testing is a technique for estimating plant-available N in the soil and reducing risks of over-application. Overall crop N needs are very small until plants are well established and growing rapidly. The N concentrations in the small rooting zone needed for plant growth at this stage can be met by careful placement of small amounts of starter or preplant N fertilizers when needed. Often, prior to the rapid growth phase, residual N in the soil can meet early plant needs.

Soil testing at or just prior to planting can indicate if enough residual N is available for plant establishment, allowing fertilizer application to be delayed, to the benefit of groundwater (Di & Cameron 2002). Preplant soil nitrate testing identifies fields with adequate N for plant establishment and presidedress soil nitrate testing (PSNT) helps to determine in-season fertilization needs (both rates and timing). Applying this knowledge can provide substantial reductions in overall N application rates (Hartz et al. 2000; Krusekopf et al. 2002; Li et al. 2007; Malone et al. 2010). For example, Breschini & Hartz (2002) reported that PSNT use in California lettuce fields could reduce seasonal N applications by 40 percent. Split applications, based partially on soil testing, can also reduce total N applications (see RP 8.3). Soil nitrate testing at or just after harvest can indicate whether N fertilizer applications were excessive and may be useful in adjusting future rates. Both laboratory testing and on-farm quick tests are available. The on-farm quick tests offer a simple and relatively inexpensive way for growers to routinely monitor and gauge fertilization needs without having to wait for the return of laboratory results (Hartz, Smith, et al. 1994).

Barriers to soil nitrate testing and/or adequate use of soil testing include associated costs (primarily labor and management), complexity of collection regime, and spatial variability within a field. Spatial variability of soil nitrate is often very high, requiring that a large number of samples be taken to adequately characterize a field. High spatial variability is especially a problem in no-till fields and under drip irrigation. In drip-fertigated fields, plant roots and residual fertilizer N may be concentrated in a small zone of wetting, leading to some uncertainty in where to collect soil samples. Panel members agreed that a large portion of growers utilize soil testing, although they were unsure of relative frequency and overall attention to the variability concerns noted above. On-farm quick-tests are not yet especially common, with the majority of growers contracting with commercial laboratories for testing. Growers of grain and other field crops (besides cotton) are exceptions to the trend of utilizing soil testing to guide application rates , although over-application of N in cereals is less common than in other field crops due to risk of lodging.[8]

RP 8.2 Adjust timing of nitrogen fertilization based on plant tissue analysis

Timing fertilizer applications to match crop need is critical to increasing nitrogen use efficiency and decreasing leaching potential (Adriano et al. 1972; Peacock et al. 1991; Christensen et al. 1994; Neetson et al. 1999; see also RP 9.3 below). Again, total N requirements are usually quite low during early plant establishment. For example, Pang et al. (1997) modeled leaching with various water application rates, fertilizer rates, and application timing. Higher N rates and earlier application dates produced the highest leaching fractions in the model, whereas delaying the second N application in grains reduced modeled leachate significantly (multiple dosing is reviewed in RP 8.3).

Plant tissue analysis can indicate if nutrient levels are adequate for meeting plant needs. During mid and late season, soil testing becomes a less accurate indicator of crop N needs. Using tissue testing in conjunction with continued soil testing can provide a superior gauge for timing applications (Pettygrove et al. 1998). These tests are primarily useful for determining nutrient deficiencies and not as useful for determining surplus N levels (Pang et al. 1997; Hartz et al. 2000; Breschini & Hartz 2002). The primary benefit of the tests then is to guide smaller applications over time by indicating when plant N levels are adequate. Note that if a defiency is detected via tissue analysis, it may be too late to fully compensate for the nutrient shortage. In-season and long-term monitoring of tissue testing result trends in relation to fertilizer application dates, and/or midseason soil testing results, can sometimes be indicative of opportunities to reduce or delay fertilizer applications (Pettygrove et al. 1998).

Soil nitrate testing in woody perennials is somewhat impractical due to their large rootzone and thus tissue analysis in these crops is generally a standard practice, most commonly using whole leaf tissue tests. Spatial variability within the tree can lead to uncertainty in comparing whole leaf tissue test results. Petiole testing is also common in some crops (e.g., cotton and grapes). The measured value can be affected by the time of day, temperature, presence of cloud cover, and plant water status, leading to uncertainty in interpretation. Similar to the literature cited above, some panel members felt that, with the test better at detecting deficiencies than surplus, its effect on leaching is questionable. Vegetable and row crop panel members disagreed over tissue testing's overall usefulness in annual crops, citing confounding factors of the results as well as the fact that crop damage or loss can occur before the lab can return the results.

---

[8] Lodging, most often associated with cereal crops, refers to the permanent loss of the plant's upright position, negatively affecting yields and increasing risk of disease, etc. Excess N applications can enhance lodging risk in cereals.

RP 8.3 Apply nitrogen fertilizer in small multiple doses rather than single large dose

To better match crop N uptake patterns (see Figure 5) fertilizer should be applied in multiple doses rather than a single application. In research on both tree and row crops, this practice has repeatedly been shown to increase N use efficiency, reduce total N fertilizer requirement, and reduce subsequent leaching below the rootzone (Chapman 1951; Russelle et al. 1981; Pang et al. 1997; Malusa et al. 2001; Breschini & Hartz 2002; Gehl et al. 2005; Quiñones et al. 2005; Vázquez et al. 2006; Gheysari et al. 2009; Lopus et al. 2010). For some crops, seasonal N uptake curves have been published and can be used by growers to estimate weekly or even daily N uptake quantities. These can be used together with soil and tissue testing to make N fertilizer timing and rate decisions. Split fertilizer application is especially straight forward and highly utilized in drip irrigation systems (fertigating), although sprinkler and furrow fertigation systems can also lend themselves to the practice, as can tractor applied sidedressings. Leaching is typically more highly reduced with fertigation, as it normally equates to higher application uniformity as well as higher numbers of split applications. For example, Alva et al. (2003) showed higher reductions in leaching from lemon orchards when N application was split between more frequent (15X) fertigations as compared to less frequent (4X) tractor applied sidedressings.

Barriers to split application practices primarily are cost and educational requirements. The practice is employed by growers in the study areas, largely independent of irrigation methodologies, although in field crops less so than in vegetable and permanent crop production. Panel members suggested that where splitting between one or two applications may be common in non-fertigated systems, it is often justified to split fertilization into three, four, or more applications, and thus there is room for improvement.

RP 8.4 Measure nitrate content of irrigation water and adjust fertilizer rates accordingly

If not regularly testing irrigation water, especially where the nitrate level in an irrigation water source is high (> 5 ppm N) and/or fluctuates during the season, N application above plant need is more likely. Any nitrate present in water from irrigation wells can be used to grow the crop, simultaneously reducing spending on N fertilizer. This is the central premise of the pump-and-fertilize groundwater remediation concept discussed in Technical Report 5 (King et al. 2012). Irrigation water samples should be taken after the pump has run for at least 15 minutes and kept cool or frozen en route to the laboratory for analysis. Several test kits are commercially available and can be used for on-farm testing.

To calculate the appropriate N fertilizer credit, farmers should use the volume of water actually used by the crop, which is usually less than the amount applied. Crop water use can be estimated with sufficient accuracy for this purpose with the CIMIS crop evapotranspiration online tool (see RP 2.1)

Panel members indicated that although some growers are measuring their irrigation water for nitrate and reducing fertilizer rates accordingly, many do not. Generally, more testing and accounting takes place in areas with relatively higher well water N, and dairy farmers are now required to test their water annually. Adjusting fertilizer rates based on nitrate levels in well water is complicated by the seasonal variation of N levels and by irrigation of individual fields using multiple water sources (e.g., additive N levels of multiple wells and/or dilution by surface waters). Panel members also suggested some reluctance by growers that rent their farmland to test their landlord's water.

RP 8.5 Use low rates of foliar nitrogen instead of higher rates applied to soil

Foliar applications of urea based N fertilizer, used in conjunction with reduced rates of soil applied N, have shown some success in increasing nitrogen use efficiency. For example, Lovatt (1999) showed that, with specifically timed foliar applications of low-biuret urea, citrus and avocado fruit set and fruit size increased, improving overall yields. While maintaining yields, leaching risk from the soil is reduced when a portion of the N needs are applied to the leaves (Dong et al 2005; Gonzalez et al. 2010). Johnson et al. (2001) found that peach quality and yield were equivalent when applying 112 kg/ha (100 lb/ac) N to soil versus a treatment with 56 kg/ha foliar application and 56 kg/ha (50 lb/ac) soil application.

Although foliar application of some micronutrients is more common, especially in tree production, foliar application of nitrogen is not as common and is used only on a very restricted number of crops, mostly subtropical tree fruits. In general, it is not as practical in field and vegetable crops, due to their relatively high N requirements. Foliar applications of N fertilizers must be applied in small doses to prevent damage to plant tissue, and thus the cost of applying materials can be significantly higher than for ground application. Also, conversion of many tree fruit and nut orchards to drip or microsprinkler irrigation and use of fertigation has eliminated some of the advantage of foliar application of N (foliar micronutrient application is still proving to be useful in some tree crop production regardless of irrigation system). Panel members agreed that although the practice may hold some promise, more research is required to prove the value of benefits compared to costs in various crops.

RP 8.6 Vary nitrogen application rates within large fields according to expected need

Large fields often vary in their soil characteristics, which in turn affects water holding capacity, N availability, and plant uptake of nitrogen. By varying N application rates according to soil physical and chemical characteristics, rather than applying the same rate everywhere, increased nitrogen use efficiency can be achieved (Khosla et al. 2002; Mann et al. 2010).

In site specific management, or so-called precision agriculture, application rates of fertilizers, pesticides and irrigation water are varied within a field to better match the field variability, such as variable soil characteristics or pest and disease pressures. Satellite imagery, GIS, and other technologies are used to detect plant and soil characteristics within the field and zone the field according to needs. GPS-equipped tractors can then be automated to make applications by zone. Precision agriculture is increasingly advancing technologically and has been adopted commercially primarily in field crops and some tree crops outside of California, where increased nitrogen use efficiency is based on site-specific management zones (Khosla et al. 2008; Mann et al. 2010). An important caveat to this practice is that although it can enhance NUE and/or yields, if the reason for a zone's low soil N is due to, for example, lower water holding capacity (i.e. an area of sandier soil), then adding more N to this area is actually going to contribute to additional loss of nitrate below the rootzone, and thus acting as a counterproductive practice in terms of groundwater quality.

A survey one decade ago of agricultural scientists from California universities (Wagner Weick 2001), indicated that advances in the GIS and GPS technologies used in precision agriculture were expected to greatly impact the state's agricultural efficiency, and in time this may be the case. Highly automated precision agricultural systems are as of yet uncommon in California and will likely remain as such until the technologies are further developed to meet local conditions and needs. Large (>80 acres) fields of combine-harvested crops in rainfed systems may have high yield potential variation, as well as high soil variability and slope variability within the same large field. Californian irrigated fields often have more uniform conditions in that rain does not complicate water application uniformity, a large percentage of crops are grown in flat valley floors, and, in most rotations, fields here tend to be smaller, meaning less variable soil characteristics. Additionally, more research is required to develop some of the techniques for the myriad crops grown here, as again, the most developed techniques are specific to large fields of grains and other combine-harvested crops. Precision agriculture techniques that may be considered currently available to California growers relate more to irrigation than fertilizer applications, and with the former it generally only applies to micro-irrigation systems, and to a lesser extent, sprinkler systems. Additional irrigation infrastructure would also be required (such as valves or soil moisture sensors). Along with the capital costs for programs and infrastructure, additional barriers include the lack of interoperability between programs and the significant time required to manage and analyze data.

Panel members agreed that the few growers who do manage to site specific variables, utilize past harvest information and soil samples to guide their N application rates spatially. This is relatively common in fruit production within the TLB, facilitated by the fact that often different varieties are planted within the same field or block and it is already necessary to manage on a row-by-row or block-by-block basis. The practice is largely not applicable to Salinas Valley producers as fields are typically small and where field boundaries have been updated to stay within more homogenous soil zones.

RP 8.7 When fertigating in surface gravity systems, use delayed injection procedure

Injection of N fertilizers into surface-run irrigation water is a practical way to provide nutrients in mid- or late-season when the crop is too big to permit tractor applications, and is commonly used in corn, tomatoes, and other row crops. The delayed injection technique is a method for improving the spatial distribution of the applied nutrients by adjusting the timing of the fertilizer injection in the water. In this method, the water is allowed to advance 25-50% across the field before fertilizer valves are opened. The fertilizer rapidly "catches up" with the advancing water front and therefore reduces the time that nitrogen is subject to leaching at the upper end of the field (Pettygrove et al. 1998). The procedure enhances N distribution uniformity and may decrease the total amount of N fertilizer needed (Schwankl & Frate 2004; Pettygrove et al. 2007).

Performance of the technique requires some additional labor time for opening the fertilizer tank out of sync with starting the irrigation run. Also, where surface gravity irrigation is already adequately uniform, there will be little or no advantage to delayed injection. Panel members agreed that although the practice has some mitigative potential, the logistical concerns associated with the additional time and labor requirements have kept adoption of this method relatively low within the study area.

RP 8.8 Develop a nitrogen budget that includes crop nitrogen harvest removal, supply of nitrogen from soil, and other inputs

A nitrogen budget is a tool for planning N fertilizer applications and for evaluating over time the N use efficiency achieved in a field. Crop N harvest removal is defined as expected yield multiplied by the expected N concentration in the harvested product. A simple budget is made by considering this harvest removal amount in conjunction with N inputs, including fertilizer, manure, soil N levels, and irrigation water N levels. After harvest each year, inputs and outputs are updated with actual values and the budget utilized in planning for the next year.

In many situations, N budgeting is not very useful for annual planning of N fertilizer requirements. This is due to the uncertainty in the magnitude of N losses due to leaching, runoff, and gaseous losses. Additional uncertainty lies in the amount of N that is likely to be provided to the plant by mineralization, the conversion of organic N forms (from plant residues, soil organic matter, and any applied manure or compost) to plant available (inorganic) N forms during the growing season. These factors may vary from year to year and among fields, and general values from the literature are not case-specific enough to allow useful budgets to be constructed. However, with careful recordkeeping and with experience, growers may be able to use a budgeting approach to approximate, for example, adjustments to N fertilizer rates in response to expected changes in crop yield or in N content of irrigation water.

Nitrogen budgets may have some use in assessing crop N use efficiency achieved in the recent past. N budgets for individual fields are currently required of dairy producers in the Central Valley under the General Order Waste Discharge Requirements, implemented in 2007. The intended purpose of these budgets is to allow the producer and the regulatory agency to evaluate, after the fact, whether nitrate leaching losses were likely low, as would be suggested by high crop N use efficiencies. Compliance with the N budgeting provision requires producers to measure or estimate and record the following on each crop in each field: crop yield, N content of harvested crops, N content of all irrigation water and volume of water applied, weight and N content of all manures (liquid and solid) applied, and amount of N fertilizers applied. These data would allow comparison of total N inputs to crop N harvest removal, thus to infer from the difference whether leaching losses of N may be excessive. This is a relatively new regulation, and it is not known whether such N budgets will provide useful information, either to farmers or to the regulatory agency. It is reasonable to ask whether such a recordkeeping approach used for crops (other than on the currently regulated dairies in the Central Valley, where most of the crops are forage species) would provide the information needed to evaluate crop N use efficiency.

Nitrogen budgeting, that is, measuring the difference between N inputs and N removed in the harvested crop, and tracking this over a period of years, appears to have the most potential as an assessment tool in annual crop rotations (on a multi-year scale), especially vegetables, forages, and grain crops. It is more difficult to envision its utility for grapes, tree fruits, and nuts, because in those crops, the permanent part of the plant (trunk, branches, and roots) stores nitrogen over a period of years. Additionally, for some crops (e.g., watermelon, lint cotton, leaf lettuce), obtaining a representative sample of the harvested crop and preparing the sample for laboratory analysis would be difficult, and protocols for doing this would need to be developed.

Panel members stated that emphasis needs to be placed on the fact that crop fertilization requirements are considerably larger than harvest removal. Members agreed that keeping this fact in mind, harvest removal does serve as an important grower evaluation tool of their overall nitrogen use efficiency on a multi-year scale. Considerable additional management time and the level of expertise required to track and analyze an N budget are the main barriers to this practice, as well as record privacy concerns. Along with the need for significant educational outreach, additional research is required to evaluate average per-crop removal rates to accommodate increased use of this figure in nutrient budgeting calculations (Heckman et al. 2003).

RP 8.9 Use controlled release fertilizers, nitrification inhibitors, and urease inhibitors

In recent decades, a number of products have emerged that have the potential to increase overall N use efficiency. Slow release fertilizers, nitrification inhibitors, and urease inhibitors have been shown to benefit crop N use efficiency as discussed below. Note that these products are not applicable to most drip irrigated crops.

Controlled (or slow) release fertilizer (CRF) pellets are either compounds of low water solubility or are coated with a material that restricts the dissolution of soluble N over time. Some success in increasing N use efficiency has been documented with some of these products (Diez et al. 1995; Chen et al. 2008). For example, Zvomuya et al. (2003) showed that Nitrate leaching was more significantly reduced in potato fields fertilized with polyolefin-coated urea than in those receiving split applications of uncoated urea. However, some studies have pointed to more soluble N being left in the soil after harvest than with traditional fertilizer, which is then subject to leaching (Delgado & Mosier 1996). Furthermore, it has been suggested that these products are most suited to conditions outside of California where summer rains minimize grower control over water applications (and thus leaching) and where growers have less room to synchronize N applications with plant need than California growers do (Hartz & Smith 2009). Although California strawberry production makes heavy use of these relatively expensive fertilizers, the drip irrigation and fertigation (offering precise control over both water and N applications, respectively) already common to California vegetable fields, would likely show little benefit with the use of CRF products. Panel members agreed that outside of strawberries, controlled release products are not highly used due both to their relatively high costs, as well as uncertainty regarding how product N release rates match crop N demands.

Nitrification inhibitors reduce the oxidation of ammoniacal N to nitrate, where the former is plant available, but not subject to leaching unless transformed. Nitrification inhibitors have been shown to increase N use efficiency and decrease leaching losses, and in some cases increase yields (Serna et al. 1994; Shi & Norton 2000; Cameron & Di 2002; Di & Cameron 2004; Quiñones et al. 2009). In his meta-analysis of the nitrification inhibitor nitrapyrin, Wolt (2004) found that in 75% of the studies reviewed, use of the inhibitor increased soil N retention and yields while decreasing volatilization and nitrate leaching. Gaseous losses have also been shown to decrease substantially with the use of the nitrification inhibitors (Dittert et al. 2001; Cameron & Di 2002; Hatch et al. 2005; Chen et al. 2008; Carneiro et al. 2009). Panel members indicated that although the use of these products is more common than use of slow release fertilizers, altogether they are not especially popular due to cost-return uncertainties.

Urease inhibitors slow the conversion of urea to ammonia, thereby reducing the potential volatilization loss of ammonia nitrogen when urea is left on the surface of the soil for more than a few hours. Immediate incorporation of urea fertilizers following application will mostly eliminate such volatilization losses. In the study areas, there are only a few situations (e.g., orchards or pastures receiving broadcast application) where urea is subject to this loss. By decreasing these gaseous losses, urease inhibitors have been shown to increase nitrogen use efficiency by reducing total N application requirements, thereby decreasing leaching risk (Watson et al. 1994; Gioacchini et al. 2002; Chen et al. 2008; Sanz-Cobena et al. 2008; Watson et al. 2008; Dawar et al. 2010a; Zaman et al. 2010; Dawar et al. 2010b; Sanz-Cobena et al. 2011). Panel members agreed that these products are utilized by some growers, but not the majority. New products are continuing to be developed and introduced into the marketplace and additional research is warranted as N use efficiency has already been shown to be significantly enhanced by both urease and nitrification inhibitors. Thus, with more research and educational outreach, the existing uncertainty and cost barriers may be overcome.

MM 9: Improve Rate, Timing, and Placement of Animal Manure Applications

Animal manures include both solid and liquid materials and wastewater from animal housing (e.g., dairy lagoon water). Such materials represent a significant source of crop nutrients in Central Valley.

Nearly all dairies in the Central Valley collect a portion of the cattle excreta by flushing concrete surfaces with water. The concrete surfaces include milking facility floors and lanes in barns and corrals. Additionally, during the rainy season, runoff from calf pens or other animal housing must be retained and usually is collected in the same system as the flushed manure water. On many dairies in the Tulare Lake Basin, more than 50% of all animal excreta is collected in this manner and stored in retention ponds as a dilute liquid, so-called “lagoon water”, prior to application to crops. This liquid manure cannot be economically transported for long distances and is usually applied to dairy forage crops and less commonly to non-forage crops on adjacent farms.

All dairies in the Central Valley are subject to regulations aimed at preventing manure nutrients from polluting surface and ground water. [9] A key feature of the regulation is the requirement that total N from all sources (manure, fertilizer, irrigation water) applied to a field not exceed 140 (or in special circumstances 165%) of removal of N by the harvested crop.

To comply with this N loading limit, while retaining current dairy stocking rates, many dairy producers in the Central Valley transfer manure solids (and to a far lesser extent, lagoon water) to other farms. A constraint to this transfer is that application of raw manure and even fully composted manures is restricted on some crops by processors and other buyers. Due to food safety concerns, use of manure products on crops destined for human consumption is decreasing.

---

[9] The General Order for Waste Discharge from Existing Dairies in the San Joaquin Valley, see: http://www.waterboards.ca.gov/centralvalley/water_issues/dairies/dairy_program_regs_requirements/index.shtml

Thus, there is a need to identify appropriate N management practices for two distinct situations: (1) application of manure and dairy lagoon water on dairy crop fields that fall under the General Order, and (2) application of manure on farms in the region that are not regulated under the General Order. In the second situation, farmers are not subject to a regulatory nitrate loading limit, and they are more likely to be applying manure (or compost made with this manure) without reducing N fertilizer application rates. Additional research is required to address the recent increase in off-farm transfer of dairy wastes and to develop proper manure recycling methods. This should include a comprehensive education and outreach effort aimed at growers not accustomed to accounting for organic N in their nutrient budgets.

Compared to commercially-manufactured inorganic fertilizers, manure, both solid and liquid forms, is far more heterogeneous in its physical properties and nutrient form and amount. It is more difficult to apply to fields uniformly, and its nutrient value to crops is less certain due to difficult-to-predict release rates of plant-available nutrient forms, fluctuating (and sometimes high) volatilization rates, influence of animal nutrition, and other factors.

Approaches for minimizing nitrate leaching losses from crop fields receiving dairy manure are listed here. For dairies, this includes installing or upgrading the infrastructure needed for collecting, storing, and applying lagoon water to fields. For non-dairy farms, this encompasses management of solid manure or composts made with manure. Recommended practices listed here are focused on careful characterization of manure nutrient content, nutrient budgeting, and more uniform application to fields. Proper collection and storage of manure prior to cropland application is covered in section 2.3.4.

RP 9.1 Apply moderate rates of manure and compost, and use materials with high available nitrogen content to meet the peak nitrogen demands

Where possible, growers should not rely solely on low-N manures, composted manures, or decomposed manures for the entire supply of N to the crop. Leaching losses have been found to be higher in manure fertilized fields than those strictly fertilized with inorganic N sources, due to poor synchronicity between plant demand and mineralization of residuals (Kirchmann & Bergström 2001). Only a small portion (5-30%) of the organic N in such materials will be converted to plant-available forms in the season following application. Therefore, to support the current seasonal crop N needs, a very high application rate would be required, resulting in a buildup of residual organic N that is released and subject to leaching when crop N demand is low. A more N-conserving strategy is to use moderate rates of low-N supplying manure and rely on inorganic N fertilizers or high N-supplying organic materials, such as dairy lagoon water, high-N poultry manure, blood meal, etc. to meet peak N needs.

The main limitation to this approach is the physical heterogeneity of manure and the uncertainty in behavior of manures and other organic fertilizers, which limits the farmer's ability to apply precisely timed and measured doses of N and other nutrients. Additionally, lowering manure N applications while retaining current dairy stocking rates translates into manure needing to be spread over significantly larger areas, often outside of the cropped property managed by dairy owners (as addressed in the overview of MM 9 above). The cost of this transportation is thus an additional barrier to adoption and the logistics involved in off-farm application will often also involve additional management and regulatory cost.

RP 9.2 Incorporate solid manure immediately to decrease NH_3 volatilization loss

Fresh manures, non-composted manures, and dairy lagoon water contain high levels of ammonium N, and are subject to ammonia volatilization loss. This loss creates uncertainty in the N fertilizer value of these materials, which may then prompt a farmer to apply additional N to reduce the risk of N deficiency. Ammonia may be lost within hours of application, and even very shallow incorporation into the soil will prevent this loss (Rotz 2004). By incorporating manure quickly, the available N forms will be conserved, allowing for a more reliable reduction of inorganic N fertilizer rates. It is a relatively common practice to quickly incorporate surface applications of solid manures and composts, especially on fields associated with dairies. Although manure product use on crops destined for human consumption is decreasing due to food safety concerns, there is some room for improvement by these growers (not associated with dairies) to match timing of custom manure spreading with incorporations. Note that solid manure applied to alfalfa and irrigated pasture and dairy lagoon water applied with furrow irrigation water cannot be incorporated into the soil.

RP 9.3 When applying liquid manure in surface gravity irrigation systems, use the delayed injection procedure to improve application uniformity

As discussed in RP 8.7, the delayed injection procedure can improve the application uniformity of fertilizers and other materials during furrow irrigation, and this is applicable to liquid manure injections as well (Schwankl & Frate 2004). In this practice, the liquid manure is not injected into the surface gravity irrigation water until the water has advanced part way across the field. The same barriers as cited in RP 8.7 (increased labor and conflicts in ranch logistics) were noted by members of the manure panel, with the addition of field delivery logistics being complicated by the fact that the lagoon may be some distance from the field to which the lagoon water is being applied.

RP 9.4 Use quick test methods to monitor dairy lagoon water nitrogen content immediately before and during application, and adjust application rate accordingly

Dairy producers in the Central Valley are required by regulation to analyze the composition of dairy lagoon water applied to each field on a quarterly basis. For many large dairies, due to high variability of the lagoon water composition, sampling and analysis needs to be more frequent in order to provide a better basis for nutrient applications. A quick test method for both the ammonium and organic N fractions has been developed, which is being used by some dairy producers as an on-farm method to guide targeted lagoon water N applications. According to panel members, the quick tests are not highly utilized in the study area.

Limiting the use of this test are the extra labor required for collection and analysis of the sample, and the extra management and education needed for recordkeeping, calculations, and interpretation of the data. Also, the test developed by UC for this purpose generates a small amount of mercury-containing waste, which must be disposed of in accordance with state and county public health law. Panel members added that, due to highly variable N concentrations and the need for testing to coincide as much as possible with planned application, development of a continuous monitoring device would be highly beneficial. At the very least, a quick test for lagoon water that does not have the mercury as a byproduct would be useful.

RP 9.5 Develop a nitrogen budget that includes crop nitrogen harvest removal, supply of nitrogen from manure, and other inputs

When using dry or liquid manure, it is important that adjustments to inorganic fertilizer application rates be made by determining the N content and N availability of the manure that will be applied. An N budget can then be created that, along with manure N-content, will consider N already present in the soil and irrigation water, as well as crop harvest removal, as discussed in RP 8.8. In setting N application rates, credit for residual N from composts and manures applied in previous years should be included. This can seem like a minor adjustment to N rates, but, as residual N builds up in the soil over a period of years with repeated applications of manure or compost, mineralization from this source will become significant. A commonly recommended strategy is to apply higher rates of compost/manure at first, then decrease over a period of years to a long-term sustainable rate based on the total (rather than immediately available) N content of the manure.

Besides the barriers described for RP 8.4, N budgets where manure is a source of nutrients are less certain than for crops receiving N only from inorganic commercial fertilizers, due to the uncertainty of mineralization rates of the organic N in manure. Variation in manure composition (for example, from one truck load to the next or during lagoon water pumping) can significantly increase costs of manure sampling and analysis (see RP 9.4).

RP 9.6 Calibrate solid manure and compost spreaders

Many growers applying manure or other organic amendments to their cropland hire custom application companies, and such companies usually weigh materials, in order to relate the weight to the volume capacity of the spreader. Knowing the water content and the weight of materials (and not merely the volume) applied is important, because the nutrient content of such materials is usually reported by analytical laboratories on a dry weight basis. Several techniques for calibrating application equipment exist. Barriers to improved management of this activity include the fact that calibration may be inconvenient, requiring extra time. Additionally, for dairy producers applying manure with their own equipment (rather than hiring a custom applicator), maintenance and calibration of spreaders is often not a high priority.

2.3.4 Improve Storage and Handling of Fertilizer Materials and Manure

Proper handling of fertilizers, manure, and other farm input materials is relatively straightforward with little to no extra time or money involved for producers. Simply ensuring farm workers are educated and trained to remain vigilant in regards to the handling of farm inputs can minimize risks to water quality. The following practices are adapted from Pettygrove et al. (1998).

MM 10: Avoid Fertilizer Material Spills and Manure Discharges During All Phases of Transport, Storage, and Application

Government and industry standards for fertilizer storage facilities exist and should be met by producers. These practices are applicable to all operations and generally have minimal financial and time costs. Training staff and regularly reminding them of the importance of observing protocol regarding the transport, storage, and application of farm input materials need to be standard operating procedure. If hiring custom applicators, farmers should verify that applicator employees are trained as well, prior to entering the business arrangement. Written cleanup procedures posted in storage, mixing and loading areas enhances staff awareness of spill cleanup protocol. Again, most operations already observe these recommendations, but ensuring vigilance should be a priority given the risks to water quality when protocol is not followed or accidents take place. Supervision of inexperienced staff during mixing and transfer activities can reduce potential for spills. Products should be clearly and properly labeled to avoid handling mix-ups.

Permanent mixing, loading, and storage areas should be located downslope of, and an adequate distance away from wells and surface water. These areas should be equipped with an impermeable floor with a curb to collect spills, and storage areas should have a permanent roof. Regular checks for signs of cracks or seepage should be conducted. As a precaution, a temporary plastic lined berm can be used when mixing and loading are performed in the field.

Storing minimal amounts of product onsite reduces the potential for spills and contamination. Hiring custom applicators and purchasing products close to the time of need are two ways to reduce the need for on-farm storage. The bermed containment area in storage and mixing areas should have a capacity to contain a minimum of 110% of the volume of product in storage.

RP 10.1 Do not overfill trailers or tanks. Cap or cover loads

Overfilling equipment beyond what it can safely handle unnecessarily increases the risk of spillage and waste. Similarly, ensuring liquid or solid fertilizer loads are properly capped or covered will keep materials in place, decreasing the opportunity for wind-born losses. This practice applies to all operations, has virtually no cost involved in its adoption, and should pose no risk to yield or quality of harvests.

RP 10.2 When transferring fertilizer, take care not to allow materials to accumulate on the soil

Bulk materials should be unloaded over concrete or other impermeable surfaces to allow for quick clean up. If leaks are noticed during liquid transfers, the transfer should be halted and the leaks attended to prior to resuming transfer. Taking precautions when utilizing a belt loader to transfer dry fertilizer can reduce the amount of fertilizer that accumulates below the belt. By opening the hopper door of the transport vehicle slowly and only after the belt has turned on, waste will be reduced.

RP 10.3 Maintain all fertilizer storage facilities and protect them from the weather

Storage facilities should be protected from the weather with a permanent roof, and should include an impermeable floor equipped with a berm to contain spills.

RP 10.4 Clean up fertilizer spills promptly

Should a spill occur, immediate attention should be given to contain the product. The goal is to reduce the amount of contamination resulting from the spill as much as possible. As such, care should be taken to ensure spilled material does not enter drains, waterways, sewers or wells. Dry spills should not be cleaned up with water. After cleanup, the spilled product should be applied to the field uniformly and at rates compatible with crop need.

RP 10.5 Shut off fertilizer applicators during turns and use check valves

A simple money- and environment-saving practice, turning off applicators when turning the tractor at non-cropped row ends saves otherwise wasted fertilizer and reduces contamination risks. Check-valves prevent leaks while the equipment is off and can be installed at all critical points besides just shank orifices.

RP 10.6 Maintain proper calibration of fertilizer application equipment

Applicator rates should be verified prior to fertilizer and manure application to the field and adjusted accordingly. Similarly, water and chemical flow metering devices should be calibrated for precise injection.

RP 10.7 Wellhead Protection

Wellhead protection via installation of wide concrete backstops circling the well is also mandated. Many wells were built prior to this legislation however, and often are only retrofitted once some other issue comes about, at which point the investigating well-technician mandates the upgrade. Poorly maintained protective devices, such as cracks in the casing also are a cause for concern. Panel members stated that on some farms fertilizer or pesticide tanks have been installed in close proximity to wells, posing a risk despite all other components being up to code. Generally however, these source protection practices are in high use.

RP 10.8 Distribute rinse water from fertilizer application equipment evenly throughout field

Rinse water should be treated just as fertilizer and applied evenly to the crop in order to avoid creating areas with nutrient concentrations beyond what is required by the crop. This can be easily accomplished by discharging the rinse water into the irrigation stream, for example.

RP 10.9 Avoid manure spills/discharges during transport, storage, and application

Manure should be transported, stored, and applied so as to prevent spills or discharges that would pollute water with nutrients and pathogens. Methods for safe handling and storage of manure are described by the Livestock and Poultry Environmental Learning Center, specifically the Animal Manure Management *Handling and Storage Options for Manure* section (2011).[10] The Central Valley Regional Water Quality Control Board adopted the General Order for Waste Discharge from Existing Dairies[11] in May of 2007. In addition to manure land application practices (see MM 9), the General Order regulates design and operation of liquid manure storage lagoons and corrals. Requirements for manure storage ponds include:

- An adequate storage volume, with the pond designed to create mixing (i.e., a uniform composition) of liquid to be delivered to crop fields
- A distribution system (pumps, pipelines) that enables delivery of small doses of lagoon water to fields, along with a flowmeter
- A conveniently located sampling valve

---

[10] http://www.extension.org/pages/8638/handling-and-storage-options-for-manure

[11] http://www.waterboards.ca.gov/centralvalley/water_issues/dairies/dairy_program_regs_requirements/index.shtml

2.4 Management Measure Summary

In this section we summarize all recommended practices in table form below (Table 2) and with short recapitulations of each practice's estimated current extent of use within the study areas and associated barriers to increased adoption.

Table 2. Summary of management practice current extent of use and barriers to increased adoption.

YQ (risk to yield or quality, poor market) CC (capital cost--infrastructure, equipment) OC (operational cost--labor, management, training) RL (ranch logistics) LT (land tenure) ED (education, training, demonstration needs) IT (insufficiently developed technology or more research needed)	**Current Extent of Use**		**Barriers to increased adoption**
	Common practice in some crops	Less common practice	
1. Perform irrigation system evaluation and monitoring			
1.1 Conduct irrigation system performance evaluation		x	OC, LT, ED
1.2 Use flow meters or other measuring devices to track water volume applied to each field at each irrigation	x		CC, OC, ED
1.3 Conduct pump performance tests	x		OC, ED
2. Improve Irrigation scheduling			
2.1 Use weather-based irrigation scheduling	x	field crops[12]	OC, RL, ED, IT
2.2 Use plant-based irrigation scheduling		x[12]	OC, RL, ED
2.3 Use soil moisture content to guide irrigation timing and amount	x	field crops[12]	OC, RL, ED
2.4 Avoid heavy pre-plant or fallow period irrigations		x	YQ, RL, ED
3. Improve surface gravity system design and operation			
3.1 Convert to surge irrigation if appropriate		x	CC, OC, RL, ED
3.2 Use high flow rates initially, then cut back to finish off the irrigation		x	OC, RL, ED
3.3 Reduce irrigation run distances (i.e., field lengths) and decrease set times		x[13]	YQ, CC, OC, LT, ED
3.4 Increase flow uniformity among furrows, e.g., by compacting furrows, use of "torpedos"		x	OC
3.5 Grade fields as uniformly as possible	x		OC, ED
3.6 Where high uniformity and efficiency are not possible, convert to drip, center pivot or linear move systems	x		CC, OC, LT, ED

---

[12] According to panel members, calendar scheduling remains common in much of the TLB's field, grain and hay production due to the barriers cited. Tree crop and vegetable producers tend to make more use of ET and CIMIS data, although historical ET is more commonly utilized over the more effective real-time CIMIS. Plant or soil moisture monitoring techniques are also frequently used in tandem to guide their water application rate and timing decisions.

[13] TLB fruit orchards and SV vegetable fields utilizing surface irrigation already have reduced run distances.

YQ (risk to yield or quality, poor market) CC (capital cost--infrastructure, equipment) OC (operational cost--labor, management, training) RL (ranch logistics) LT (land tenure) ED (education, training, demonstration needs) IT (insufficiently developed technology or more research needed)	**Current Extent of Use**		**Barriers to increased adoption**
	Common practice in some crops	Less common practice	
4. Improve sprinkler system design and operation			
4.1 Monitor flow and pressure variation throughout the system		x	OC
4.2 Repair leaks and malfunctioning sprinklers, follow manufacturer recommended replacement intervals	x	x (optimal frequency)	CC, OC, ED
4.3 Operate sprinklers during the least windy periods (when logistically possible)	x		RL
4.4 Use offset lateral moves		x	OC, RL, IT
4.5 When pressure variation is excessive, use flow control nozzles		x	CC, LT, ED
5. Improve drip and microsprinkler system design and operation			
5.1 Use appropriate lateral hose lengths to improve uniformity	x		ED, CC
5.2 Check for clogging potential and prevent or correct clogging	x	x (optimal frequency)	OC, CC, ED
6. Make other irrigation infrastructure improvements			
6.1 Installation of subsurface drains		x	CC, IT[14]
6.2. Backflow prevention	x		CC, ED
7. Modify crop rotation			
7.1. Grow cover crops		x	YQ, CC, OC, RL, ED, IT
7.2 In annual crop rotations, include deep-rooted or "N scavenger" crop species, such as oilseeds, and sugarbeet		x	YQ, CC, OC, RL
7.3 Grow more crops per year, e.g., dairy forage triple crop rotation		x	OC, RL
7.4 Include perennial crop in rotation, e.g., alfalfa or perennial grasses		x	CC, RL, LT

---

[14] Subsurface drains are already commercially developed; rather effluent disposal and the option of installing drains outside of areas of perched water tables need more research and development.

YQ (risk to yield or quality, poor market) CC (capital cost--infrastructure, equipment) OC (operational cost--labor, management, training) RL (ranch logistics) LT (land tenure) ED (education, training, demonstration needs) IT (insufficiently developed technology or more research needed)	**Current Extent of Use**		**Barriers to increased adoption**
	Common practice in some crops	Less common practice	
8. Improve rate, timing, placement of N fertilizers			
8.1 Adjust N fertilizer application rates and timing based on soil nitrate testing	x	x (frequency, quick tests)	YQ[15], OC, ED
8.2 Adjust timing of N fertilization based on plant tissue analysis	x (where appropriate)		YQ[1515], OC, ED
8.3 Apply fertilizer N in small multiple doses rather than single large doses	x	x (optimal frequency)	OC, ED
8.4 Measure N content of irrigation water and adjust fertilizer rates accordingly		x	OC, LT[16], ED
8.5 Use low rates of foliar N to replace a portion of soil applied N (when applicable)		x	OC, ED, IT
8.6 Vary N rates within large fields according to expected need, rather than applying the same rate everywhere		x	OC, CC, ED, IT
8.7 When N fertigating in surface gravity systems, use delayed injection procedure		x	OC, RL, ED
8.8 Develop N budget that includes crop N harvest removal, supply of N from soil, and other inputs		x	OC, ED, IT
8.9. Use controlled release fertilizers, nitrification inhibitors and urease inhibitors		x	YQ[15], CC, ED, IT
9. Improve rate, timing, placement of animal manure and organic amendment applications			
9.1 Apply moderate rates of manure and compost, and time the use of materials with high available N content to meet the peak N demands		x	YQ, OC, RL, ED, IT
9.2 Incorporate solid manure immediately to decrease NH_3 volatilization loss	x		OC, ED

---

[15] If soil or tissue tests or use of inhibitors indicate an opportunity to delay or reduce fertilizer applications, the grower may still have concern for yield or quality impacts should they not retain an over-application buffer to mediate this.

[16] Land tenure may present a challenge due to renting growers being hesitant to report contaminated water sources to landlords.

YQ (risk to yield or quality, poor market) CC (capital cost--infrastructure, equipment) OC (operational cost--labor, management, training) RL (ranch logistics) LT (land tenure) ED (education, training, demonstration needs) IT (insufficiently developed technology or more research needed)	**Current Extent of Use**		**Barriers to increased adoption**
	Common practice in some crops	Less common practice	
9.3 When applying liquid manure in surface gravity irrigation system, use delayed injection procedure to improve application uniformity[17]		x[17]	OC, RL, ED, IT
9.4 Use quick test methods to monitor dairy lagoon water N content immediately before and during application, and adjust application rate accordingly	x	x (optimal frequency)	OC, ED, IT[18]
9.5 Develop N budget that includes crop N harvest removal, supply of N from manure and other inputs	x (in dairies as regulated)	x	OC, ED, IT
9.6 Calibrate solid manure and compost spreaders	x		OC, RL, ED
10. Avoid fertilizer material and manure spills during transport, storage and application			
10.1 Do not overfill trailers or tanks. Cap or cover loads	x		ED
10.2 When transferring fertilizer, take care not to allow materials to accumulate on the soil	x		ED
10.3 Maintain all fertilizer storage facilities and protect them from the weather	x		CC, OC, ED
10.4 Clean up fertilizer spills promptly	x		ED
10.5 Shut off fertilizer applicators while turning at the end of the field and use check valves	x		OC, ED
10.6 Maintain proper calibration of fertilizer application equipment	x		ED
10.7 Wellhead protection	x		ED
10.8 Distribute rinse water from fertilizer application equipment evenly throughout field	x		OC, RL, ED
10.9 Avoid manure spills/discharges during transport, storage and application	x		ED

---

[17] Note dairy lagoon water is very rarely applied to crops other than forages.

[18] Although such tests are already commercially available, development of a quick test without a hazardous byproduct and/or a continuous monitoring system would significantly improve adoption.

2.4.1 Commonly utilized practices

California's high-value agricultural framework already demands from its practitioners a certain amount of "future-oriented and innovation-seeking attitudes" in order to survive economically (Brodt et al. 2006). This is reflected in the number of practices listed herein that have already been widely and voluntarily adopted by the farmers of our study areas. UC Cooperative Extension, the USDA NRCS, and other research, education, and outreach organizations have been instrumental in providing the technical advice and the proof that farmers demand when changes in management are under consideration (Pence & Grieshop 2001; Goodhue, Klonsky, & Mohapatra 2010).

The rate and period of time over which management practices have changed is largely unknown due to sparse survey data. Additionally, field and crop variables alter effects of various management schemes on leaching (Tilman et al. 2002; Fixen 2011). These facts, coupled with the usually long travel time of nitrate to groundwater, mean that it is impossible to say with certainty to what degree future groundwater nitrate concentrations will respond to the positive management changes already instituted and their increasing use.

Based on input from the five expert panels convened during April and May 2011, we conclude that the following practices that contribute to N use efficiency have been adopted by a significant portion of the growers in the two project study areas and represent a positive change from past practices (as summarized in Table 1).

MM 2: Improve Irrigation Scheduling, RP's 2.1, 2.2, 2.3, 2.4

The use of weather based irrigation scheduling tools (i.e., CIMIS), in conjunction with monitoring of soil moisture and/or plant water indices, has the potential to reduce excessive water applications, keeping nutrients within the rootzone longer. Tree crop producers using micro or drip irrigation, as well as many vegetable producers, commonly utilize ET data (usually historical) to guide their scheduling and more often monitor soil moisture or plant water status as well. Calendar scheduling still dominates field crop and forage production. Barriers to the use of these scheduling tools for all crops are described in section 2.3.1 and 2.4.2.

MM 3: Surface Irrigation Improvements, RP's 3.5 and 3.6

- Optimizing field grades by use of laser leveling technology is in widespread use.
- Converting to mechanized sprinkler or drip irrigation systems is employed by growers when economically feasible and crop appropriate. High value crops, such as most vegetables and many orchards and vineyards have already largely been converted to more efficient drip or microsprinkler systems.

MM 4: Sprinkler Irrigation Improvements, RP's 4.2 and 4.3

- Attention to irrigation system repair needs is generally adequate, with leaks and malfunctioning nozzles repaired or replaced as necessary. More regular monitoring and attention to gradual declines in performance would be beneficial however, particularly with better attention to manufacturer recommended nozzle and sprinkler component "life spans."
- Growers avoid operating sprinklers during periods of high wind as much as possible, although scheduling concerns can make this difficult.

MM 5: Drip and Microsprinkler System Improvements, RP's 5.1 and 5.2

- Engineering of drip and microspinkler systems has continually improved, as has the understanding of their optimal management. Appropriate lateral hose lengths are the norm in newly installed systems and the higher upkeep and replacement needs of these systems (as opposed to gravity systems, for example) allows for design improvement opportunities that are generally attended to by producers.
- Growers have greatly improved their understanding of the maintenance requirements of drip and microsprinkler systems, generally attending well to clogging from chemical and mechanical contaminants through both prevention and treatment. Commonly, new users of these systems experience a learning curve, and management may not be optimal during this phase and may remain as such without adequate education.

MM 6: Make Other Irrigation Infrastructure Improvements, RP 6.2

- Concrete backstops for wellhead are mandated by law on newly constructed wells and thus well attended to by growers. Exceptions include older uninspected wells, although growers are more often than not conscientious of wellhead protection measures such as not locating fertilizer tanks too close to wellheads.

MM 8: Rate, Timing, and Placement of Nitrogen Fertilizers, RP's 8.1, 8.2, 8.3, 8.6

- Soil testing to help guide fertilizer application rates is a common practice in some row crop production and nearly all large scale vegetable crop production. However, increased use of quick testing methods or more frequent laboratory testing has the potential to further refine rate decisions throughout the season.
- Plant tissue analysis to guide fertilizer timing decisions is also a relatively common practice in some operations but may be unhelpful in some crops where result turnaround time and rapid changes in growth make it difficult to reflect realtime changes in the field.
- Splitting fertilizer applications over the course of the growing season to better match plant uptake curves is relatively common and represents a large contribution to overall nitrate

leaching reduction and improvement over past practices. In non-fertigated crops, although split applications are common, further division of N applications is likely warranted to optimize timing with plant needs.

MM 9: Rate, Timing, and Placement of Animal Manure, RP's 9.2, 9.5

- Immediate incorporation of solid manure is a common practice that reduces gaseous N losses and thus increases N use efficiency.
- Estimation of annual harvest removal for N budgeting purposes is a newly mandated practice for California dairy operations in the Central Valley. However, these new limitations to on-farm recycling of manure have resulted in increased transfer of manure off-dairy. The consequence is an increased application of organic N to unregulated fields by producers that may not be properly accounting for the N content. The value of requiring the N budgeting methodology for crops that do not regularly receive dairy manure, as a means of reducing nitrate leaching, is uncertain at this time.

MM 10: Material Storage and Handling

- All recommended material storage and handling practices are generally assumed to be followed by the bulk of producers although continued vigilance in the form of regular educational reviews is important. The new dairy wastewater discharge regulations are applicable to management and construction of lagoons and corrals along with manure land application protocols.

2.4.2 Less Commonly Utilized Practices

Significant barriers limit the ability of producers to adopt some of the practices known or theorized to lessen leaching of nitrate to groundwater from agricultural land. The feasibility of overcoming some of these barriers varies, with some practices facing significant impediments to increased adoption and others with fewer obstructions to overcome their underutilization. As outlined in Table 1, these include economic barriers (operation and capital costs or yield risks) of varying degrees, educational requirements, farm operation logistical conflicts, land tenure conflicts, and need for additional research.

For example, growers who rent their land may be reluctant to invest in equipment that will remain with the land owner (land tenure conflict). Water district delivery schedules or pumping capacity may logistically constrain the farmer's ability to more precisely time irrigations to match crop need for water (logistical conflict). Additionally, some practices have good theoretical potential to reduce nitrate leaching from irrigated cropland, but require more research, development, and/or verification of cost effectiveness before becoming widespread commercially viable options (newer controlled release fertilizers, for example).

In many cases, increased adoption of improved practices is enhanced by access to effective educational programs. Panel members discussed the educational barriers associated with a number of management practices regarding water and nitrogen budgeting. Outreach and knowledge transfer efforts are crucial to increasing adoption of improved management practices. Delivery of this information will largely depend upon certified crop advisors, UCCE agents and NRCS personnel. According to some panel member commentary, attention to delivery methods needs to be considered when meeting the training and continued educational needs of growers. They emphasized that text heavy pamphlets and web pages are often ineffective and that field days, how-to videos, and picture-laden pamphlets are, in their experience, a more effective and efficient means of reaching the audience and increasing voluntary adoption of improved practices. Additionally, as many management tasks are carried out by farm laborers who communicate primarily in Spanish, attention to language is important when developing knowledge transfer activities and materials.

As summarized in Table 2, according to the literature and expert panel members, implementation of one, or a combination, of the following practices represents an opportunity to reduce agricultural nitrate leaching risk with increased adoption; however, overall feasibility will be determined by the noted barriers. Recall that not all practices are adaptable or appropriate to all crops, soils, or irrigation systems, and thus the extent of any increased use is also limited by farm-specific characteristics.

MM 1: Perform Irrigation System Evaluation and Monitoring, RP 1.1

- Irrigation system performance evaluations are the critical first step to addressing water use efficiency and uniformity of application. Although the mere act of evaluation will not mitigate nitrate leaching, acting upon the knowledge gained has the potential to reduce leaching from some fields. Past programs (i.e., DWR/NRCS Mobile Irrigation Laboratories) were successful in providing these evaluations free of charge, and with the decline of this service, the percentage of growers that keep up with regular performance evaluations has also declined, due primarily to cost and time constraints.

MM 2: Improve Irrigation Scheduling, RP's 2.1, 2.2, 2.3, 2.4

- The use of weather based irrigation scheduling tools (i.e., CIMIS), in conjunction with monitoring of soil moisture and/or plant water indices, has the potential to reduce excessive water applications, keeping nutrients within the rootzone longer. Vegetable and tree crop producers do commonly utilize ET data (mostly historical data) to guide their scheduling and often monitor soil moisture as well (especially in orchards), but calendar scheduling remains the most common method of scheduling in field and forage crops. Barriers for all crop groups include conflicting labor schedules, ranch logistical conflicts (e.g., timing of necessary pest control measures), water availability, field variability, and irrigation system constraints (generally more difficult in surface systems than drip or sprinkler systems). Better grower education and access to irrigation specialists can provide the training required to maintain and use these technologies and can help overcome one of the main barriers (besides logistical issues) that keep better water budgeting (especially use of real-time ET data) from being more highly utilized.

- Growers are typically aware of the disadvantages of excessive pre-plant and fallow period irrigations and many try to apply the bulk of their N fertilizers after pre-irrigation and stand establishment. However, salt control concerns and the fear of poor crop germination and establishment (along with inexpensive water in some areas) tend to keep over-application of water during this vulnerable period relatively common. The reduced nutritional needs of crops during early establishment equates to high loss levels only if soil nitrate is significantly present during this phase. High water application will not present a problem when soil N levels are low, and, as such, strict N management can be equally critical to overall N use efficiency. Keeping in mind the importance of salinity control and successful plant establishment, the potentially highly mitigative practice of conservation of water during fallow and early growth periods deserves to be a continued focus of educational outreach programs.

MM 3: Improve Surface Gravity Design and Operation, RP's 3.1, 3.2, 3.3, 3.4

- Surge and cutback irrigation methods offer increased water use efficiency in surface irrigation systems, but the increased labor costs, ranch logistics and, in some cases, capital costs have led to the underutilization of these techniques. While automated valves can reduce the labor cost barrier, they would impose equipment costs. Note surge irrigation is only appropriate on some soils in furrow irrigated row crops.
- Reduced field length can improve irrigation efficiencies and reduce leaching risk, but the significant economic barriers (reduced yield through loss of land, and increased capital and operational costs) are difficult to overcome in most circumstances. Even so, the number of fields under a half mile has increased since times past. Most fruit orchards and the majority of Salinas Valley vegetable fields are already short in length.
- Optimizing flow uniformity via furrow compaction through the use of torpedoes, bolas, or other weighted objects is utilized by some furrow-irrigating growers, although not the majority. Research on cost-effectiveness may overcome economic barriers, while educational opportunities exist to increase adoption.

MM 4: Improve Sprinkler Design and Operation, RP's 4.1, 4.2 and 4.4

- Better monitoring of pressure and flow variations within sprinkler irrigation systems represents a feasible improvement option. The implementation challenges of labor costs and required expertise should be surmountable especially if programs, such as the DWR/NRCS Mobile Laboratories irrigation evaluation services offered in the past, were reinstated.
- Nearly all growers using sprinklers attempt to maintain the equipment. However, a more proactive maintenance schedule would encourage earlier detection of gradual declines. More

timely nozzle, head seal, and impact "spoon" replacement schedules could also be beneficial. Labor and capital costs are the main impediments to optimized sprinkler maintenance.

- Offsetting lateral moves generally improves irrigation uniformity and, although not utilized by a majority of growers that sprinkler irrigate, the practice is not rare. Additional labor costs present the main barrier, along with logistical issues, such as limitations to adjusting irrigation scheduling. Additionally, more research is warranted in comparing the mitigation potential between offsetting laterals or simply spacing the laterals closer together, and which may be the most cost-effective option.

MM 5: Improve Drip and Microsprinkler Design and Operation

- Although drip systems are capable of high distribution uniformity and offer theoretically more control over matching water application rates to specific plant needs, without adequate attention to system maintenance and scheduling, the overall efficiency can drop below that of a well-managed surface system. Distribution uniformity and scheduling practices are quite varied, and increased vigilance would be beneficial. Labor and capital costs, along with a need for adequate training, present barriers to drip systems meeting optimum efficiencies.

MM 6: Make Other Irrigation Infrastructure Improvements, RP 6.1

- Closely spaced subsurface drains can divert a significant amount of any leached nitrate from entering the groundwater in areas of perched water tables, thus representing a groundwater contamination reduction strategy where they are installed. However, the drainage water must be treated, and current methods for treatment are not yet fully developed. Should treatment technology improve, much more research will be required to determine whether installation of deeper drains in areas with deeper water tables might be an effective option for mitigating groundwater pollution in these areas.

MM 7: Cover Crops and Crop Rotations, RP's 7.1, 7.2, 7.3, 7.4

- Covercropping has been shown to significantly reduce leaching during fallow periods when excess N may remain in the upper soil horizons. Increased grower use is impeded by intertwining and sometimes unpredictable aspects, depending on both the cover crop and cash crop species. More educational outreach and research (crop and site specific), along with economic incentives would allow for some increased use of cover crops. Although logistical issues (water availability, planting schedule disruption, disease introduction) will continue to present barriers in some sectors, the evidence suggests this practice has high mitigative potential and some increased adoption is likely feasible, but the added cost of covercropping (especially the cost of the additional water needed to produce it) with little economic return still needs to be addressed to see more widespread adoption.

- The incorporation of deep rooted scavenger species or perennial species into crop rotation schemes faces barriers similar to covercropping, including capital and operating costs and planting schedule disruptions, but does provide some opportunity for income, unlike traditional cover crop species. Alfalfa, an excellent scavenger, is already grown extensively for the numerous dairies in the TLB, although its rotation diversity is somewhat limited (e.g., not used in vegetable crop rotations, etc.).

MM 8: Rate, Timing, and Placement of Nitrogen Fertilizers, RP's 8.4, 8.6, 8.7, 8.8, 8.9

- Delayed injection of fertilizers into surface irrigation systems can improve fertilizer application uniformity, although economic incentive to overcome the additional labor costs is currently lacking. Labor costs would be traded for capital costs, should there be development of automation devices for this practice.

- Automated precision agriculture technology has been shown to enhance N use efficiency, particularly in the rainfed mid-West. The economic benefit of these technologies in the diverse irrigated fields of California has been mixed. Further research and development are required before these technologies can significantly and consistently benefit the high crop diversity found in California.

- Nutrient budgeting that accounts for harvest removal, as well as nitrogen already present in irrigation water and soil organic matter pools, is a complex tool that, in some instances, can be used by farmers to identify opportunities to reduce N fertilizer or manure application rates and timing. Increased adoption is dependent upon more crop specific research and associated education and outreach, as well as addressing the economic burdens associated with the operating costs of increased recordkeeping and analysis.

- Research shows potential for increased N use efficiency using some of the recently commercialized nitrification and urease inhibitors. Additional research under more variable and specific field conditions is needed to show product cost-effectiveness and the ability to reduce crop nitrogen fertilizer requirements.

MM 9: Rate, Timing, and Placement of Animal Manures, RP's 9.1, 9.3, 9.5

- Reducing plant-available nitrogen release from organic matter at times of low crop need can be accomplished by only applying moderate amounts of solid manures and composts and supplementing with inorganic nitrogen fertilizers to meet crop need. Estimating release rates from organic N sources still represents a problem in calculating optimal application rates of both organic and inorganic fertilizers in these systems. The increasing levels of dairy manure that is transferred off-farm to unregulated fields (often to growers that do not properly account for organic N in their fertilization regimes) demands additional research, monitoring, and education efforts.

- Delaying injection of liquid manure into surface irrigation water can enhance uniformity of nutrient application, but logistical constraints and the current lack of automated methods for doing this burdens producers with labor costs, making the practice difficult to consistently implement.

- Monitoring dairy lagoon water N content via quick test methods is not highly utilized at present although the new dairy waste discharge regulations now require quarterly sampling and analysis. By testing just prior to every application, a better estimate of total N application is expected. Although the practice is meant to address the nutrient level fluctuation and varying dilution ratios, the variability of concentration values, inadequately educated farm personnel, and cost concerns stand as major barriers, along with additional research and development of a quick test that is not associated with a hazardous waste byproduct as is currently the case.

In summary, it is certain that with the increased adoption of improved management practices, the mass of nitrate leached from the crop rootzone can be reduced to well below the rate of loss that has resulted in the currently observed nitrate concentrations in affected aquifers. Furthermore, the rate is expected to have already decreased to some degree due to increasing use of improved management practices by growers in the study areas. The applicability and effectiveness of any one management practice, or group thereof, varies according to field specific variables (crop and soil characteristics), and the current level of NUE achieved. Overcoming significant barriers remains a hurdle, although moderate increases in use of improved practices should be feasible. Logistical, educational, and financial constraints are the most frequently cited impediments to increased adoption of better management practices.

2.5 Crop Management Practice Scenarios

In this section, hypothetical scenarios of combinations of practices are presented for example crops of four main crop groups: vegetables; tree crops and grapes; field crops, including grain and hay; and forages receiving dairy manure. The purpose of presenting these scenarios is not to prescribe particular management measures for these crops, but rather to illustrate the complexity in decision making for growers and the barriers that will need to be addressed.

Maximizing crop nitrogen use efficiency (NUE), and thereby minimizing nitrate leaching losses, often requires a combination or “bundle” of management measures, rather than just a single practice. For example, improvements in both irrigation and fertilizer application timing may be needed, and making only one of these improvements would likely have little impact.

Because of the wide variation in soil properties, crop characteristics, water supply availability, weather, and production economics, the particular combination of practices for achieving efficient N use will be farm- and even field-specific.

However, certain management measures and recommended practices are applicable to all farming operations, regardless of crop category, including:

- Irrigation system evaluation and monitoring
- Improving irrigation scheduling via use of weather-, plant-, or soil-based scheduling systems
- Adjusting N application rates and timing based on soil or tissue testing and irrigation water N content
- Recordkeeping for evaluation of success with any altered management scheme
- Wellhead protection, backflow protection, and proper storage and handling of fertilizer products

Other recommended practices are appropriate only for certain crop species, irrigation systems, soils, or climatic conditions. Selection of management practice bundles requires site-specific considerations, as field and crop variables alter effects of various management schemes (Tilman et al. 2002; Fixen 2011). Thus, many of the practices described in sections 2.3 may be very good choices for a particular farm, but may not be applicable to the entire, diverse crop group.

Crop-specific examples of improved management options that could be used in tandem to improve nitrogen use efficiency are presented for each crop group. Crops used in these examples occupy a large acreage within the study area and have been the focus of N management research and, in some cases, nitrate leaching.

The objective for all management changes is essentially the same for all scenarios: increase N and water use efficiency, reduce deep percolation of nitrate-laden water, and maintain crop yields and quality. Evaluation of the outcomes of adoption of new practices is a crucial component of any change in management and should be considered an implied management measure for all example scenarios.

Records of crop yield and quality, total water use, total N use, costs, and other notable outcomes must be evaluated and analyzed for effectiveness and cost-benefit ratio.

Again, because each unique farming situation demands individualized management plans, the scenarios presented here are provided to give a more realistic sense of the constraints or barriers a producer may face, and are not meant as required formulas for reduction of N transfer to groundwater for these crops. For example, covercropping in orchards may be feasible in some cases, while in other orchard crops harvest machinery (sweepers) requires that the orchard floor be smooth and firm, making covercropping an impossibility. Irrigation system and soil characteristics of individual fields will also influence strongly the impact of practices on crop N use efficiency and Nitrate leaching losses.

2.5.1 Vegetable Crops

Vegetable crops grown in the study areas are both highly diverse and profitable with a well-developed infrastructure surrounding their production and marketing. These crops, because of their (usually) shallow root systems are inherently less efficient in use of water and nitrogen; and some of the vegetable crops, for example leafy greens, require an ample supply of N up to the point of harvest. However, opportunities to increase these efficiencies via good management do exist, and many practices known to contribute to reductions in Nitrate leaching have already been adopted by a large portion of producers (as outlined in section 3). For example, the generally profitable nature of vegetables has led in recent years to widespread conversion from furrow and overhead sprinklers to drip irrigation systems, which can offer more precisely controlled water delivery under good management and maintenance. Besides the practices listed above that are applicable to all crop categories, practices generally recommended specifically to vegetable crops include weather-based irrigation scheduling; restricting heavy fallow period and pre-plant irrigation as much as possible; covercropping; soil N quick-tests and split fertilizer applications.

Following are examples of practice bundles that might be adopted for lettuce production, a very important crop in the Salinas Valley (Table 3); and processing tomatoes, a highly important TLB crop (Table 4).

Table 3. Example management bundle: Lettuce.[19]

Region: Salinas Valley **Crop: Lettuce** **Irrigation: Sprinkler to establish, then drip**	
Improved Practices	**Costs & other barriers**
Irrigation system evaluation and monitoring	
Conduct irrigation system performance evaluation and identify opportunities to improve uniformity and reduce water application during sprinkler phase	• Consultant services to measure sprinkler water distribution and application efficiency
Install and use flow meters to track water volume applied to each field at each irrigation	• Flow meters and installation • Software to manage large amount of data • Management time to review information
Irrigation scheduling	
Use weather-based irrigation scheduling and focus on reducing sprinkler irrigations used during germination and establishment	• Customized software • Training of managers • Irrigator work schedules may be affected.
Improve rate, timing, placement of N fertilizers	
Adjust N fertilizer rate based on more intensive soil nitrate testing	• Cost of collection and analysis of soil samples • Management time to interpret results
Measure N content of irrigation water and adjust fertilizer rates accordingly	• Cost of analysis. • Recordkeeping • Management time to interpret results.

---

[19] (Smith & Cahn 2011) Lettuce trial: CIMIS guided germination irrigation reduced water application by ~2.5” and led to reduced leaching per lysimeters. Use of presidedress soil tests allowed for average reduction of 61.6 kg N/ha (55 lb N/acre) with no change in yield. Low residue covercropping considered possible tool as well, but only in soils of low to moderate soil nitrate levels. Breschini & Hartz (2002) Lettuce trial: PSNT-guided fertilization plots averaged 8mg/kg lower residual soil NO_3-N than controls. Jackson et al. (1994) Lettuce field trial (EPIC model): Highest leaching coincided with sprinkler irrigation to germinate the second crop. Model without pre-plant irrigation yielded ~40% decrease in leaching. Jackson et al. (1993) Lettuce trial: Non-leguminous covercropping reduced winter leaching without interrupting planting schedule.

Table 4. Example management bundle: Processing tomatoes.[20]

Region: San Joaquin Valley **Crop: Processing tomato from transplants** **Irrigation: Sprinkler to establish, then drip**	
Improved Practices	**Costs & Other Barriers**
Irrigation system evaluation and monitoring	
Conduct irrigation system performance evaluation and identify opportunities to improve uniformity and reduce water application during sprinkler phase	• Consultant services to measure sprinkler water distribution and furrow distribution uniformity and application efficiency
Install and use flow meters or other measuring devices to track water volume applied to each field at each irrigation	• Flow meters, installation, software. • Management time to review information.
Irrigation scheduling	
Use weather-based irrigation scheduling	• Improved software. • Training of managers. • Irrigator work schedules may be affected
Improve rate, timing, placement of N fertilizers	
If very high N fertilizer rates are being used to provide for the increased yields under drip irrigation, experiment with lower N rates, e.g., similar to or lower than rates used for furrow-irrigated tomatoes.	• Potential risk to yield • Difficult for farmers to conduct rate comparisons on commercial fields
Adjust N fertilizer rates based on soil nitrate testing during season	• Cost of collection and analysis of soil samples • Some management time to interpret results
Use soil nitrate testing at or immediately after harvest and consider results in determining the next year's N fertilizer program	• End-of-season soil analyses can be difficult to interpret
Measure N content of irrigation water and adjust fertilizer rates accordingly	• Cost of analysis • Management time to interpret results

---

[20] Hartz & Bottoms (2009) Processing tomato trial: Switch to drip allowed for a seasonal N application reduction sufficient to maintain the increased yield that comes with drip irrigation for this crop. (Hartz, LeStrange, & May 1994) CIMIS ET data for drip irrigation scheduling reduces N fertigation requirements.

2.5.2 Tree Fruits, Nuts and Vines

Tree fruits and nuts represent a large industry of their own in the southern San Joaquin Valley TLB study area, representing over 35 % of the irrigated agricultural land of the basin at the time of the most recent DWR reports. Vineyards, including table, raisin and wine grape production are also an extremely important in both valleys, representing over 18% of the total TLB agricultural land and 20 % of the Salinas Valley agricultural production. According to the most recent DWR reports, permanent crops in the TLB amount to over 566,000 hectares (over 1,400,000 acres) or 58 % of the irrigated agricultural land. Vines, deciduous fruit, subtropical fruit and nut trees are all managed differently from each other, with contrasting N and irrigation needs. Tissue testing is generally advisable over substantial soil testing regimes in these crops.

Table 5. Example management bundle: Almonds.[21]

Region: San Joaquin Valley **Crop: Almonds** **Irrigation: Microsprinkler**	
Improved Practices	**Costs & Other Barriers**
Irrigation scheduling	
Use weather-based irrigation scheduling	• Custom software • Training of managers and irrigators • Irrigator work schedules may be affected
Improve rate, timing, placement of N fertilizers	
Collect leaf samples for nutrient analysis on routine basis, not just for trouble shooting	• Cost of collection and analysis of soil samples. • Management time to interpret results.
Consider published UC leaf sample N critical values in making N fertilizer use decisions	• Recordkeeping • Consultant costs • Lack of confidence in tissue sampling and recommended critical values; lack of UC multi-year research
Time N fertilizer applications according to UC recommendations	• Management time • Adjustment to labor schedule
Measure N content of irrigation water and adjust fertilizer rates accordingly	• Cost of analysis. Management time to interpret results.

---

[21] Brown (unpublished) Almond trial: Split applications and microirrigation.

Table 6. Example management bundle: Peaches.[22]

Region: San Joaquin Valley **Crop: Peaches** **Irrigation: Furrow or basin**	
Improved Practices	**Costs & Other Barriers**
Irrigation scheduling	
Check soil moisture to aid decision on timing and amount of water applied	• Water supply delivery schedules may limit grower flexibility in irrigation timing
Use weather-based irrigation scheduling	• Custom software • Training of managers and irrigators • Irrigator work schedules may be affected • Water supply delivery schedules may limit grower flexibility in irrigation timing
Improve rate, timing, placement of N fertilizers	
Collect leaf samples for nutrient analysis on routine basis	• Cost of collection and analysis of soil samples • Management time to interpret results
Consider published UC leaf sample N critical values in making N fertilizer use decisions	• Recordkeeping • Consultant costs • Lack of confidence in tissue sampling and recommended critical values; lack of UC multi-year research
Split N applications during season, and time applications according to UC recommendations	• Management time • Adjustment to labor schedule
Measure N content of irrigation water and adjust fertilizer rates accordingly	• Cost of analysis • Management time to interpret results

---

[22] Malusa, Buffa, & Ciesielska (2001) Peach trial: Split application of fertilizer retains yield. (Johnson et al. 2001) Peach trial: Applying 50% N requirements as foliar retains yield. Niederholzer et al. (2001) Peach trial: Spring N applications sufficient to maintain growth and yields, no need for fall N application.

2.5.3 Field Crops, Grain, and Hay

Field crop, grain, and hay production amounts to over 55% of the irrigated agricultural land in the TLB, and cotton alone accounted for nearly half of this production per most recent DWR surveys. In the Salinas Valley, grain and hay production accounted for about 10% of the production in 1997. Most of these crops are surface irrigated, with a smaller percentage being sprinkler irrigated. In general, drip is either totally non-applicable or economically unfeasible. Optimizing surface irrigation efficiency is thus of high importance in this group, which is more adaptable to using plant-based irrigation scheduling and incorporating perennials into crop rotation schemes than vegetables.

Table 7. Example management bundle: Cotton.[23]

Region: San Joaquin Valley **Crop: Cotton** **Irrigation: Furrow**	
Improved Practices	**Costs & Other Barriers**
Irrigation improvements to reduce leaching	
Grade fields so that slope is decreased in bottom ~one quarter of field	• Potential cost of additional earth moving during field grading
Use weather-based irrigation scheduling	• Custom software • Training of managers and irrigators • Irrigator work schedules may be affected • District water delivery schedules may limit grower flexibility in scheduling
Modify crop rotation to capture more N	
Include alfalfa in rotation and reduce N fertilizer application on following crop	• Water availability • Alfalfa hay price is sometimes unattractive compared to alternative crops in rotation • Lack of definitive UC "alfalfa N credit" methods and values
Improve rate, timing, placement of N fertilizers	
Adjust N fertilizer rates based on soil nitrate testing	• Cost of soil sample collection and analysis • Management time to interpret results
Measure N content of irrigation water and adjust fertilizer rates accordingly	• Cost of analysis and management time to interpret results • Data collection and interpretation can be complex (e.g., when irrigating fields from multiple sources (wells and surface waters)

---

[23] Hutmacher et al. (2005) Cotton trial: Accounting of N in irrigation water, soil testing, and tissue testing necessary to overcome yield reduction concerns and economic return (fertilizer cost savings versus increased management costs).

2.5.4 Forage and Silage Crops Receiving Manure

These typically surface-irrigated crops are most often grown as livestock feed; consequently, they receive a substantial portion of their nutritional needs from manure, and have less economic return than other crop groups of the study areas. New regulations, with an aim to decrease nitrate leaching concerns from dairy farms, include N testing and budgeting.

Table 8. Example management bundle: Silage Corn.[24]

Region: San Joaquin Valley **Crop: Silage corn** **Irrigation: Furrow with dairy lagoon water applied in some irrigations**	
Improved Practices	**Costs & Other Barriers**
Irrigation scheduling	
Use weather-based irrigation scheduling	• Custom software • Training of managers and irrigators • Irrigator work schedules may be affected
Improve rate, timing, placement of N fertilizers	
Collect corn stalk samples for nitrate analysis at harvest and evaluate manure/lagoon water/fertilizer program efficiency; make improvements in following year	• Cost of collection and analysis of plant • Lack of California research to show effectiveness of this practice
Measure N content of fresh irrigation water and adjust fertilizer and dairy lagoon water rates accordingly	• Cost of analysis • Management time to interpret results
Improve rate and timing of dairy lagoon water and manure application	
Measure NH_4 content of lagoon water frequently during applications and adjust application rate accordingly	• Additional cost for collection and analysis beyond quarterly sampling required by dairy waste discharge regulation • Dairy lagoon water infrastructure (pumps and piping) may not allow for fine-tuning of application rates or for very low flow rates
Adjust N fertilizer rates based on soil nitrate testing	• Cost of collection and analysis of soil samples • Management time to interpret results • Excessive spatial variability of soil nitrate may deter usefulness • Not effective in highly permeable soils

---

[24] Gehl et al. (2005) Silage trial: Weather-based irrigation scheduling and split N applications reduced leaching.

2.6 Vulnerability Assessment

Our approach in this report is to identify and describe practices and technologies that are potentially available to growers for achieving high crop N use efficiencies. We have also indicated which practices appear to be currently in common use by farmers and the barriers (such as high costs or perceived risk to yields) to increased adoption. In this section we provide an analysis of the results of the nitrate groundwater pollution hazard index, assessing the portion of cropland in each of the two study regions where the risk of Nitrate leaching loss is highest, and therefore where adoption of more N-efficient practices may have the greatest effect.

To make this assessment, we have used the Nitrate Hazard Index (HI) (Wu et al. 2005) as described in the methods section above (2.2.3). The HI assigns an index value from 1 to 80 (very low to very high risk of nitrate leaching loss) based on the soil series, crop species grown, and the type of irrigation system in use in any one field. An HI under 20 is considered to be of low risk to leaching and any value over 20 is considered potentially highly vulnerable to nitrate leaching. The HI does not take into account farmer use of specific management practices, depth to groundwater, or the underlying hydrogeology. Rather than an indicator of actual nitrate loss or pollution to groundwater, the HI is an indicator of how much focused effort a farmer needs to place on efficient N management, where attention to improved management may have the most effect on groundwater quality, and, by identifying which factors contribute most to risk, the HI can be used to help guide choice of specific management practices.

It is important to emphasize again that the HI values do not reflect the management decisions that contribute highly to overall leaching risk, as discussed in the bulk of this report. A slowly draining field cropped to an inherently lower risk species for example, may in fact pose a significant hazard to groundwater quality if poorly managed in regards to water and nitrogen use efficiency. The specific utility of the hazard indexing tool to the grower is rather then to help identify which inherent component or components (crop, soil, or irrigation system) are driving risk, and as such providing information useful for guiding the choices of which alternative management options may be the most appropriate for the given situation. The analysis provided here serves as a showcase of the variability that exists between single fields within the study area and the associated variability in appropriate farm management options. In areas identified as being of high risk, the actual loading will be highly influenced by how the grower manages their crop N use efficiency. In this way, the analysis provides an estimation of where adoption of mitigative management practices would likely have the most effect on nitrate leaching and the associated groundwater quality at the basin scale.

Individual component HI values for soil, crop, and irrigation system were assigned to each irrigated agricultural field in the study areas using the online HI tool database, and based on the most recent crop, irrigation, and soil surveys available to us. We present an analysis of each individual component and follow with the results of the overall vulnerability, computed by multiplying the component values together. A more detailed discussion of the methods, caveats, and assumptions involved in this analysis can be found in in the Methods Section 2.2.3.

Our analysis indicates that 32% of the irrigated cropland in the Tulare Lake Basin and 52% of the irrigated cropland in the Salinas Valley is especially vulnerable to low crop N use efficiency based on the combinations of crop, soil, and irrigation system characteristics assigned. That is, these percentages represent the area with HI values greater than 20, the critical point over which potential for risk is high as suggested by the authors of the HI (Wu et al. 2005). Note that if any one of the three components – soil, crop, or irrigation system – has a value of 1 (the lowest risk category), the overall HI will be less than 20, regardless of the values for the other two factors. For example, an intrinsically higher risk irrigation system utilized on a highly permeable soil will still not compute as a particularly vulnerable situation (that is, an HI>20) if the crop grown is classified as very low risk, such as alfalfa.

2.6.1 Crops

The majority of the Salinas Valley irrigated land is cropped to relatively high risk cool season vegetables. The high risk is a reflection of shallow rooting, high market sensitivity to N deficiency, and harvest of the plants at the peak of growth and N requirements. Based on the most recent DWR crop survey (1997), 70% of the crops in this basin are vegetables rating either HI 3 or HI 4; low risk vineyards (HI 1) cover another 20% of the area and the remaining ~10% of the area is in orchards and field crops with an HI of 2. We expect that, for the most part, current crop acreages are similar, with the exception of strawberries which have increased in production in the past decade.

In contrast, in the Tulare Lake Basin, over 50% of the irrigated cropland was devoted to lower risk permanent crops (vineyards and orchards) and alfalfa (at the time of the DWR surveys: Fresno 2000, Kern 2006, Kings 2003, and Tulare 1999). An additional 35% of the area is devoted to production of HI 2 rated field, grain, and hay crops (excluding corn, an HI 3 crop), with just under 15% of the irrigated agricultural land planted to the higher risk crops of vegetables and corn.

The spatial distribution of these crop groups according to their HI value is shown in Figure 6 below.

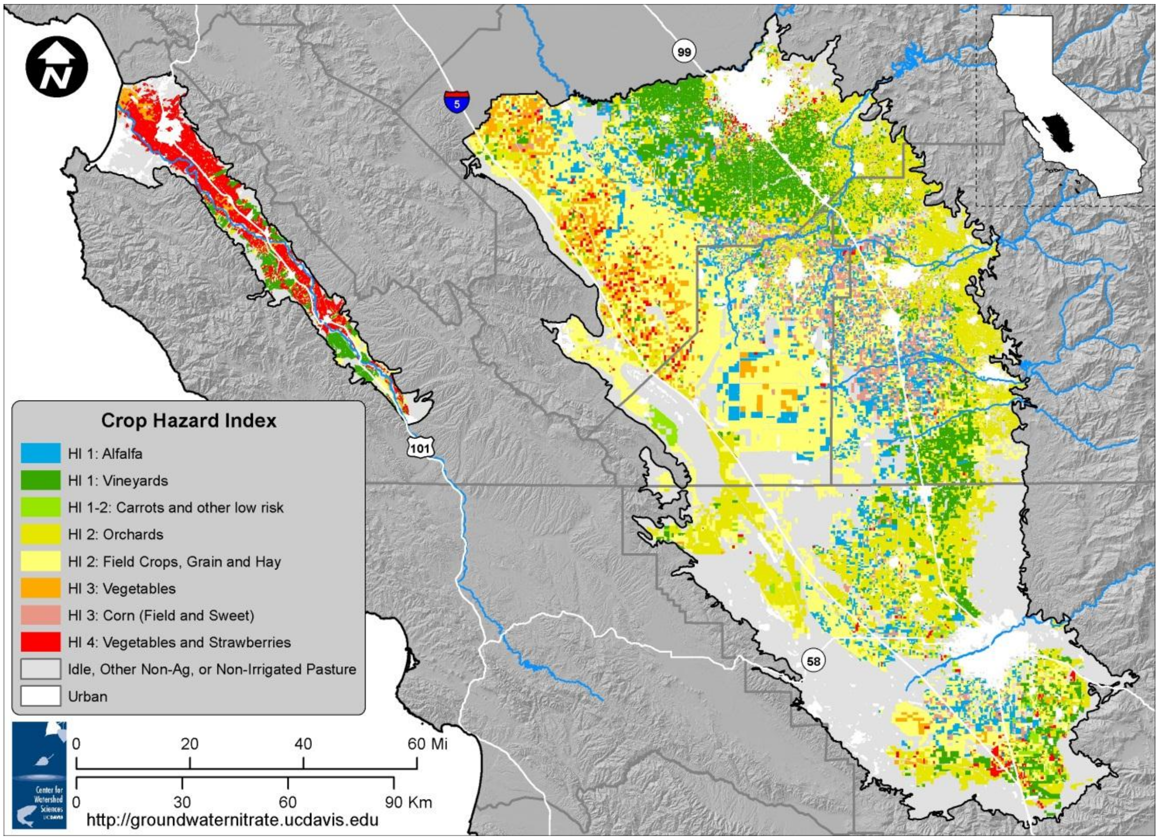


Figure 6. Study area crop distribution categorized by the crop group's hazard index values, based on the most recent DWR reports for each county (see text). Higher values denote crops with higher nitrate leaching risk.[25] (Source: DWR, UCANR WRC, internal designations, and Wu et al. 2005.)

2.6.2 Soils

The majority of both the TLB and SV soils are rated HI 3 or above, 62% of the TLB irrigated agricultural area and 72% of the SV area. The SV has only minimal areas rated 2 or below, primarily around Gonzales and to the east and southeast of King City. Higher risk soils predominate and are rated 4 and 5 all along the river, widening south of the confluence of the Arroyo Seco and Salinas Rivers to Greenfield and continuing south to the end of the valley. The TLB has larger areas of reduced permeability (HI 1-2) surrounding and north of the old Tulare Lake bed and along the eastern edge of Tulare County, as well as areas of Kern County. Higher risk soils surround Fresno, Hanford, and Visalia and extend south in a loose belt roughly following Highway 99 into McFarland, spreading south through the fields surrounding

---

[25] Note that the category "HI 1 or 2, Carrots and other low risk" is nearly 70% carrots (HI 2), with the bulk of the remaining proportion in sugarbeets (HI 1): sugarbeets are no longer produced in the basin. The category "HI 2 Orchards" includes 5 tree varieties not classified as HI 2: Olives, Apricots and Figs are rated HI 1 and Grapefruit and Kiwis are rated HI 3: all of these crops are of very low area comparatively and thus were included in the orchard category as a simplification strategy despite the different HI values. For the same reason, the "HI 2 Field Crop" category includes both dry beans and sudangrass, both rated HI 1, but where each represents a very small portion of the total category area. The category "HI 4 Vegetables" includes both onions and garlic, although garlic is rated as an HI 3 vegetable. The DWR surveys on which this map is based groups both crops together and does not differentiate the fields, thus the need to categorize garlic with the HI 4 vegetables.

Wasco and Shafter, and finally beyond Bakersfield to the southeast (Figure 7). The highest risk soils (HI 5) surrounding Fresno are planted mainly to vineyards (a low HI crop), although much of the remaining HI 5 area and a large portion of HI 4 soils are cropped with higher risk species or are irrigated with higher risk systems, driving up the overall HI rating (see Section 2.6.4).

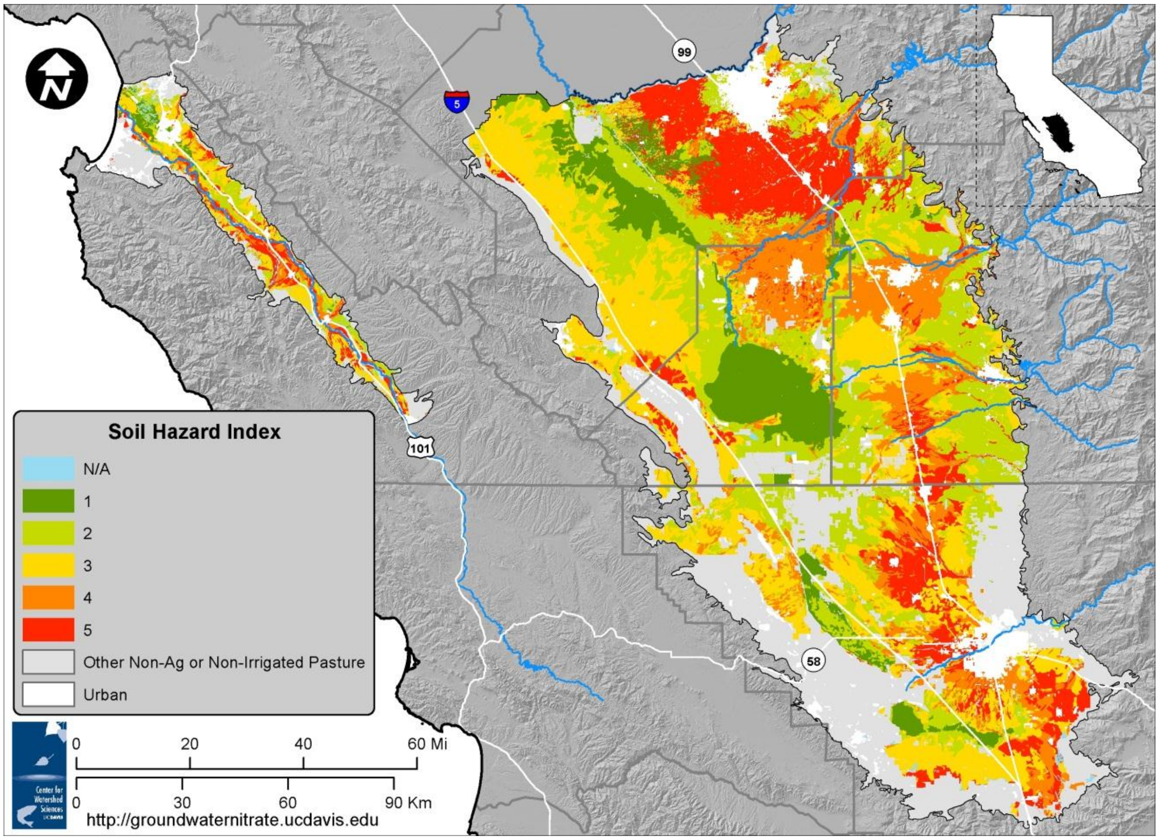


Figure 7. Soil hazard index value distribution for irrigated agricultural soil series. (Source: NRCS, SSURGO, UCANR WRC, internal designations, and Wu et al. 2005.)

2.6.3 Irrigation

As shown in Figure 8, at the time of the DWR surveys (Tulare 1999, Fresno 2000, Kings 2003, and Kern 2006), the majority of the TLB (over 68%) was recorded as being surface irrigated. According to the DWR reports for the study area, about 8% was sprinkler irrigated and nearly 25% of the area was already under drip or microsprinkler irrigation, especially in orchards and vineyards surrounding Fresno and those along the eastside of the basin (Figure 8). Permanent crops irrigated by these systems (60% in the DWR survey) will receive an overall HI of 20 or less regardless of the value for the soil component of the HI due to the HI value of 1 given the irrigation component.

The consensus of our tree and vine panel was that currently, much more than 60% of the permanent tree and vine crop area in the TLB is irrigated by drip or microsprinkler. Furthermore, according to members of our expert panel for TLB vegetables, nearly all of the processing tomato acres in the TLB are now irrigated by drip, and very few acres are irrigated by furrow systems – a change from the 85% furrow irrigated tomatoes reported in the DWR survey. They also confirmed that a significant number of other vegetable crop growers in the TLB had likewise adopted drip irrigation, but at a lower rate than processing tomatoes. A simulation was performed to look at how the overall HI may change should drip and microsprinkler use increase among permanent and vegetable crop producers and is discussed in the next section (2.6.4).

It is safe to assume that unlike vegetables, nuts, and citrus, most field crops remain surface irrigated and that the relative area of these crops has remained similar, with only small areas converting to potentially more efficient automated sprinkler systems (center pivot, linear move, or LEPA). According to panel members, carrots, onions, and some garlic are often sprinkler irrigated throughout the cropping pattern. Thus, the expected reduction in leaching vulnerability due to changes in irrigation methodology presents itself more heavily in the movement towards higher proportions of drip irrigated vegetables, vineyards, and orchards (especially nuts and citrus).

For the Salinas Valley, there are no recent irrigation surveys that include spatial information. The 2010 Monterey County Groundwater Summary Report (MCWRA 2011) details present and past irrigation system usage for just over 71,000 of the nearly 95,000 hectares of irrigated agriculture in the Salinas basin, although not spatially. Of that area, nearly 55% was reported to be drip irrigated, and 20% each sprinkler and surface systems (expected for the 2011 season). This drip irrigated area includes the valley’s vineyards, as well as vegetable and berry growers who reported only 46% of their crops to be on drip. Based on input from our Salinas Valley expert panel, we estimate that 50 to 70% of the total vegetable acreage is irrigated by drip. As we do not know which vegetable acres are irrigated by drip, to create the field-specific irrigation layer of the HI estimate, we made the simplifying assumption that all vegetables in the SV are drip irrigated (except carrots, spinach, broccoli, and onions designated as sprinkler irrigated) and that all field crops are surface irrigated. As drip irrigation contributes to a lower composite HI value than furrow or sprinkler, this simplification results in a larger area of low-HI vegetable fields than actually exists in the SV, and therefore underestimates the vulnerability to nitrate lost below the rootzone (see Section 2.2.3 for more information).

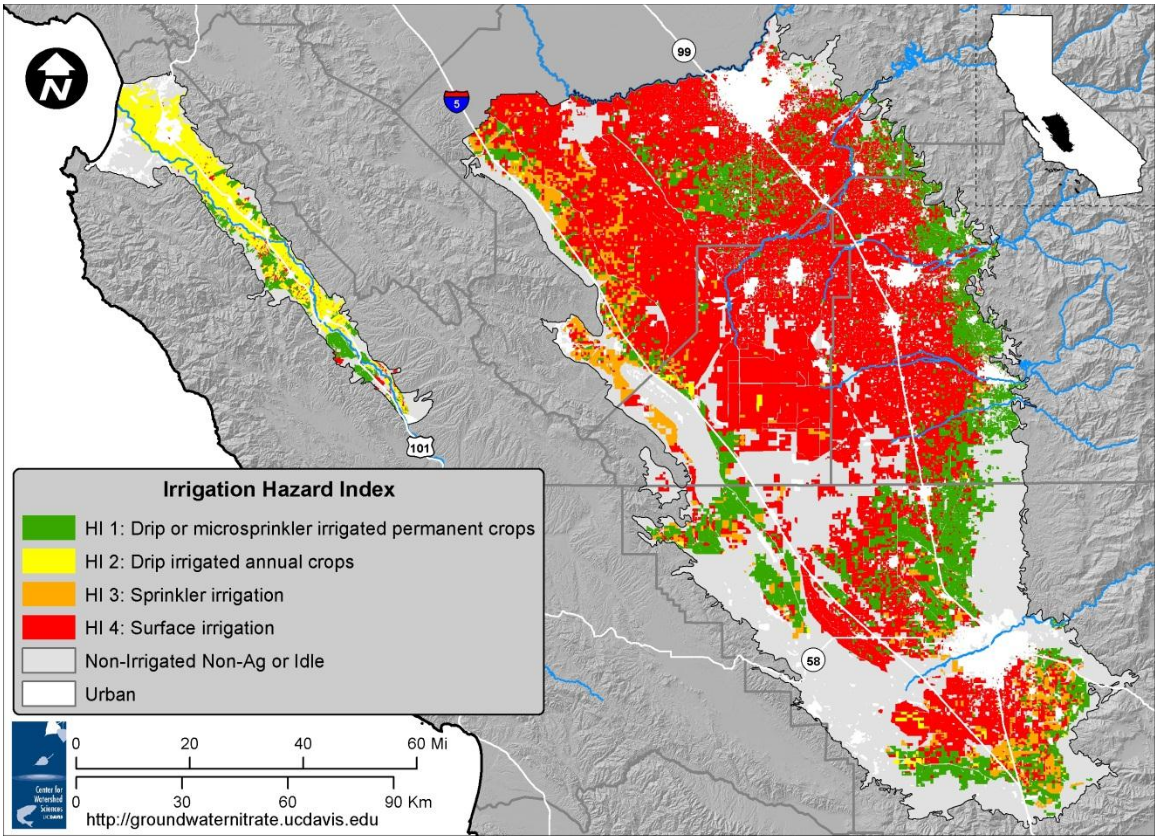


Figure 8. Irrigation hazard index value distribution. The most recent DWR reports for SV did not include irrigation data and thus for spatial representation it was necessary to designate 100% of each crop group to one specific irrigation system.[26] The prevalence of drip irrigated vegetables in the Salinas Valley is thus highly overestimated. In contrast, drip and microsprinkler irrigation is underestimated in the TLB due to the increased use of these systems in general (primarily in orchards, vineyards, and vegetables) since the time of the DWR irrigation survey data for these counties. (Source: DWR, UCANR WRC, internal designations, and Wu et al. 2005.)

2.6.4 Overall Hazard Index: Crop, Soil, and Irrigation

A large portion of the area of each basin falls within the low vulnerability definition (an overall HI of 20 or less) as shown in Figure 9. In areas in which HI<20, there is not as likely to be a significant decrease in N lost to leaching by adoption of improved practices. Either the soils are not as readily leached, or crop-irrigation combinations already make it easier to manage N conservatively. However, this does not mean that growers actually are managing optimally in these areas or that producers in such areas should not equally attempt to optimize their N use efficiency.

---

[26] In the SV, for the purpose of spatial analysis and calculation of an overall HI, field crops were designated as surface irrigated, tree crops (the majority of which are lemons in SV) and vineyards as micro-irrigated, and vegetables as drip irrigated (with the exception of carrot, spinach, onion, and broccoli fields designated as sprinkler irrigated)—see Section 2.2.3 for more information. Current actual estimates of drip irrigated vegetables in the SV are between 50% and 70% total.

In the Salinas Valley, 52% of the irrigated agriculture has an HI above 20 and is therefore considered vulnerable. The actual percent is even higher. As more recent irrigation type data were not available, we assumed all vegetables and strawberry fields to be irrigated by drip systems, and all vineyards and orchards to be drip or microsprinkler irrigated. In reality, it is estimated that only 50 – 70% of that acreage is irrigated by drip or microsprinkler, which would raise the percent of land with an HI>20. Highly permeable soils and shallow rooted leafy greens and other vegetable crops contribute to the large area of land that requires careful management to attain high crop NUE and low leaching losses (see Figure 10). However, with the large portions of the vegetables already converted to fertigated drip systems, increases in NUE have certainly occurred since times past, assuming proper maintenance and management of these systems is in place. Fallow period N management, especially during the rainy season and when pre-irrigating or germinating annual crops, continues to be critical, regardless of the irrigation/fertigation system used. Increased research, education and farmer outreach, and development of funding avenues will be required to increase adoption of other potentially high impact practices, such as fallow period covercropping.

In the Tulare Lake Basin, the areas of reduced concern are primarily those with the low risk soils, in areas of drip and microsprinkler irrigated trees and vineyards, and in areas in which alfalfa was recorded as growing at the time of the surveys. Although the majority of the area is cropped to lower risk crop species (Figure 6), the prevalence of higher risk surface irrigation and well-drained soils results in 1/3 of the basin having a calculated HI above 20, based on the available data. These results indicate that tight water and N management is required, especially in corn and vegetable production, as well as in the surface irrigated field crops grown on high risk soils. The TLB's high concentration of dairies contributes to overall leaching risk from both land application of manure and liquid manure storage lagoons and, to a much lesser extent, corrals (see Technical Report 2, Section 4, Viers et al. 2012). Most of the corn in the TLB is grown as silage for dairy cow consumption, and most of this silage corn receives manure and/or dairy lagoon water fertilizations applied by surface irrigation. Furthermore, these dairies are concentrated in areas of more permeable soils, driving risk upward. However, rotational effects may negate some of this risk, in that alfalfa, a highly effective perennial N scavenger (see MM 7, RP 7.2 and RP 7.4) is often included in the rotation scheme of forage crop producers.

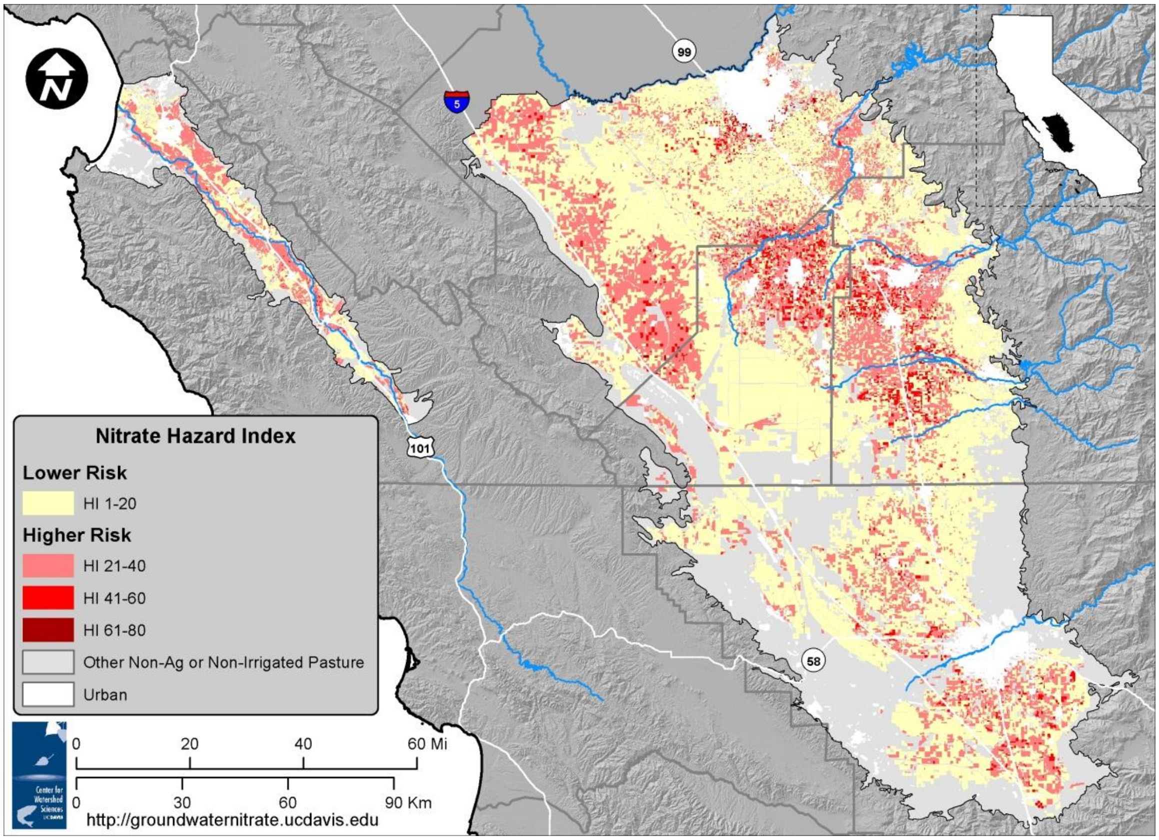
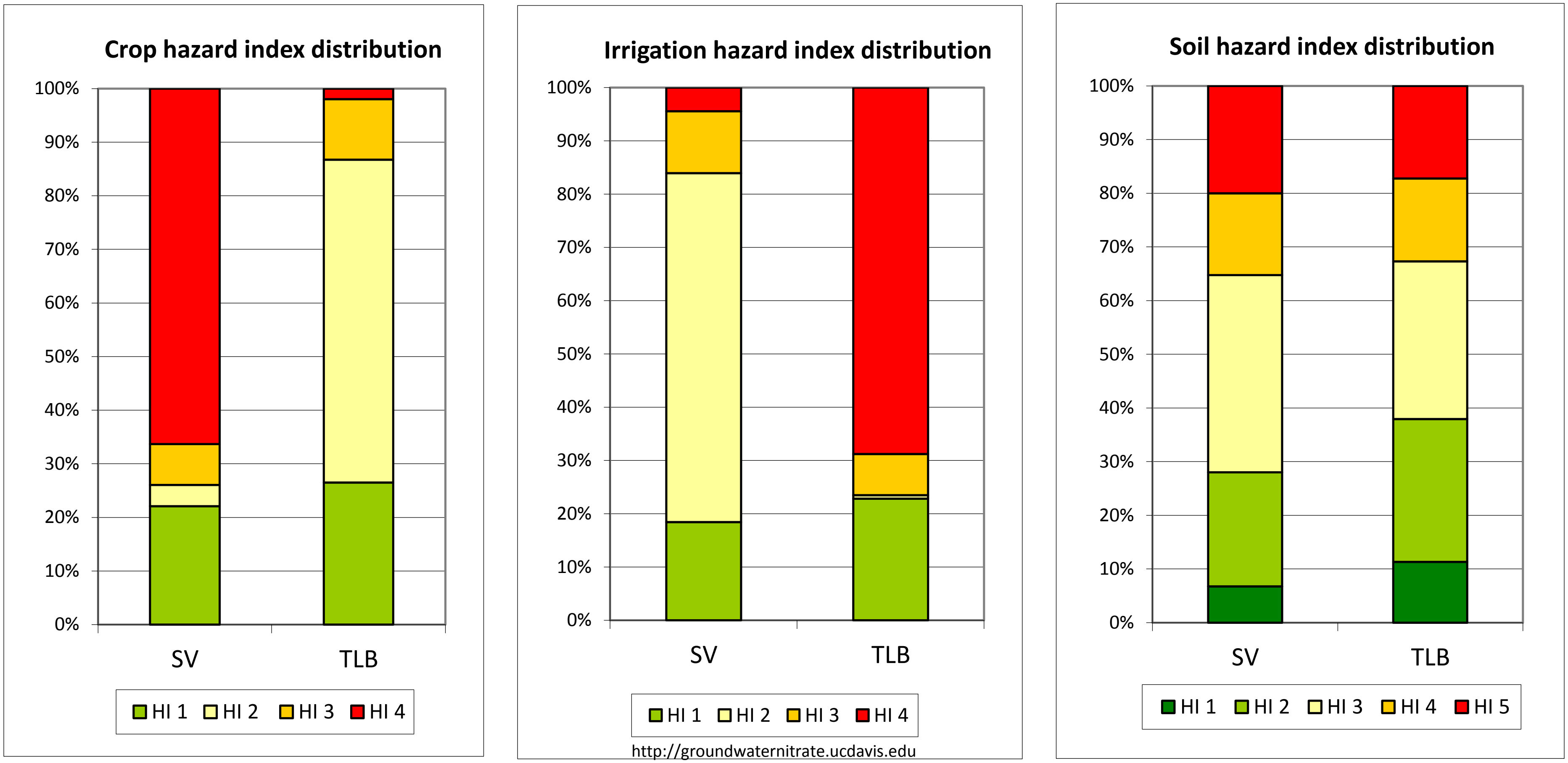


Figure 9. Overall hazard index calculated for the study area fields according to the most recent county DWR crop and irrigation data (Monterey 1997, Tulare 1999, Fresno 2000, Kings 2003, Kern 2006) and NRCS SSURGO soil series. All index values over 20 are considered vulnerable and indicate where improved management practices will likely have the greatest effect. Comparison between values in this category is not necessarily an indication of further risk differentiation, but may indicate that multiple variables are involved in risk. The less vulnerable areas still require vigilance in exercising good farm management practices. (Source: DWR, USDA, UCANR WRC, internal designations, and Wu et al. 2005.)

Again, the calculated final hazard index value is representative of risk of nitrate loss below the crop rootzone and not necessarily loading to groundwater, and is independent of management factors currently in use: vulnerability is based only on inherent characteristics of the soil, crop, and irrigation system in each polygon at the time of the DWR surveys (as described in Section 2.2.3). The proportion of the component HI values for each region is shown in Figure 10 below.

Changes in crop rotation will affect the overall HI distribution, especially if there is a continuing conversion on the more vulnerable (i.e., permeable) soils from lower-value, furrow irrigated crops to higher-value, drip or micro sprinkler-irrigated crops. Additionally, dairy forage crop producers routinely rotate corn, a high risk crop, with alfalfa, a nitrogen scavenging crop. Some of the most vulnerable fields shown in Figure 9 (primarily around Hanford, Visalia, and south beyond Tulare) are those on which field corn is grown (see Figure 6) and if rotated with deep rooted alfalfa (see RPs 7.2-7.4), a highly significant crop in the area, this may reduce risk slightly.



http://groundwaternitrate.ucdavis.edu

Figure 10. Distribution HI values by percent area for each component used in the determination of the overall hazard index values. SV = Salinas Valley. TLB = Tulare Lake Basin. Center figure: Note that all vegetables, strawberries, orchards, and vineyards in the SV had to be designated as drip or microsprinkler irrigated for spatial demonstration purposes (except spinach, broccoli, carrots, onions, and garlic; designated as sprinkler irrigated). This overestimates the percentage of lower risk irrigation in the SV, as it is estimated that only 50-70% of these crops are irrigated via low volume systems, rated HI 1-2 (see text for discussion).

A simulation was performed to illustrate how changes in irrigation system choice affect the overall vulnerability of the TLB. Over the past 20 years in the Tulare Lake Basin, many orchards, vineyards, and vegetable fields have been converted from surface gravity irrigation to low volume irrigation systems (drip and microsprinkler). Figure 11 shows both the overall HI value distribution in each region and illustrates the impact on the overall HI if the remaining area of these crops (orchards, vineyards, and vegetables) in the TLB were converted to such low volume systems. The rightmost bar in Figure 11 shows that the proportion of cropland with low vulnerability (HI<20) increases from 67% to about 78% due to such a conversion. It is likely that the conversion of orchards, vineyards, and vegetable fields to low volume irrigation will continue to increase in the coming years.

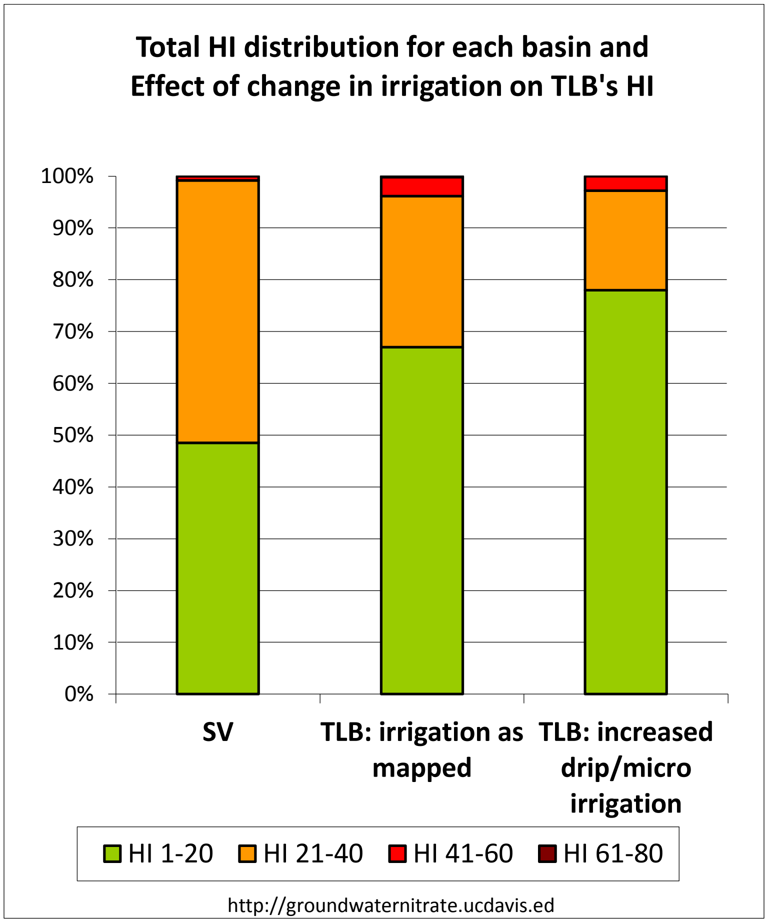


Figure 11. Composite hazard index values. Righthand bar shows a ~10% reduction in the area of high vulnerability in the TLB following an increase in the adoption of drip or microsprinkler irrigation systems over surface systems. That is, a change from the scenario as mapped (Figure 9, per DWR survey dates-- Tulare 1999, Fresno 2000, Kings 2003, and Kern 2006), to one where 100% of all vegetable, orchard, and vineyard area is drip or micro-irrigated. Note that while further conversion is expected in the area, a 100% adoption rate would be unrealistic, as it is inappropriate for some crops in those categories.

This exercise, again, ignores how these fields and irrigation systems are actually managed. As discussed in section 2.3.1 (see RP 3.6), optimally managed surface irrigation systems can outperform poorly managed and maintained drip systems in terms of overall efficiency and uniformity. However, due to the increased control the operator has with low volume irrigation systems, a higher efficiency is expected when properly managed. These systems are not appropriate for some crops and remain economically unfeasible for others. Interest in center pivot and linear move sprinkler systems has increased in the San Joaquin Valley in recent years. These systems can deliver water with higher efficiencies than some of the traditional surface gravity systems; however, it is too soon to know whether these will be used on a significant fraction of cropland.

In summary, about 50% of irrigated cropland in the Salinas Valley and 25-35% of irrigated cropland in the Tulare Lake Basin has a nitrate hazard index over 20 and therefore is considered especially vulnerable to nitrate leaching losses according to the UC Nitrate Hazard Index tool. This evaluation is based on field soil series characteristics and the most recent spatial surveys of crop species grown and type of irrigation used on each field. It does not take into consideration management practices in actual use, crop rotational effects, or distance to groundwater. Thus while these results are not indicative of risks to groundwater (rather to risk of nitrate losses below the rootzone), the analysis illustrates the variability within the study areas and provides an estimate of the proportion of cropland (at a resolution similar to USDA county soil surveys) where use of mitigative practices would be most effective in decreasing overall nitrate leaching.

2.7 Conclusions

Nitrate leaching from the crop root zone is controlled by the interaction of farm management practices with inherent properties of the soil, weather, and crop species being grown. We have identified 10 farm management measures that contribute to efficient use of nitrogen by crops and detailed individual practices that can be used to achieve the management goals. Use of these practices, individually or in combination, can reduce nitrate leaching losses. Many of the identified practices are suited for use only with certain crop species or irrigation systems, and a few are suited for use only on certain soil types. The extent to which any one practice can contribute to NUE is site and crop specific. A suite of management practices appropriate to each field will have the most impact on NUE and leaching reduction. In general, NUE can be increased by optimizing the timing and rates of applied fertilizer N, animal manures, and irrigation water to better match crop needs, and to a lesser extent by modification of crop rotations and careful on-farm handling and storage of fertilizer and manure.

Based on the commentary from our expert panels, we found that a number of the identified practices have been adopted by study area farmers in recent years. An example is the conversion of vegetable fields from furrow and sprinkler to drip irrigation methods. While drip irrigation provides the key infrastructure for allowing reduced nitrate leaching losses, some farmers using drip have not yet optimized their systems to minimize leaching. For example, nitrogen fertilizer may still be applied in excessive amounts or at inappropriate times. Practices that are not already commonly in use by farmers in the study areas are generally associated with multiple barriers to an increased rate of adoption. High operating or capital costs and ranch logistical constraints represent significant and common barriers for a number of practices. Lack of access to adequate education and outreach activities is also one of the primary barriers for many of the less utilized practices.

Even where farmers are using “best management” or the recommended methods analyzed in this report, there are practical limits to the crop nitrogen use efficiency that can be achieved. The limits are due to spatial variability of soil hydraulic properties within fields, unpredictability of rainfall, the complexity of the N cycle and difficulty in predicting the rate of mineralization of organic N in the soil, and the need to leach salts from the rootzone. Where crop N use efficiency is low, significant improvements are possible with use of currently available technology, but due to the basic constraints mentioned here, NUE values above 80% are not likely achievable. However, understanding of the soil-crop system continues to improve, and future technologies may allow farmers to manage inputs even more precisely. It should be noted that nitrogen use efficiency should not be the only standard used to evaluate practices. In fact, the highest numeric NUE value may be achieved at yield levels that are not economically viable.

Not all croplands are especially vulnerable to nitrate leaching. Increasing the use of improved practices in areas that are the most vulnerable to leaching will have the most impact on groundwater nitrate concentrations. Based only on inherent characteristics of soil, crop, and type of irrigation system in use we identified those areas that are at least likely to present nitrate leaching, and those areas that are more vulnerable. We found that approximately 52% of irrigated cropland in the Salinas Valley and 35%

of such land in the Tulare Lake Basin is vulnerable to nitrate leaching, utilizing a Nitrate Hazard Index (Wu et al. 2005). While this assessment is not indicative of actual nitrate loading rates to groundwater, nor does it take into account actual management practices on individual fields or their location relative to sensitive aquifers, it does provide an estimate of the number of acres and general location of fields where attention to improving crop N use efficiency could have the most benefit.

While farm management has most certainly improved since times past, the rate of change has not been documented. Due to the generally long travel time of nitrate molecules to aquifers, current measurements of well water nitrate levels are most representative of past management regimes. The effect any one practice has on leaching is variable and depends on climate, soil characteristics, crop characteristics, crop rotation strategies, irrigation strategies, and other factors. For all of these reasons, it is impossible to assess the level of impact the improved management regimes employed by today's producers will have on future groundwater quality, and impossible to assess to what degree increased adoption of mitigative practices will have on this quality. However, it is certain the impact will be positive and that current average management, while an improvement over past practices, can still be considerably improved in terms of groundwater protection. Tandem implementation of improved management practices, chosen in relation to each unique farm situation, is the best approach to reducing nitrate leaching from agricultural fields.

Promising Actions: Based on all of the above findings, it is clear that expanded efforts to promote the adoption of nitrogen efficient practices are needed:

- The educational barriers that are associated with many of the identified practices highlight the importance of increased funding of research, education, and knowledge transfer (outreach) activities, to better assist farmers in applying best management strategies and nutrient management.
- More research is required that directly compares the effect of changes in management on nitrogen use efficiency or nitrate leaching under California conditions.
- Support development of crop-specific N-accounting methods that allow growers to evaluate their success in achieving high crop nitrogen use efficiency. An example of such is a "nitrogen mass balance metric" which is the ratio of the amount of N from all sources applied to a crop to the amount of N removed in the harvested crop. This would serve in lieu of direct estimates of nitrate to the groundwater, which is extremely difficult to monitor at the individual farm or farm field scale. Input:harvest ratios need to be averaged over multiple years to provide useful data.
- Implementation of a task force to review and fine tune methods for identifying cropland areas that are most vulnerable to nitrate loss below the rootzone. Several methods have been used or are under consideration for doing this in California; some attention should be given to methods that can be used at the farm and county scale for on-farm applied research and outreach activities. Such methods should include consideration of the spatial soil characteristics, as well as probable monitoring requirements.
- As the recently instituted Central Valley dairy regulations (CVRWQCB 2007) restrict on-farm cropland applications of manure, the volume of off-dairy transfer of animal waste to

unregulated fields has increased. It is not known which crop species and soils are receiving this manure or how the receiving farmers have integrated the manure into their N fertilization practices. Development of adaptive research and education programs that will promote conversion of solid and liquid dairy manure into forms that meet the food safety and production requirements for a wider range of crop species holds promise. Providing guidance to non-dairy farms in co-managing organic and conventional N sources is necessary to ensure that the nutrient value of the manure is properly accounted for in fertilization regimes.

3 Agro-Economic Analysis of Nitrate Source Reductions

Prepared by:

Josué Medellín-Azuara, Todd S. Rosenstock, Richard Howitt, Thomas Harter,
G. Stuart Pettygrove, Kristin N. Dzurella, Jay R. Lund, Katrina K. Jessoe

Acknowledgments

We are thankful for the valuable feedback received during the project's Interagency Task Force meetings. This helped substantially improve our focus and our modeling efforts. Comments from Gerald Horner, John Letey, and Kurt Schwabe were extremely helpful to identify areas in our study that are now improved. We also appreciate the input from Allan Hollander and Joshua Viers for facilitating land use information from the California Augmented Multisource Landcover Map (CAML), and research assistance led by Anna Fryjoff-Hung on cartography and compiling of crop yield information and nitrogen fertilizer application rates from the literature. Findings, conclusions and remaining caveats are solely responsibility of the authors. This work was funded by the State Water Resources Control Board under agreement number 09-122-250.

3.1 Introduction

Improving nitrogen and water management on croplands is an important strategy to minimize future groundwater contamination. Nutrient, soil, and water management practices capable of reducing the impacts of croplands on groundwater quality are available (as reviewed in Section 2 of this report). However, implementation of new practices often requires increasing the intensity of management and hence changes costs and farming profitability. We develop a novel methodology of determining how policies aimed to reduce nitrate loading to groundwater would financially impact farmers in the Tulare Lake Basin and the Salinas Valley of California.

Widespread application of synthetic nitrogen fertilizers is a foundation for California's robust agricultural economy. However, excessive use has contaminated groundwater throughout California's agricultural regions (Stephany et al. 1998, Burrow et al. 1998; Zhang et al. 1998). Nitrate in groundwater is a public health concern. A majority of Californians rely on groundwater for their primary source of drinking water (DWR 2003) and ingesting nitrate has been linked to a series of negative health outcomes (Ward et al. 2005). Agriculture is both the largest contributor of nitrate to groundwater (see Technical Report 2, Viers et al. 2012) and is a primary driver of local economies in the Tulare Lake Basin and the Salinas Valley, as the five counties that comprise these regions are among the most agriculturally productive in the United States. Poorly planned nitrogen management policies may have significant impacts on the agricultural productivity and, consequently, economic health of these regions.

Various technologies and practices can help crop producers use nitrogen more effectively and reduce leaching losses, as outlined in Section 2 of this report. Conventional wisdom suggests that reducing nitrate loading will demand more intensive management and cost growers more money to produce, reducing net profit. The dual goals of maintaining profitability and reducing leaching potential may not always be at odds; N monitoring has been regarded as a possible low cost strategy (Knapp and Schwabe 2008) and can even lead to net profit increases (Hartz 1994). Identifying and implementing practices that produce similar win-win results has the potential to preserve the rural agricultural economy and groundwater for future generations.

In practice, farming operations often change several practices simultaneously (Technical Report 2, Viers et al. 2012). Suites of practices effectively increase nitrogen use efficiency and decrease pollution potential (Broadbent and Carlton 1978; Stark et al. 1983; Meyer and Marcum 1998; Letey et al. 1982). Combinations of production practices can be thought of as "bundles" of practices as they co-produce the desired benefits (see Section 2 of this report). Similar to individual practices that decrease leaching, bundles typically require capital costs for improving technology and additional operational costs by moving towards more intensive labor practices and education. Few studies quantify the costs of implementing technology bundles and their results on nitate loading. Knapp and Schwabe (2008) offer an example of a dynamic multi-year approach that accounts for water and nitrogen application as well as irrigation systems bundles. In our approach we account for water and nitrogen use efficiency, yet our focus is on the economics of nitrate leaching to groundwater as a result of both regulation and cost policies.

In this study, we develop a novel approach to estimate the cost of a menu of policies on farm profits. It is worth noting that we address only the production economics perspective. It is not the intention of this analysis to estimate the costs of the externalities to human health and other natural resources. Thus, results of our economic analysis of farm sector impacts need to be examined within a larger examination of societal trade-offs and options that considers alternatives outside the farm sector, including those for mitigation options such as drinking water treatment to address impacts of declining groundwater quality.

Modeling the interaction between nitrogen fertilizer, irrigation water use, crop mix, crop yield, and the costs and revenues of agricultural production is rather complex and involves a number of uncertainties. Previous research efforts have focused on the policy aspects of regulating nitrate, with less attention to economic effectiveness. Daberkow et al. (2008) offer a comprehensive literature review on economic modeling of public policies for changing nitrogen use practices in agriculture. In general, adverse impacts to farm income result from taxes on fertilizer or nitrogen effluent, or increasing limits on nitrogen application or effluent discharge. Effectiveness and costs vary across studies, but literature seems to concur that modest improvements in nitrogen use efficiency may come at little cost to farm net income (Knapp and Schwabe 2008).

Policy instruments for reducing groundwater nitrate loading may vary in effectiveness and ease of application. The policymaker needs to take into account heterogeneity in production to address equity issues from applying a given policy. Helfand and House (1995) found that, for nitrate in the Salinas Valley, implementing individual input taxes may lead to more socially optimal solutions, but such taxes are harder to apply. In contrast, second best policy instruments such as output taxes or uniform taxes or cutbacks may be close to the best performing policy and are often easier to apply. Nevertheless Helfand and House (1995) found that taxing a single production input such as N can be effective. Conversely, Knapp and Schwabe (2008) conclude that taxing water may be more cost effective than taxing N. In our approach, we simultaneously consider tradeoffs in costs and efficiency in nitrogen and irrigation, which accounts for different tax, cost, and nitrate load restriction schemes for water and nitrogen use efficiency. Thus we undertake an economic assessment of nitrogen limiting and nitrogen price policies. We complement our work with a sensitivity analysis that considers increases in the marginal costs of improving nitrogen use efficiency.

3.2 Crop Selection and Area of Study

A wide range of crops are grown in the Tulare Lake Basin and Salinas Valley, and they account for much of California's agricultural production. The final crop categories and their currently harvested areas are shown in Table 9. This crop mix covers more than 90 percent of the irrigated crop area of the two regions.

Table 9. Crop groups and land areas for modeling economics of nitrogen source reductions in crop farming.[27]

Crop group	**Tulare Lake Basin** (Acres)	**Tulare Lake Basin** (Ha)	**Salinas Valley** (Acres)	**Salinas Valley** (Ha)
Alfalfa	367,578	148,754	599	242
Almonds and Pistachios	407,007	164,710	--	--
Corn[27]	209,731	84,875	125	51
Cotton	605,154	244,897	--	--
Grain and Field[27]	667,910	270,293	18,618	7,535
Lettuce	3,048	1,234	48,209	19,510
Orchards[27]	212,056	85,816	342	138
Strawberries	364	148	8,492	3,436
Subtropical Tree Fruit[27]	305,691	123,709	1,423	576
Tomato[27]	132,804	53,744	2,858	1,157
Vegetables	175,085	70,854	100,470	40,659
Vineyards[27]	475,484	192,422	46,157	18,679
All other uses	1,699,329	687,694	169,622	68,643
Total	**5,261,242**	**2,129,149**	**396,916**	**160,626**

---

[27] Crop grouping follows DWR land and water use surveys available at http://www.water.ca.gov/landwateruse. Areas are from the California Augmented Multisource Landcover Map (CAML, http://cain.ice.ucdavis.edu/caml). Alfalfa is excluded from our analysis because it is often a nitrogen sink and our emphasis is on crops with higher NUE improvement potential. Field and Grain may include safflower, dry beans, sunflower, barley, wheat, oats, and excludes corn (all classes) and cotton. Likewise, vegetable crops are a composite of about twenty crops, excluding tomatoes (fresh and processing), strawberries and flowers, and others listed individually. Orchards exclude almonds and pistachios. Subtropical includes olives, avocado, citrus, and other. Small acreages are excluded. Corn includes all classes of corn and vine crops include grapes only. Kiwis and other vine fruit besides grapes are within the subtropical category.

3.3 Model

We developed a self-calibrated profit-maximizing model for agricultural production to assess the economic impact on farmers of policies that reduce nitrate loading from croplands.[28] Because nitrate loading to groundwater in irrigated cropping systems is largely a function of nutrient and water management, the model is based on economic and environmental consequences of changes in nutrient use and irrigation efficiency. It is assumed that better management will require additional monetary input (e.g., infrastructure cost, labor cost, costs for information and education, etc.), but will reduce total nitrate loading from croplands. The model allows for tradeoffs between monetary investments in production inputs (management practice bundles) and total nitrogen and water use. The optimization model maximizes profits from farming, while keeping yields constant in the constraint set definition.

3.3.1 Conceptual Framework of Model: Nitrogen Use Efficiency, Nitrogen Surplus, and Irrigation Efficiency

The mass of nitrate leaching to groundwater from irrigated croplands is a simple function of the amount of nitrogen applied times the quantity of water moving beyond the rootzone. Both of these critical pieces of information (and remedial strategies) must be considered. Our modeling approach presented here allows producers to adopt changes to both or either factors.

For the nitrogen part of the equation, our model is based on two interrelated metrics that, together, represent nitrate leaching potential: nitrogen use efficiency and nitrogen surplus. Measures of nitrogen use efficiency (NUE) are ratios of nitrogen taken up by the plant to nitrogen applied.[29] Given the total applied nitrogen N, a generally smaller *effective* amount of nitrogen, $\tilde{N}$, is used and taken up by the crop. The ratio $\tilde{N} / N$ is the "partial nutrient balance" (PNB), one measure of NUE.[30] Nitrogen surplus, or 'surplus,' equals the amount of N remaining in the field after harvest; in the model description section below we present, in equation form, these interrelationships. Hence, surplus is the difference between nitrogen applied and that taken up by the crop or surplus = amount of nitrogen applied * PNB. If the total applied nitrogen were equal to the effective nitrogen (100% NUE), $\tilde{N}$ as a function of N, $\tilde{N}(N)$, would yield a straight line with a 1:1 slope (Figure 12 below). We represent management practice bundles requiring specific capital and other investments in terms of their nitrogen use efficiency curves. For each practice bundle, the nitrogen use efficiency at low N application rates tends to be very high (albeit with low yields) and the value of $\tilde{N}(N)$ is close to the 1:1 line.[31] As the N application rate

---

[28] In this setting, the self-calibrated model (Howitt 1995) employs non-linear cost functions derived from the first order conditions of a farm profit maximization program, such that input use in the base policy model calibrates to those in the base dataset. These cost functions are referred to as Positive Mathematical Programming (PMP) cost functions after Howitt (1995).

[29] There are at least 18 ways to calculate nitrogen use efficiency (Ladha et al. 2005).

[30] It is worth noting that PNB is an indiscriminate proxy for NUE. That means that it cannot differentiate between nitrogen in plant material derived from mineralization or that derived from fertilizer. Thus, the inherent fertility of the soil can have a marked impact on PNB.

[31] In this way, our model aims to reflect a primary concern of using NUE as a measure of sustainable nitrogen management. The most nitrogen efficient producers are those that apply too little nitrogen. It is one of reasons that we chose to base our approach on a suite of indicators that included NUE, but also surplus and irrigation efficiency.

increases, the nitrogen uptake typically increases at a slower rate. Hence, the nitrogen efficiency decreases and the $\tilde{N}(N)$ curve levels off relative to the 1:1 line of $\tilde{N}(N)$ (see Figure 12 below). Plotting such curves for various (hypothetical) management practice bundles on a single graph, we can compare the nitrogen use efficiency of various practices. Bundles with lower slopes at a given nitrogen application rate are considered less desirable (e.g., Bundle 0), whereas bundles with higher slopes are preferred (Figure 12).

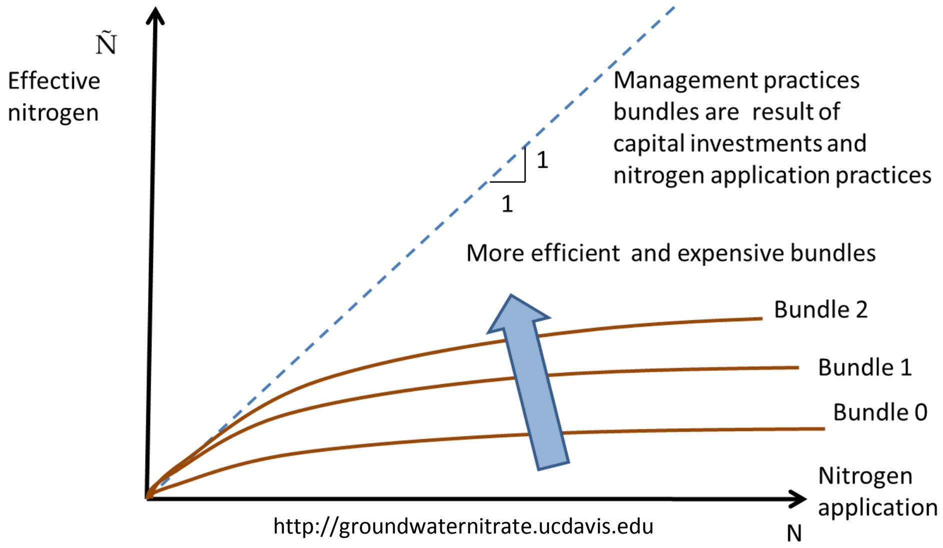


Figure 12. Effective nitrogen versus applied nitrogen by management practice bundle. Bundle 0 refers to practices before any improvements. Bundles 1 and 2 refer to more efficient and expensive bundles.

We use a substitution relationship between capital investments for nitrogen application practices and total nitrogen application calibrated to surveyed costs of application bundles. These tradeoff curves follow a Constant Elasticity of Substitution (CES) functional form and assume effective nitrogen use remains constant. One challenge for our approach is that bundles are discrete costs (i.e., they are either adopted or not adopted by the farmer) and therefore must be approximated to a non-linear function as shown in Figure 13. This figure shows an entropy-adjusted tradeoff curve of the cost of improving PNB versus the reciprocal of PNB for almonds and pistachios in Tulare Lake Basin. With respect to Figure 12 above, the lower right end of the tradeoff curve in Figure 13 corresponds to Bundle 0. As nitrogen use efficiency is increased by moving to the left along the tradeoff curve, the farmer shifts to more costly bundles (i.e., bundles 1, 2 or 3 in Figure 12). Since yields have to be maintained, the slope of *superior* bundles in Figure 12 increases at an increasing rate as do costs, as seen in the left portion of Figure 13. With the maximum entropy approach it is possible to estimate expected values for the parameters of a given curve with small or incomplete datasets. The theory behind the maximum entropy approach was developed by Shannon (1948) to quantify the expected value of a random variable.

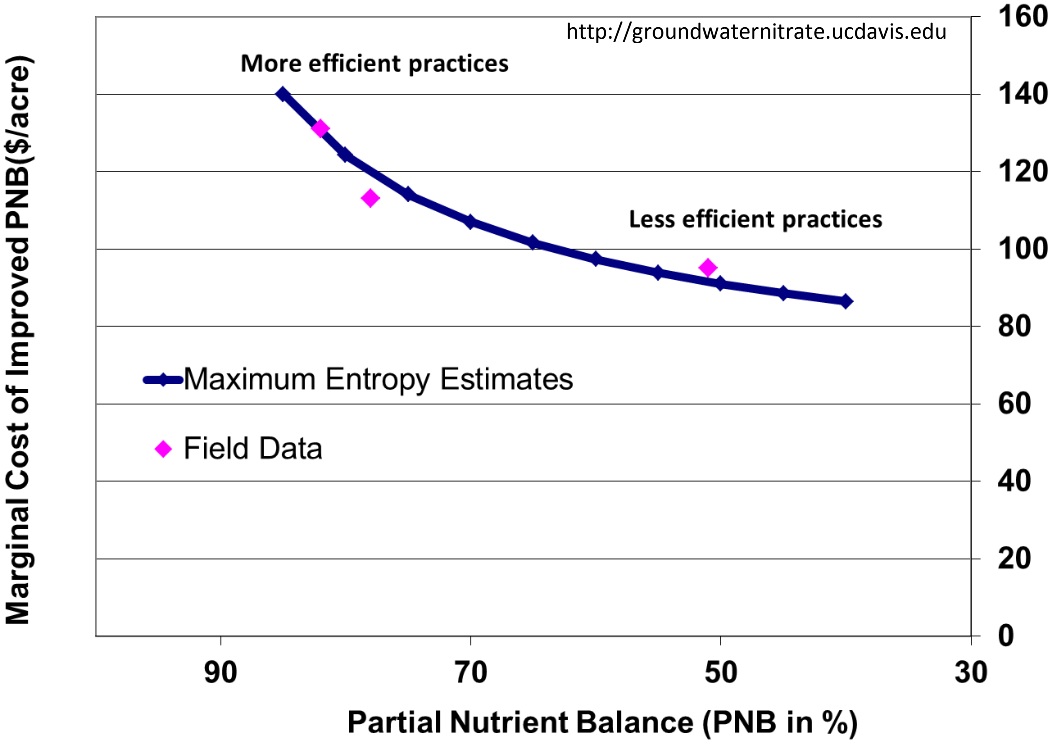


Figure 13. Tradeoff curve between Nitrogen Use Efficiency as Partial Nutrient Balance (PNB) and marginal costs per unit area to increase PNB. Within the tradeoff curve, yields are assumed constant. Higher nitrogen use efficiency (left in the horizontal axis) is achieved by increasing capital investments (labor, technology, and management) in nitrogen use efficiency (vertical axis).

Likewise, for irrigation efficiency, we assume that bundles with higher irrigation efficiency require capital investments to maintain crop yields. We measure irrigation efficiency as the inverse ratio between applied water and evapotranspiration of applied water. The United States Bureau of Reclamation (1997) conducted a study on the Central Valley to parameterize this tradeoff relationship (Figure 14).

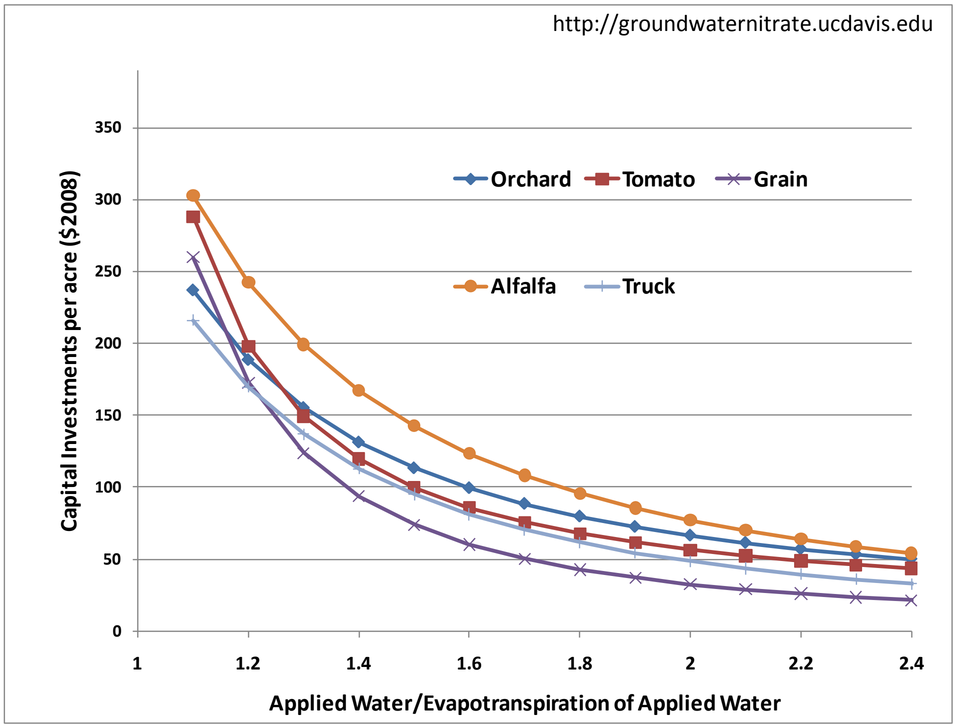


Figure 14. Sample tradeoffs between capital investments and irrigation efficiency for selected crops for a constant crop yield (adapted from USBR 1997).

Information on irrigation technology and an approximation of the tradeoffs between capital investment and efficiency exists from previous studies (USBR 1997). However, with the exception of Knapp and Schwabe (2008), very few analyses have been published comparing cost of improved N use practices, crop N use efficiency, and economics of nitrate leaching to groundwater. In the following subsection we present the model formulation and assumptions to derive such relationships for bundles of nitrogen management practices.

3.3.2 Model Formulation

Our model follows a multi-step calibration process using a CES function with two nests: efficient water use and effective nitrogen. In our first step we employ a Leontief technology which allows no substitution among inputs. The production function for the farmer for each crop includes six variable inputs:

- Land
- Water
- Supplies(Supp)
- Capital investments in water application (Wcap)
- Nitrogen (AppN)
- Investments in improving nitrogen use efficiency and management (CPNB)

Supplies refers to other variable inputs including labor and farming supplies, other than nitrogen and water, which have been lumped into an amalgam of variable production costs per acre. In our program, *capital investments* refers to expenditures on equipment, management and operation costs, which may include additional training of personnel, increased supervision, and use of crop consulting services. Two tradeoff curves exist in the model as mentioned above: one for water versus water capital investments and another for nitrogen versus nitrogen capital investments. Medellin-Azuara et al. (2012) present the full set of equations of a similarly nested model for irrigation efficiency only. In our present application we provide a simplified set of equations for the three steps. The footnote in this page describes the variables, parameters and subindexes employed in the equations to follow. In the first step the objective function (Eqn. 1) is given by:[32]

$$\max Z = \sum_{g}\sum_{i}\left(V_{gi}Y_{gi}XL_{gi} - \sum_{j}\left[a_{gij}XL_{gi}\omega_{gij}\right]\right) \quad \text{(Eqn. 1)}$$

Where Z stands for total net revenues; V_{gi} , Y_{gi} crop i (Table 12) in region g (TLB and SV) prices and yields, respectively; and $XL_{gi,}$ is the decision variable for input allocation of land. On the cost side, the parameters a_{gij} and ω_{gij} are the Leontief coefficient normalized to land and the unit cost coefficient, in region g and crop i.

The program is constrained in Eqn. 2 to a limiting amount of water and land:

$$\sum_{i} a_{gij}XL_{gi} \le b_{gj},\ j \in \{land, water\} \quad \text{(Eqn. 2)}$$

with supplies, effective water, and effective nitrogen use as in Eqn. 3, being and $\tilde{X}_{gij}$ the base *observed* value of the production input:

$$a_{gij}XL_{gi} = \tilde{X}_{gij}\,\forall g, i, j \in \{EffW,\ EffN,\ Suppl\} \quad \text{(Eqn. 3)}$$

In other words, the objective function (Eqn. 1) maximizes the net revenues for a limited amount of land, water, and for a given amount of supplies, water and nitrogen use efficiency. By comparing the optimized values for land, water cost, nitrogen cost, and crop allocation (including costs of increasing

---

[32] Sub-indexes ***i***, ***j***, and ***g*** stand for crop group (see Table 12), input (land, effective water, effective nitrogen, investments in water use efficiency, investments innitrogen use efficiency, applied water and applied nitrogen) and region (TLB and SV). The two virtual inputs on *j* : effective water (EffW) and effective nitrogen (EffN) are used in the two lower level nests.

Z, NL2, net revenues in the objective functions respectively for the linear and last optimization steps.

$\tilde{X}_{gij}$ observed input use in region *g, for crop i.*

XL, **XN**, and **XNN:** Decision variables land in the linear program, nested CES, and main CES function..

$\mathbf{V_{gi}}$ and $\mathbf{Y_{gi}}$, $\mathbf{b_{gj}}$: Respectively, Price per ton, and yields in tons per unit land area of crop *i* in region *g*; and available land and water (limited resources) for region *g*, where$\mathbf{b_{gi}}=\Sigma\tilde{X}_{gij}\ and\ j\ \in \{land, water\}$

$\mathbf{a_{gij}}$ and $\boldsymbol{\omega_{gij}}$ Leontief coefficient (normalized to land) and linear cost of production input *j* for crop *i* in region *g.*

β1, β: Respectively share parameters for the nested (effective water and effective nitrogen) and main (production) CES functions.

$\boldsymbol{\tau_{1gi}}$, $\boldsymbol{\tau_{gi}}$ Scale parameter of the nested and the main (production) CES functions respectively.

$\boldsymbol{\alpha_{gij}}$, $\boldsymbol{\gamma_{gij}}$: parameters of the PMP quadratic cost function, efficiency) at different water and nitrogen use efficiencies, we can compare the cost of improving nitrogen use efficiency, which in turn has the potential to decrease nitrate groundwater load. The model of nitrogen application efficiency versus capital investments in nitrogen use efficiency and the model of water capital investments versus irrigation efficiency are described below.

3.3.3 Water Capital Investments versus Irrigation Efficiency

Capital investments for improvements in irrigation efficiency versus total applied water can be likewise modeled following USBR (1997). The evapotranspiration of applied water for each crop is used as a proxy for irrigation efficiency. Formulation is as in Eqn. 4:

$$a_{gi,EffW} XL_{gi} = \tau 1^{W}_{gi} \left\{ \left[\beta 1^{W}_{gi} a_{gi,water} XL_{gi} \right]^{\rho_i} + \left[(1-\beta 1^{W}_{gi}) a_{gi,Wcap} XL_{gi} \right]^{\rho_i} \right\}^{1/\rho_i} \qquad \text{(Eqn. 4)}$$

Information to calibrate this component exists from previous work by the USBR (1997). The effective water amount, on the left hand side is given by the *observed* evapotranspiration of applied water. The parameters τ_{gi} and $\beta 1_{gi}$ are the scaling and the share factors in CES functional form. On the right hand side, $a_{gi,EffW} XL_{gi}$ for applied water and capital investments in applied water, represent the factors within the water efficiency nest that may substitute for each other. Finally, ρ_i is given by the elasticity of substitution[33] σ_I of crop *i,* such that $\rho_i = (\sigma_i - 1)/\sigma_i$.

3.3.4 Investments in and Costs of Increasing Nitrogen Use Efficiency

The second nested component[34] in the objective function (Eqn. 1) is used to represent tradeoffs between nitrogen application and costs associated with improving nitrogen use efficiency, assuming agricultural yields are not negatively affected by these improvements. We employ, again, a constant elasticity of substitution relationship between costs of reduction and nitrogen application (Eqn. 5), such that:

$$a_{gi,EffN} XL_{gi} = \tau 1^{N}_{gi} \left\{ \left[\beta 1^{N}_{gi} a_{gi,AppN} XL_{gi} \right]^{\rho_{Ni}} + \left[(1-\beta 1^{N}_{gi}) a_{gi,CPNB} XL_{gi} \right]^{\rho_{Ni}} \right\}^{1/\rho_{Ni}} \qquad \text{(Eqn. 5)}$$

Where, $a_{gi,EffN} XL_{gi}$ or effective nitrogen is proportional to the PNB and corresponds to the vertical axis in Figure 12. On the right hand side, applied N and capital investments in NUE conform the substitutable factors in this second nest. The rest of the parameters are as in the water efficiency nest (Eqn. 4). In Figure 13, the PNB is shown on the horizontal axis and the investments in NUE per unit area, given by $a_{gi,CPNB} XL_{gi}$, are shown on the vertical axis. $a_{gi,CPNB} XL_{gi}$ is the estimated unit cost of labor, supervision,

---

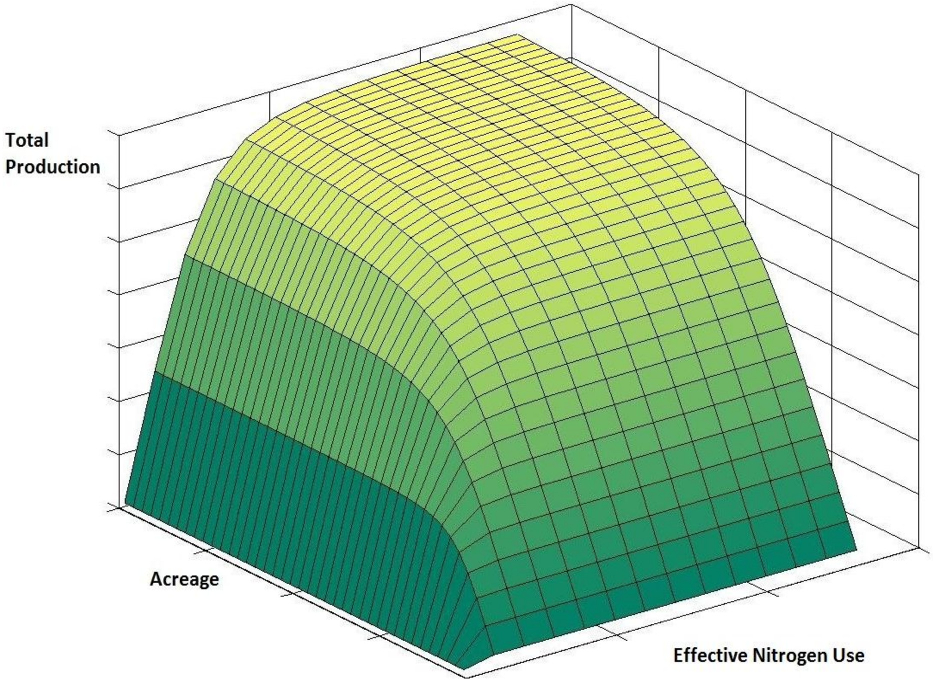
[33] The elasticity of substitution is a measure of how one production input can substituted for another. Low elasticities of substitution indicate low substitution possibilities (such as water for labor). Constant elasticity of substitution production functions constrain the ability to substitute among production inputs to remain constant at any level of production.

[34] The components are called nested because the left hand side variable in Eqn. 4 and 5 are nested in the constant elasticity of substitution production function in Eqn. 1.

and materials associated with the level of NUE on the horizontal axis, over a c*onstant yield* tradeoff curve.

In this case, the substitution parameter ρ_{Ni} was estimated empirically using a maximum entropy approach, as only a small dataset existed for PNB versus costs per unit area required to achieve that particular PNB. Maximum entropy theory (Jaynes 1957; Shannon 1948) makes maximum use of the existing information to estimate probability distribution of a particular parameter. Figure 13 exemplifies an estimation taken for this study.

A tradeoff between production and inputs is shown in the simplified graph below (Figure 15), where tradeoffs between nitrogen uptake, planted acres, and crop production are illustrated. This illustrates that total production is the result of combining inputs, which also share tradeoff relationships between them.



http://groundwaternitrate.ucdavis.edu

Figure 15. Simplified representation of crop production tradeoff surface between effective nitrogen use and land use.

In addition to Eqns. 1 – 5, a calibration constraint on XL_{gi} that restricts land to observed values $\tilde{X}_{gi,land}$ is employed following Howitt (1995). Once a solution to the linear program of these six equations is found, the second step in our model consists of taking the Lagrangian of the land use constraint to estimate a PMP quadratic cost function as in Medellin-Azuara et al. (2012). In the third and fourth steps (not shown here), the parameters for the CES water efficiency and nitrogen use efficiency are obtained. The resulting calibrated program in the fifth step is given by Eqns. 6 – 9, below.

$$\max NL2 = \sum_{g}\sum_{i} v_{gi}\left[\tau_{gi}\left(\sum_{j}\beta_{gij} XNN_{gij}\right)^{\rho_2}\right]^{1/\rho_2} - \sum_{g}\sum_{i}\sum_{j}\left(\alpha_{gij} XNN_{gij} + \gamma_{gij} XNN_{gij}^{2}\right) \qquad \text{(Eqn. 6)}$$

The first term in the right hand side of Eqn. 6 represents the main CES production function containing two nests of Eqns. 7 and 8. The last term in Eqn. 6 represents the calibration PMP cost function (Howitt 1995). To the objective function, two nested CES and a resource constraint follow:

$$XNN_{gi,EffW} = \tau_{gi}\left\{\left[\beta 1_{gi}^{W} XNN_{gi,water}\right]^{\rho_i} + \left[(1-\beta 1_{gi}^{W}) XNN_{gi,Wcap}\right]^{\rho_i}\right\}^{1/\rho_i} \qquad \text{(Eqn. 7)}$$

$$XNN_{gi,EffN} = \tau_{gi}\left\{\left[\beta 1_{gi}^{N} XNN_{gi,AppN}\right]^{\rho_{Ni}} + \left[(1-\beta 1_{gi}^{N}) XNN_{gi,CPNB}\right]^{\rho_{Ni}}\right\}^{1/\rho_{Ni}} \qquad \text{(Eqn. 8)}$$

$$\sum_{i} XNN_{gi} \leq b_{gj} \ ,\forall \text{ g,j } \in \left\{land, water, suppl\right\} \qquad \text{(Eqn. 9)}$$

The mass balance and policy constraints are described in the next subsections. Modifications to the mass balance constraints and costs of inputs (second term in Eqn. 6), allow us to model the cost of different policy options.

3.3.5 Nitrate Loading to Groundwater from Agricultural Production

In our modeling approach, to estimate nitrate load to groundwater in irrigated systems, a simplifying assumption is that nitrogen use efficiency cannot exceed the irrigation efficiency. In other words, farmers that employ efficient irrigation practices are more likely to adopt (if they have not done so already) more efficient nitrogen application practices. In addition, to compute groundwater nitrate loading, we assume that 10 percent of the applied nitrogen is lost to the atmosphere as ammonia, nitrogen oxides, or di-nitrogen gas. The remaining 90% of the (annually) applied N is either taken up by the crop or leached to groundwater. The groundwater nitrate load is the maximum between fraction of applied nitrogen that remains after atmospheric losses and nitrogen removed by harvest. The maximum potential fraction of nitrogen that can leach into groundwater is thus formally:

$$GW_{NO_3 load,gi} = Max\ \{0, XNN_{gi,AppN}(0.9 - PNB_{gi})\} \qquad \text{(Eqn. 10)}$$

Where $GW_{NO3load,gi}$ in Eqn. 10 is the estimated groundwater nitrate load and the rest of the terms, as defined earlier. Note that nitrate load to groundwater cannot be negative thus, there is a minimum of zero in the aforementioned computation. In Eqns. 11 and 12 below, we present Partial Nutrient Balance as related to surplus, harvested, and total applied nitrogen:

$$PNB_{gi} = 1 - \frac{SurN_{gi}}{AppN_{gi}} = 1 - \frac{AppN_{gi} - HarN_{gi}}{AppN_{gi}} = \frac{HarN_{gi}}{AppN_{gi}} \qquad \text{(Eqn. 11)}$$

$$HarN_{gi} = PNB_{gi} AppN_{gi} \qquad \text{(Eqn. 12)}$$

$SurN_{gi}$ is nitrogen surplus and $HarN_{gi}$ is the nitrogen removed by harvest. We also assume that irrigation efficiency is greater or equal to PNB, as some farming operations may, for example, have a well-managed drip irrigation system with a high water use efficiency, but still have very low PNB due to remaining inefficient nitrogen management practices. We assume that a high PNB cannot be achieved when irrigation efficiency is low.

One caveat of this approach is that there may be events or seasonal cases in which the irrigation efficiency is poor, yet nitrate leaching is also low. This may occur, for example, if soil nitrate concentration is low during pre-irrigation or during the winter (rainy season), where groundwater recharge is high. Likewise, reducing soil nitrogen during these times represents an improved practice. In our approach we consider total annual groundwater nitrate loading, and are particularly concerned with losses during the irrigation season.

3.3.6 Policy Simulations for Nitrogen Use Efficiency

Our policy simulations are aimed at estimating changes in agricultural revenues from changing cropping patterns (including increases in fallow land area), resulting from implementation of nitrate load reducing policies. We also estimate changes in revenue from efficiency improving management measures, taxes on nitrogen use and maximum load limits, and other policies. We are not concerned here with neither the specific aspects of such policies, nor with the feasibility of these policies. Instead we investigate expected shifts in cropping patterns and changes in farm revenues at different levels of restrictions to nitrate leaching.

To represent restrictions in nitrate load to groundwater, our modeling approach imposes a constraint on the amount of nitrogen such that, for region *g*, the maximum nitrate load is given by:

$$\sum_i GW_{NO_3load,gi} \leq Red_g \sum_i \tilde{X}_{gi,AppN} (0.9 - PNB_{gi}) \qquad (13)$$

On the left hand side groundwater nitrate load for region *g* is as in Eqn. 10; Red_g is the policy determined factor to reduce loading to groundwater by some percentage for region *g*, and the summation over *i* is the *current* groundwater nitrate load from crop *i* in region *g,* assuming that, from the *observed* applied nitrogen ($\tilde{X}_{gi,AppN}$), 10 percent is lost to the atmosphere and the rest is removed by harvest. Thus, Red_g would equal one unit if we are modeling a base case with no reductions, and 0.75 if we are cutting down nitrate load to groundwater by 25%. Water use efficiency is constrained to be greater than NUE, such that the weighted PNB is less than the weighted water use efficiency in a region.

In summary, the process consists of five steps: 1) linear land constrained program (Eqns. 1 to 5); 2) estimation of a calibration PMP cost function; 3) parameterization of the irrigation efficiency nest; 4) parameterization of the nitrogen efficiency nest; and 5) base calibrated model (Eqns. 6 to 11). In this fifth step, we maximize regional producers' surplus (Eqn. 6, above) accounting for tradeoffs between costs and efficiency in irrigation and nitrogen management (Eqns. 7 and 8), resource constraints (Eqn. 9), mass balance (Eqn. 10), and policy-based nitrate leaching limits (Eqn. 13).

3.4 Model Datasets

The model is calibrated based on publically available datasets. Because data are insufficient to estimate a baseline and improved irrigation and nitrogen set of practices for all crops in the two study regions, we opted to perform the analysis on crop groups. Data were thus aggregated into crop groups based on an area-weighted average. One shortcoming of using this crop group approach is the aggregation of the response: all crops within a group are assumed to respond equally to costs of improvement.

3.4.1 Irrigation and Cost Data

Production input usage for land, water, labor, and supplies (excluding nitrogen) are obtained from the Statewide Agricultural Production Model (SWAP) .[35] Irrigation efficiency, the ratio of evapotranspiration of applied water to applied water, was taken from the California DWR crop group as reported in the California Water Plan Update (DWR 2009).[36] The capital costs per unit area for irrigation efficiency were obtained from USBR (1997) and scaled up to 2008 dollars, as were the rest of the monetary costs on inputs. Production information from UC Davis agricultural cost and return studies was employed for crops that were not included in the original SWAP formulation including lettuce and strawberries.[37] The irrigation technology parameters employed for the CES trade-off curves in Figure 14 follow USBR (1997).

3.4.2 Nitrogen Use and Cost Data

Because data are generally unavailable to estimate nitrogen use or cost data for individual practices, let alone, bundles of practices, we developed datasets to estimate efficiency and costs for three scenarios of practices: a current baseline scenario (Bundle 1), an improved scenario (Bundle 2), and an idealized and most efficient scenario (Bundle 3). Bundle 1 represents the efficiency and cost of current practices. Bundle 2 represents the scientifically tested improvement in nitrogen management possible with currently available practices. Bundle 3 represents the presumed benefits for NUE, surplus, and nitrate loading and economic costs for practices that are under development or not yet practically feasible at scale.

3.4.2.1 PNB of Bundles

The first step in developing the dataset was to estimate the PNB for each of the three bundles. Bundle 1 was presumed to be the baseline or current practice. For Bundle 1, we calculated PNB from available statistics.[38] Calculating a PNB requires knowing yield, moisture, and nitrogen content of the crop, as well as nitrogen application rates. We derived these values from the following sources: yields (USDA 2011a), moisture and nitrogen content (USDA 2011b), and nitrogen application rates (Rosenstock et al. in

---

[35] http://swap.ucdavis.edu
[36] http://www.waterplan.water.ca.gov
[37] http://coststudies.ucdavis.edu/
[38] It is worth noting that statistics on nitrogen usage are notoriously difficult to come by and any statistics found can at best be an approximation due to the variation among fields, farms, and regions.

review). Because the PNB of Bundle 1 reflects statewide average reported values, it aggregates across all of the practices that are occurring currently. This includes both advanced nitrogen management practices in some cases, as well as relatively traditional nitrogen management practices in others. Yet we assume that the PNB derived from the statewide averages is equal to the PNB for the most common unimproved bundles. Implicitly this means that depending on the current extent of adoption of improved practice bundles, the baseline PNB may be an overestimate.

Bundle 2 is the so-called “improved,” scientifically verified, collection of practices. For this bundle, PNB figures were compiled through a literature review. We surveyed published literature and collected unpublished data to find the most recent research on nitrogen management in California for 22 economically important crops (see footnote of Table 9 for references). These studies and data reflect recently developed and tested nitrogen and irrigation best management practices. We made every attempt to include research from field-scale nitrogen trials. Research conducted at research stations was excluded when other research existed because these trials generally outperform results observed in a grower’s field. That is, PNB will be higher under research-station conditions than in the field. Data relevant to calculating improved PNB values using the above equation were obtained adhering to the following prescription:

- Only reported yield and nitrogen application rates that corresponded to realistic nitrogen application rates for a particular crop were used. We only included data from research scenarios with reasonable application because nitrogen rate trials historically also include a zero-N treatment (no nitrogen applied) and an excessive nitrogen treatment with large amounts of nitrogen applied. Including these two values in the calculations would have potentially biased the PNB values.
- Where research reported the amount of nitrogen in the harvested portion of crop, those values were used directly. Where research only reported yield, but not crop nitrogen content, the amount of nitrogen in the crop was calculated based on the USDA Crop Nutrient Tool (USDA 2011b).

Bundle 3 represents the highest potential gains plausible. Many practices that are currently used by growers or are under development, such as weather based irrigation scheduling in cool-season vegetables, and will potentially reduce nitrate loading further than the improved practices identified above. However, data quantifying PNB and nitrate loading are not currently available. We represented these most efficient practices by including a third hypothetical bundle in our tradeoff between nitrogen application improvement and the costs of those improvements, in which we assumed PNB to be 5% higher than in the improved practice bundle.

3.4.2.2 Costs of Bundles

Estimated costs of ‘bundles’ are unavailable, especially when considering the range of crops grown in the study regions. Because of the paucity of data, we developed an index to estimate costs and the differences in costs among the bundles (hereafter referred to as the ‘cost ratio’). The cost ratio estimates the relationship between the cost of applying fertilizing materials (labor, machine time, information, etc.) and the fertilizing materials themselves. The cost ratio is based on the assumption that improving PNB generally results from more active management, demanding greater resources. As nitrogen and water management improve, the relative cost of application compared to fertilizer itself increases.

Cost ratios for the baseline and improved scenarios for each crop group were derived from the UC Agricultural and Resource Economics Department Cost and Return Studies (CS, http://are.ucdavis.edu). Cost ratios are not costs directly reported in the CS studies, rather they are estimates calculated from the available data. Estimated costs of bundles were developed to be consistent with the agronomic practices used to calculate PNB (e.g., industry standard practices for Bundle 1 and the practices used in the nitrogen trials for Bundle 2). Cost studies are inconsistent in how they present data, so we adopted a few basic rules to standardize estimations (Table 10). Rules needed to be created to disaggregate co-mingled costs. For example, CS studies often include the labor costs of fertigation with irrigation. Yet, increasing the frequency and number of fertigation events is a practice to increase NUE and decrease pollution potential. A fraction of the irrigation labor therefore must be attributed to the fertigation costs to obtain a realistic estimate.

Often there were CS studies that approximately reflected baseline and improved practices (e.g., furrow versus drip irrigation). In these cases, costs were derived from studies created for each practice. However, when improved practices represent only slight modifications of existing systems or if only one recent CS was available, costs for both baseline and improved PNBs were estimated from the same study. Since we created ratios of costs and they were consistent within a study, the ratios are comparable across studies.

The PNB and the respective cost ratios can be found in Table 11. These points correspond to Figure 13 and are employed to estimate the depicted CES relationship. Improvements in NUE modeled in this study lay within the continuum of this entropy-estimated relationship and will not necessarily correspond to Table 11 data points.

Table 10. Rules and justification to standardize data extraction from UC ARE Cost and Return Studies. These data were used to produce cost ratios for baseline and improved PNB.

Practice	Issue	Rule	Calculations
Fertigation	Labor costs of fertigation often included with irrigation labor costs.	Cost of labor depends on the number of fertigation events.	< 2 events: 5% of irrigation labor
			2 – 5 events: 10% of irrigation labor
			> 5 events: 15% of irrigation labor
Mixed operations	Fertilizer is often spread in conjunction with other operations.	Cost of labor is proportional to the number of operations.	Divide labor by number of operations performed.
Fertilizer blends	Fertilizer costs often includes other elements.	The cost of fertilizer is proportionate to the amount of N in the fertilizer blend.	Divide % N by total % NPK and multiply by cost of material.
Pest control advisor/consultant	Consultants advise on more than fertility decisions	Fertility is largely an add-on service estimated at 20% of cost.	Multiply custom cost by 0.20. Consultant costs limited to improved PNBs.
Diagnostic tests	CS only include more than 1/season.	Scale cost by the number used to create PNB.	Cost of test x number of tests.
Fertilizer rates	CS fertilizer costs usually for different N fertilizer rates than used in either PNB.	Scale costs to match fertilizer rate used to create PNB.	Use cross products to scale costs.

Table 11. Costs of improving N fertilization practices. The cost ratio is the ratio of cost of labor to N fertilizer materials.[39]

	Current practice		Improved practice	
Crop	**PNB[1] (%)**	**Cost ratio[2]**	**PNB[1] (%)**	**Cost ratio[2]**
Almond and pistachio	51	0.04	78	0.07
Corn	89	0.17	90	0.22
Cotton	61	0.05	67	0.15
Grain	80	0.13	91	0.19
Lettuce	35	0.24	51	0.35
Strawberry	34	0.07	55	0.14
Other vegetable crops	42	0.21	46	0.34
Other tree crops	36	0.12	33	0.36
Processing tomatoes	66	0.18	89	0.21
Subtropical	44	0.23	47	0.47
Vineyards	51	0.22	63	0.31

[1] PNB = (N exported in harvest/N applied) * 100

[2] Cost ratio = Labor : Fertilizing Material

[3] Excludes alfalfa, pasture, rice, and sugarbeet

---

[39] Data sources used to calculate PNB of improved practices: Brown, P.H. (personal communication), Allaire-Leung et al. (2001), Hartz et al. (2000) Fritschi et al. (2005), Frate et al. (2008), Peacock et al. (1991), Christensen et al. (1994),Ali. & Lovatt. (1994), Saenz et al. (2001), Johnson et al. (2001), Hartz et al. (1993), Rosenstock et al. (2010), Southwick et al. (1995), Meyer and Marcum (1998), Bendixon (1997), Hartz et al. (1994), Hartz and Bottoms (2010) and Richardson and Meyer (1990).

3.5 Modeling Results

3.5.1 Policy Modeling

We modeled two different baseline crop mixes, one for the Tulare Lake Basin and one for the Salinas Valley, considering the so-called Nitrogen Hazard Index grouping as described in section 2.2.3 and 2.6 of this report. The hazard index is an indicator of nitrate leaching vulnerability based on soil characteristics, the crop grown, and the irrigation system utilized on a specific field. Similar approaches have been used to quantify vulnerability of groundwater in agricultural regions (Loague et al. 1996). We employed existing cost information in the SWAP model and information on the likely PNB and its cost before and after application of best management practices. The model calibrates for all selected crops and production factors to within 3% of the *observed* input values.

Four policies were modeled: 1) a 25 percent reduction in the total nitrate load to groundwater, 2) a 50 percent reduction in the total nitrate load to groundwater, 3) a tax on applied nitrogen of 7.5% and 4) a $2.00 surcharge per kg of nitrogen applied, for fields that have exceeded a maximum allowed leaching rate of 35 kg/ha/yr. Finally, we test the robustness of our approach by undertaking a sensitivity analysis of the marginal cost of improving nitrogen use efficiency. In previous work, tax or fee-based N reduction policies have been found to have the highest social costs (Helfand & House 1995); however, these uniform input taxes and regulations (same for all users) are close to the socially optimal solution when accurate pollution charges are hard to implement. We quantify the impact of uniform-type regulations for agricultural production in our study area.

3.5.2 Modeling Results

Our preliminary model results indicate a relatively mild economic adjustment response in terms of cultivated land at the 25% nitrate load reduction level. However, a 50% reduction from the current nitrate load across the entire region translates into higher production costs and some decreases in net revenues from farming, even assuming yields are maintained by improving nitrogen and irrigation efficiency. Figure 16 and Figure 17, below, show the percent change in measures of water and nitrogen use efficiency by scenario and region. Base water use efficiencies are on the order of 72% and 68% for all crops in the Tulare Lake Basin and Salinas Valley, respectively. Baseline nitrogen use efficiency for the crops analyzed is 51 for the TLB and 40 for the SV. Overall, the TLB has higher NUE than the SV. The Salinas Valley has a higher value crop mix; however, the TLB has a higher proportion of more nitrogen efficient crops such as corn, processing tomatoes, almonds, and pistachios.

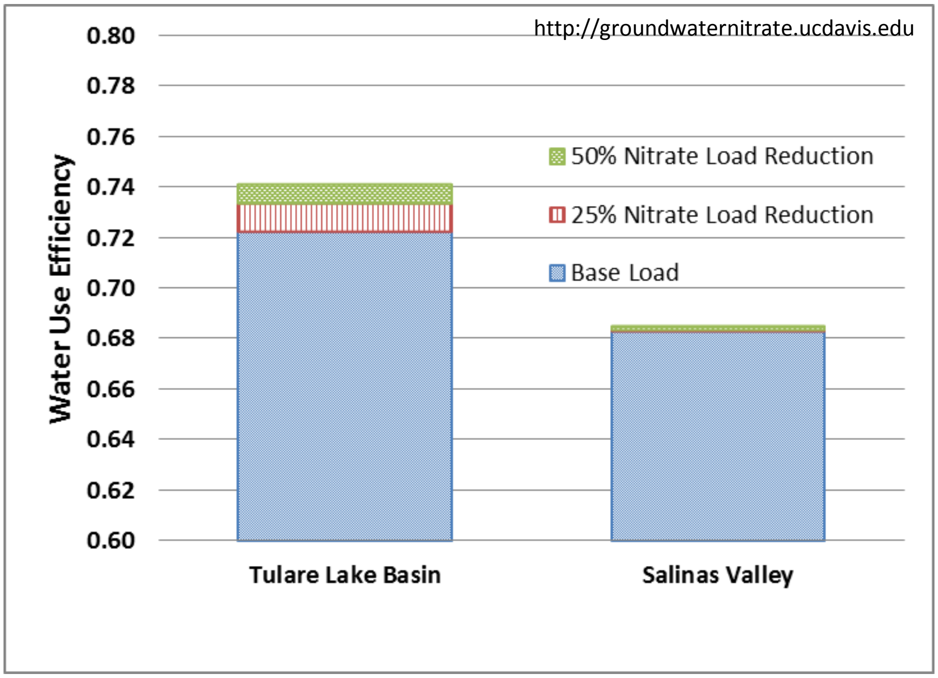


Figure 16. Water use efficiency for the Tulare Lake Basin and the Salinas Valley at different levels of reduction in nitrate load to groundwater.

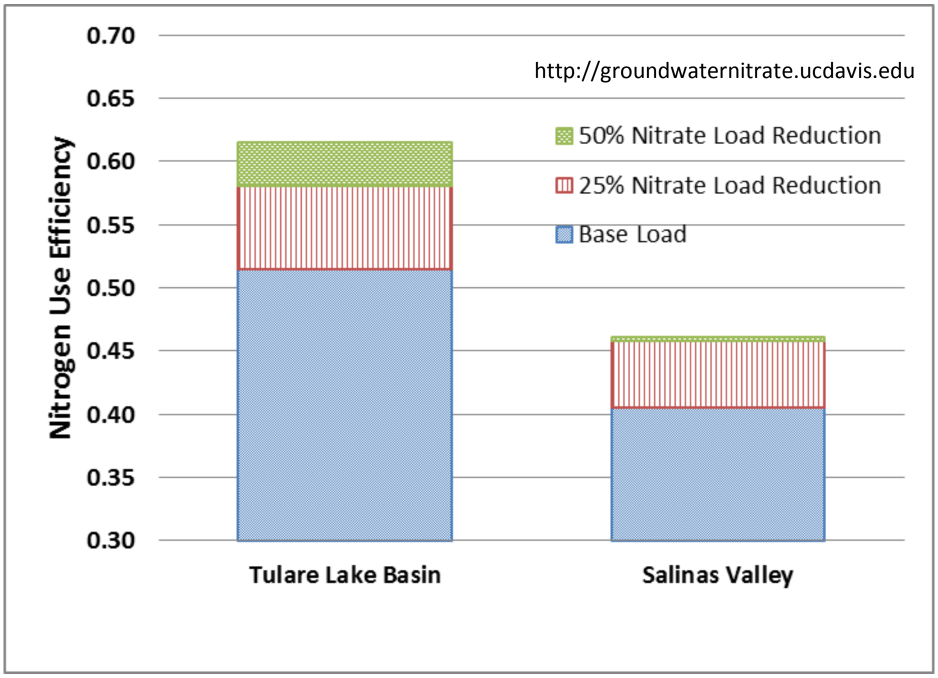


Figure 17. Nitrogen use efficiency for the Tulare Lake Basin and the Salinas Valley at different levels of reduction in nitrate load to groundwater.

Both water and nitrogen use efficiency increase with restrictions on total nitrate load to groundwater (Figure 16 and Figure 17, above). The marginal cost (not shown) of increasing irrigation efficiency is higher than the marginal cost for increasing nitrogen efficiency. Thus, the model allocates fewer resources to improve irrigation efficiency. To represent the interaction of water and nitrogen use efficiency on nitrate percolation to groundwater, we have constrained the model so that water efficiency is always greater or equal to nitrogen use efficiency.

Table 12 shows how applied water, applied nitrogen, land area, and net revenues would change with 25% and 50% nitrate load reductions. Reducing deep percolation loading by 25% can be achieved at relatively small costs in net farm revenue, assuming basic N management education is in place. However, net revenue losses increase at an increasing rate as greater reductions are sought. On average, in the TLB, a reduction of 3.6 metric tons of applied nitrogen for every 405 hectares (1000 acres) must be enacted to achieve a 25% decrease in nitrate load to groundwater.[40] For the Salinas Valley, this reduction is close to 5.6 metric tons per 405 hectares. For a 50% reduction in nitrate load to groundwater, the required reduction per 405 hectares increases to 5.2 metric tons for the TLB and 12.9 metric tons for the Salinas Valley. In the TLB, net revenue losses of 14% result from a 50% reduction in nitrate load to groundwater, which is four times the cost of a 25% reduction (3.5% loss in net revenue), with similar relationships in the SV. Figure 18, below, summarizes the relative changes in applied water, net revenues, irrigated land area, applied nitrogen, and nitrate load reductions for 0, 25 and 50 percent reductions in nitrate load.

Table 12. Groundwater nitrate load reduction scenarios and associated changes in total applied water, annual net revenues, irrigated land area, and applied nitrogen. The model keeps crop yields constant.

Region	Scenario	Applied Water km^3/yr [million AF/yr]	Net Revenues \$2008 M/yr	Irrigated Land 1000 Ha [ac]	Applied Nitrogen Gg N/yr (%) [1000 t/yr]
Tulare Lake Basin	Base Load	10.5 [8.5]	4,415 (0%)	1,293 [3,194]	200 (0%) [221]
	25% load reduction	10.0 [8.1]	4,259 (-3.5%)	1,293 [3,064]	181 (-9%) [199]
	50% load reduction	7.9 [6.4]	3,783 (-14%)	952 [2352]	135 (-32%) [149]
Salinas Valley	Base Load	0.37 [0.30]	309 (0%)	92 [227]	18 (0%) [20]
	25% load reduction	0.33 [0.27]	285 (-7.5%)	83 [205]	15 (-16%) [17]
	50% load reduction	0.25 [0.20]	239 (-22%)	62 [153]	10 (-46%) [11]

---

[40] This is calculated from Table 12 as the difference in the ratio of total nitrogen applied (last column Table 12) to irrigated land area (fifth column) for each scenario.

At base load conditions average weighted PNBs of 0.51 and 0.40 are estimated for TLB and SV, respectively. If a 25% reduction in the nitrate load to groundwater is implemented, weighted average PNB increases to 0.58 and 0.44 for TLB and SV, respectively. Similarly, the ratio of applied nitrogen to effective nitrogen decreases under nitrate load to groundwater restricting policies. Conversely the ratio of investments in NUE to effective nitrogen, weighted by region, increase as the nitrate load to groundwater is restricted. Changes in these sets of ratios suggest crop farming adaptation to nitrate load reduction to groundwater policies by reducing applied nitrogen, increasing NUE via investments in NUE, reducing irrigated crop areas or switching to more N efficient and/or profitable crops.

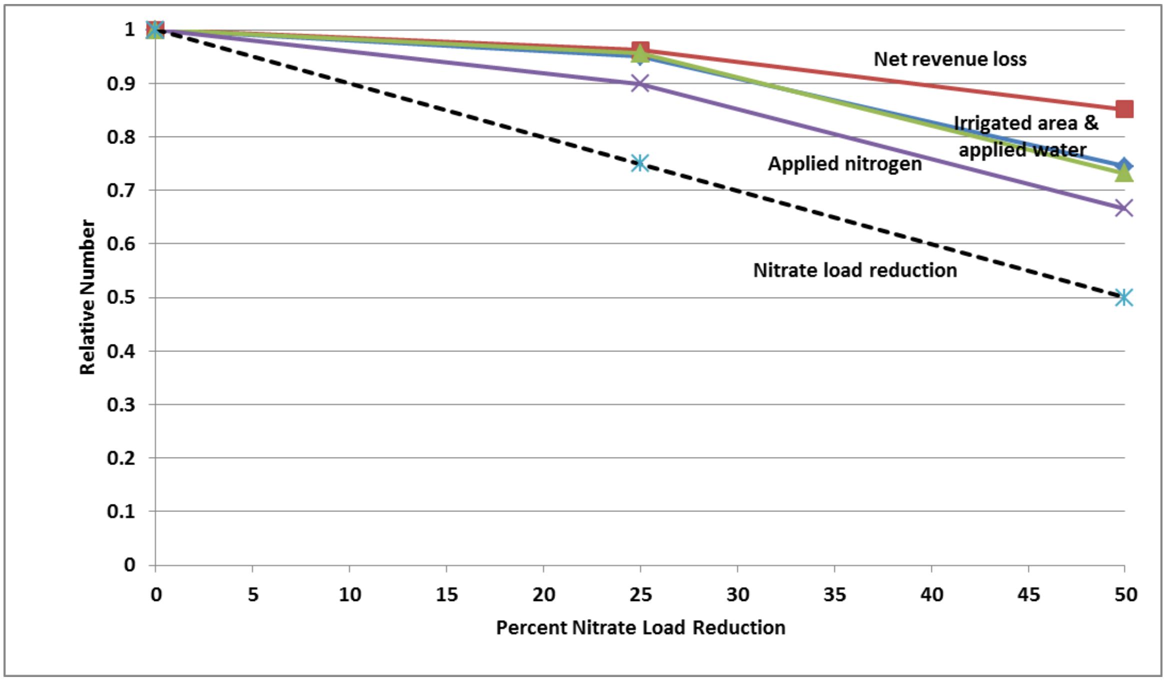


Figure 18. Relative applied water, net revenues, irrigated land, nitrogen applied, and nitrate load reduction as a function of reductions in the nitrate loading to groundwater by agriculture averaged over the Tulare Lake Basin and Salinas Valley.

Net percentage of revenue losses shown in Figure 19 below correspond to the net revenue in Table 12. Net revenue losses start increasing rapidly with larger reductions in total nitrate loading to groundwater. Reductions in total nitrate loading by 25% have an average cost of $8.1 per kilogram ($3.7/pound) of applied nitrogen in the TLB and $9.71 per kilogram ($4.4/pound) in the SV. When loading to groundwater is reduced by 50%, the average cost per kilogram of reduced nitrogen is approximately $9.7 per kilogram ($4.4/pound) for the TLB and $9.1/kg ($4.1/pound) for the SV.

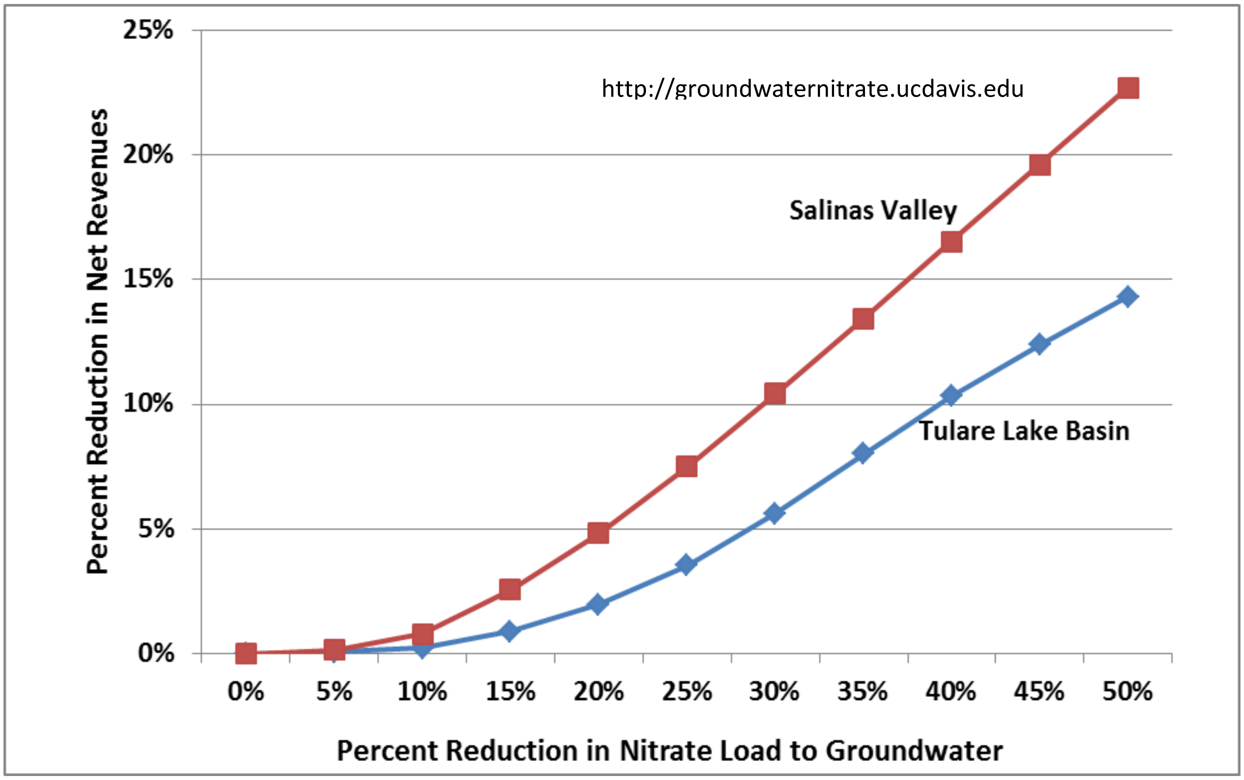


Figure 19. Percentage reduction in net revenues estimated from different levels of reduction in nitrate loading to groundwater.

Furthermore, Figure 20 below shows the marginal and average net revenue losses by kg of nitrate load reduction. As limits on nitrate leaching to groundwater increase, the average cost (as net revenue loss) per kg of nitrate load to groundwater increases. However, the marginal cost of nitrate load reductions to groundwater has two regions. In the first one, the marginal cost increases reaching a maximum, while in second one the marginal cost decreases and starts to flatten. This is analogous to stages of production in which a marginal product increases through stage 1, and is above average product but decreasing in stage 2 of production (Perloff 2004). This measure is useful for estimating costs of nitrate load limiting policies over the range analyzed in this study. For instance, the average net revenue loss per kg of nitrate load to groundwater is roughly $8/kg when the total nitrate load to groundwater is reduced by 25 percent. At this level, the marginal[41] net revenue loss per kg of nitrate load reduction is $18/kg, nearly twice as much as the average net revenue losses at 25% nitrate load reduction.

---

[41] The marginal net revenue loss per kg of nitrate load reduced to groundwater is the cost of an additional percent unit of reduction in the total nitrate load to groundwater.

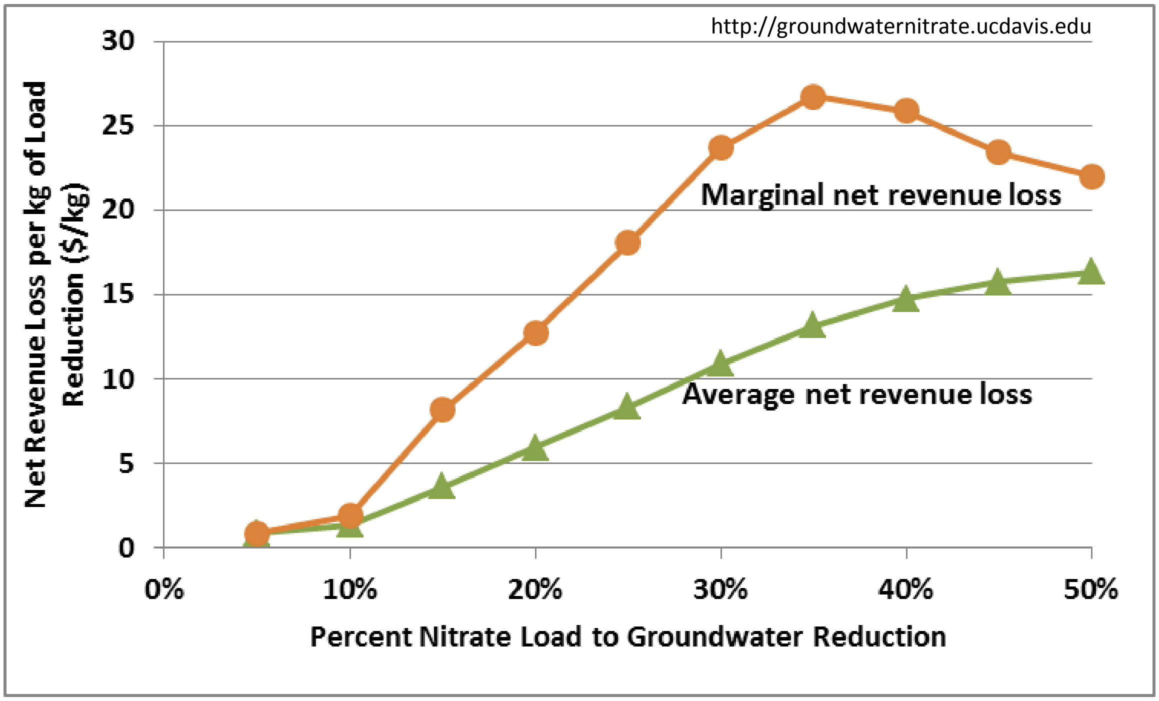


Figure 20. Average and marginal net revenue losses per kg of nitrate load reduction to groundwater.

We also present the resulting cropping pattern changes, from applying the two policies, in Figure 21 and Figure 22, below, for selected crops. At higher levels of reduction (e.g., 50%) cotton, corn, and other field and grain crops face the largest reductions in the Tulare Lake Basin. Likewise, the irrigated field and grain crops area is reduced in the SV, where higher value crops are grown. Irrigated area for high-value crops such as strawberries and lettuce remain about the same. However, vegetable crops as a group, due to their generally relatively low NUE, are subject to significant reductions in their irrigated crop area at highly restrictive nitrate loading policies. Similarly in the TLB, vegetable crops face significant reductions in their crop area when the total nitrate load to groundwater is required to be reduced by half.

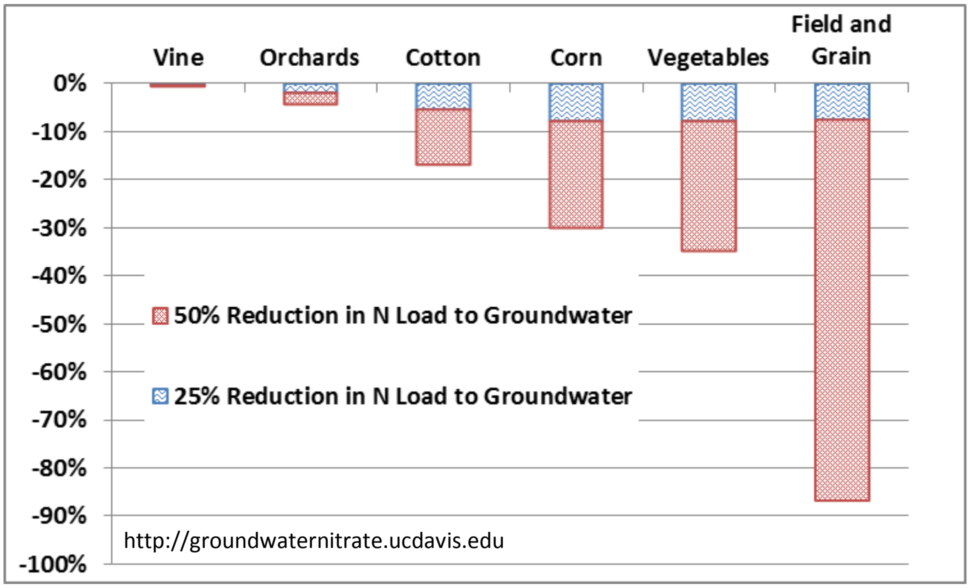


Figure 21. Cumulative change in cropping patterns with respect to base conditions for selected crops in the Tulare Lake Basin.

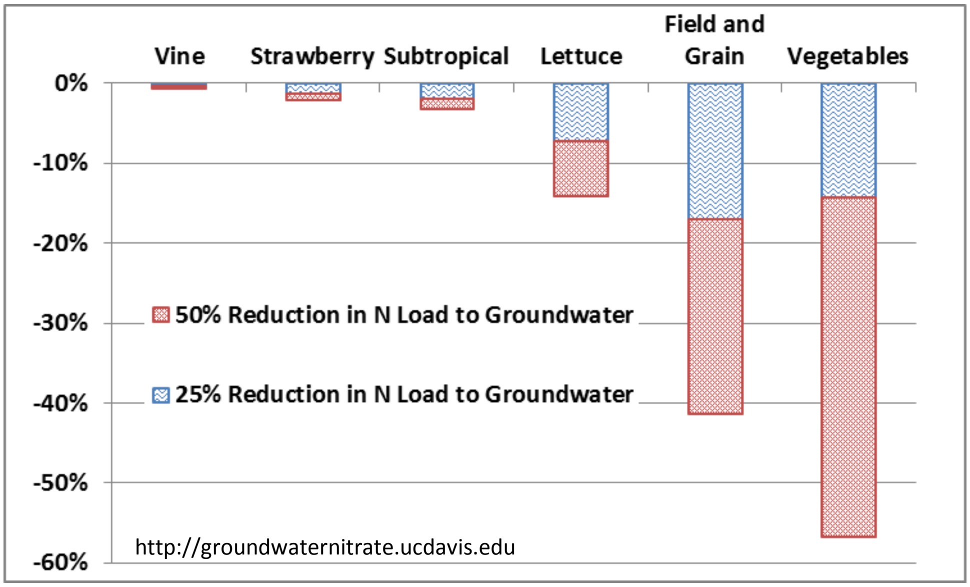


Figure 22. Cumulative change in cropping patterns with respect to base conditions for selected crops in the Salinas Valley.

Figure 23, below, illustrates the substitution between total applied nitrogen and investments in nitrogen use efficiency per unit area. The light shaded (blue) bars correspond to the percentage reduction of applied nitrogen per unit area, whereas the dark (red) shaded bars correspond to increases in the capital employed to produce the same crop mix per unit area. An interesting result is that the investment in nitrogen use efficiency improvements is maximized under the 25% reduction scenario, but is not increased with the 50% scenario for both study area regions.

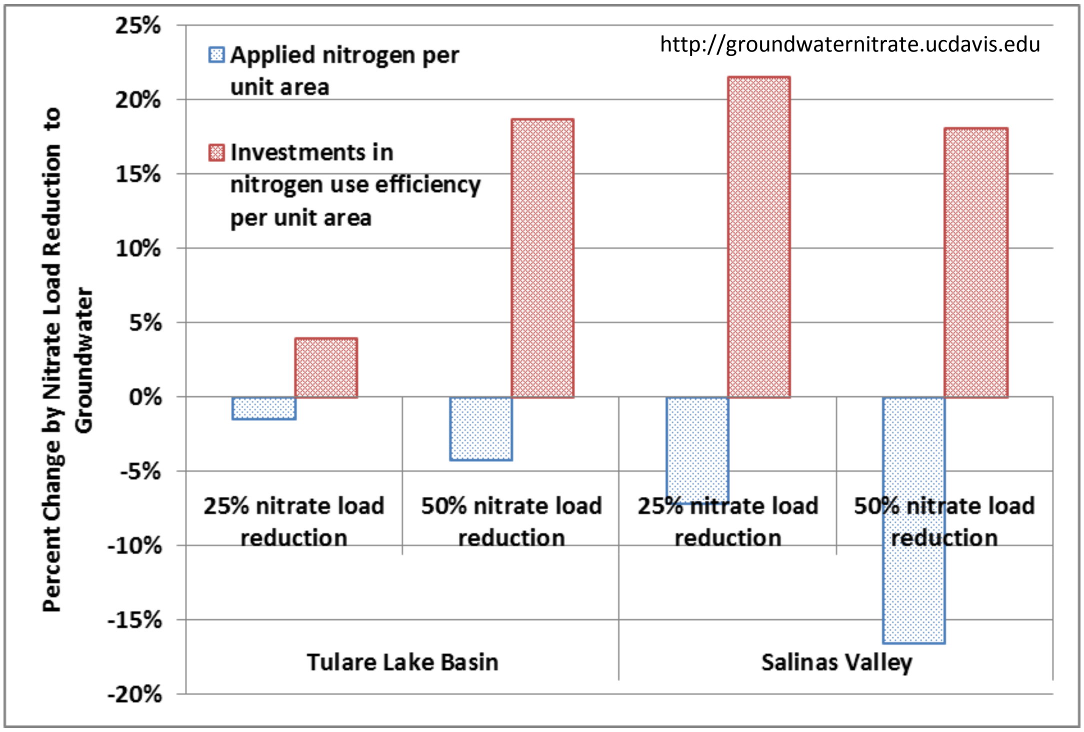


Figure 23. Average percent change, across all crops, in applied nitrogen and investment in nitrogen use efficiency per unit area with respect to current conditions.

3.5.3 A Tax on Nitrogen

Levying a tax on the use of nitrogen is one way to simultaneously reduce nitrogen use and to raise revenues to fund alternative water supplies. Currently the sale of nitrogen fertilizer is not subject to the California sales tax. The economic model is run under conditions that this tax relief is removed and the purchase of nitrogen is subject to the normal 7.5% California sales tax. Under this tax, the model predicts that farmers will respond in several ways to minimize the costs of the tax. There is a small difference in revenues and reductions in the levels of nitrogen applied in response to cost increase and are mostly offset by increases in investment in improving nitrogen use efficiency. Overall, nitrogen application is reduced by roughly 1.6% for both study area regions. Interestingly, the total irrigated acreage remains essentially unchanged. Figure 24 shows net revenue losses for both the TLB and the SV from zero to 50% tax on applied nitrogen. The trend is nearly linear for tax levels below 50% on applied nitrogen. Cropping patterns are maintained roughly constant with respect to base conditions. Net revenue losses for both the TLB and the SV from a sales tax policy of 7.5% are close to $29.4 million (0.6% of base net revenues).

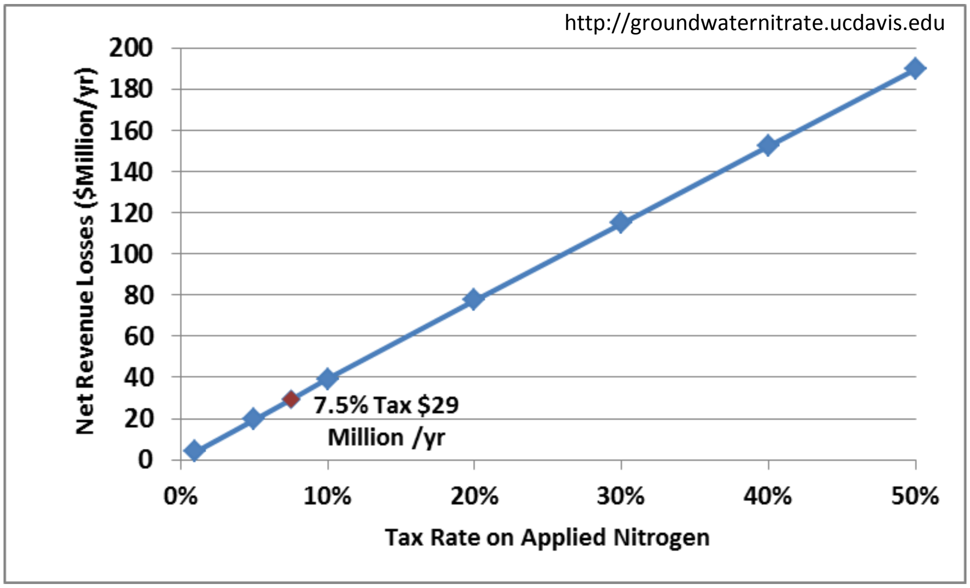


Figure 24. Net revenue losses for both the TLB and the SV per tax rate level.

3.5.4 A Penalty for Nitrogen Exceeding a Given Threshold

If a penalty of $2 per kg of N applied were set for any field exceeding a maximum leaching threshold of 35 kg/ha/yr (32 lb/acre/yr), irrigated crop area reductions are more evident in the model. For the TLB a 4.5% reduction in irrigated crop area may occur as a result of this threshold-based penalty. For the SV, this reduction can be as high as 5.6%. Total revenue losses can be 2.3% and 4.4% for the TLB and the SV, respectively, and are roughly in line with irrigated crop area reductions. Net revenue losses in this case exceed, on a percentage basis, land use reductions. Nearly 20% and 26% reductions in net revenues can be expected for the TLB and the SV, respectively. Thus, a high penalty on nitrogen application for crops with estimated loads to groundwater exceeding 35 kg/ha seems more effective in helping reduce total nitrogen application and load to groundwater. Reductions on the order of 3.5% in total revenues and 13% in the load to groundwater could be achieved; however, the net revenue loss can be high for this option.

3.5.5 A Sensitivity Test

One of the most questionable parameters is the marginal cost of improving nitrogen use efficiency. The sensitivity of the model results to this cost assumption is tested by doubling the cost in the initial model data. The model is then calibrated using the higher marginal cost and the same elasticities of substitution and supply as the base results model. When the 7.5% tax is coupled with the higher marginal cost for improving NUE, the difference in the results is interesting. The 7.5% tax results in higher reductions in total nitrogen applied of nearly 2.3% in the TLB, and 3.2% in the SV. Under these assumptions, the cost minimizing policy is to also reduce the total irrigated agricultural area by 2.3% in the TLB and 3.2% in the SV. The high cost of substituting a technology for improved nitrogen use efficiency makes it a cheaper alternative to reduce irrigated crop acreage of certain crops than to adopt the efficiency enhancing practice. Crop area reductions are concentrated in field crops and corn, grown both in the TLB and in the SV, to less than 10% of the base cultivated land. Likewise, net revenues decrease by 10.4% in the TLB and 15.3% in the SV. For the nitrate load to groundwater restriction policies, at a 25% reduction, irrigated crop area decreases 10% for the TLB and 15% for the SV. This sensitivity analysis confirms our expectations: the cost at which substitution between capital for improving NUE and the resulting NUE is a critical parameter in determining both the cost and type of policy response of the model.

The range over which we can substitute best management practices for nitrogen use efficiency is critical to the costs of both policy scenarios. We had great difficulty in finding reliable measures of the ability to substitute in the agronomic literature. Additional research on this topic is required to more reliably model the cost of nitrogen reduction policies.

3.5.6 Limitations

Several limitations are worth mentioning in our modeling approach. First, aggregation of crops may bias crop farming response to nitrate load limiting policies in both directions. Second, the restriction that keeps yields constant will clearly over-estimate the cost of both limiting nitrate load and nitrogen cost policies, as higher NUE may result in higher yields and therefore increased gross revenues from farming (Hartz 1994). Third, carryover nitrogen (Knapp and Schwabe 2008) and crop rotation may influence multi-year cropping decisions, currently not captured in our modeling approach, which may result in cost over estimation of the policies modeled in our study. Finally, given California's market power for some specialty crops, irrigated crop area shifts may actually have an endogenous price effect which will influence production decisions that might also partially compensate the estimated losses to agriculture. A more comprehensive approach to capture price effects (Medellin-Azuara et al. 2012) could be used. With these limitations in mind, our approach proves to be useful in eliciting likely crop response and costs of nitrogen use efficiency management for California.

3.6 Conclusions

Consistent with the literature (Larson et al. 1996; Vickner et al. 1998; Knapp & Schwabe 2008), small reductions in nitrate leaching to groundwater from croplands can be made at relatively low costs. However, nitrogen-limiting policies that require larger reductions, on the order of half the current loads to groundwater, may have significant consequences on net farm revenues and cause significant reductions in total irrigated area. A sales tax on applied nitrogen may reduce total applied nitrogen and groundwater nitrate loading, with a very modest effect on net farm income. The response to policy measures is shown to be sensitive to both the cost of increasing nitrogen use efficiency and the range over which improved efficiency can substitute for applied nitrogen.

The cost of reducing nitrate loading to groundwater from irrigated crop farming appears to increase with reductions that are greater than 25%, but this will depend on the true costs of implementing efficiency improving management practices. Adjustments occur in three ways: 1) changes in nitrogen use efficiency, 2) changes in irrigation efficiency, and 3) changes in cropping patterns. In constructing the model, we found that the ability and cost of improving nitrogen use efficiency is exceptionally difficult to define quantitatively, given current agronomic studies and available data. As shown in our sensitivity analysis, the marginal cost of increasing nitrogen use efficiency is clearly the most critical parameter in terms of uncertainty, and should be the focus of additional empirical field studies such as those done for irrigation efficiency, before policies are based on results such as these.

Several conclusions arise from this work:

1) Modest increases in nitrogen use efficiency will increase production costs, but are unlikely to affect total irrigated crop area. Less than 4% of the total irrigated area and net revenues will be lost with such modest increases to NUE via improved management practices.
2) Larger reductions in excess nitrogen will be much more costly to implement and may ultimately lead to net reductions in irrigated crop areas, higher costs in terms of net revenue losses, and shifting cropping patterns towards more profitable and nitrogen efficient crops. In this case, more than 20% of the total irrigated grain and field crops area would be reduced.
3) A sales tax on applied nitrogen may slightly decrease total applied nitrogen with some loss in farm net revenues. A sales tax of 7.5% could help reduce applied nitrogen by nearly 2% under the modeling and cost assumptions developed here.
4) Larger than estimated marginal costs for increasing nitrogen use efficiency increases farming response to nitrogen limiting and tax policies. A two-fold increase in the marginal cost of improving nitrogen use efficiency results in net revenue losses of more than 14% in the TLB and 21% in the SV when total nitrate loading is limited by 25% of base values.

Despite the information uncertainty, due to poor understanding of costs for nutrient management and nitrogen use efficiency improvements, this analysis shows that it is fruitful and insightful to combine quantitative economic and agronomic data into a model that can reflect the cost differences in the level and location of reductions in groundwater nitrate load. This type of modeling will improve with better development of field data.

4 Reducing Urban Landscape Nitrate Loading

Prepared by: G. Stuart Pettygrove

Turfgrass is grown in parks, golf courses, athletic fields, and school grounds, and around residential and industrial buildings. In many of these locations, maintenance of a high visual quality (i.e., a green and healthy appearance) has significant economic value. High visual quality of turfgrass usually requires N fertilization; as the cost of N fertilizer materials and application is low compared to the economic value of the turf, there is potential for over application, resulting in leaching of N to groundwater.

Recent studies conducted by the University of California show that Nitrate leaching from the rootzone of well managed turfgrass is very low (Wu et al. 2007, 2010). In one study, leachate passing the roots of bermudagrass turf had a lower concentration of N than the water used for the irrigation, even though the turf received N fertilizer applications that are typical of resort golf courses (Wu et al. 2007). Low leaching N loss is due to the dense continuous plant canopy and root system of healthy turfgrass and its perennial growth habit, which allows for continuous N uptake over at least 8 months of the year depending on the species used. Furthermore, N applications at rates exceeding the minimum needed to maintain acceptable appearance simply results in "luxury uptake" by the turf and increased growth.

Poorly managed turf with a discontinuous canopy and presence of weeds, if it is growing on permeable soils and is overirrigated, presents a greater risk of Nitrate leaching loss, especially if fertilized at high rates during the dormant season of bermudagrass or similar tropical species of turfgrass. It is less likely that turfgrass in such condition in residential areas will be managed according to professional N fertilization guidelines; however, it also is less likely that in such situations, high rates of N fertilizer will be applied.

Therefore, an effective approach to limiting Nitrate leaching losses from urban turfgrass to very low levels is to follow standard N fertilization guidelines published by land grant universities and the golf course industry. These guidelines provide recommendations for N fertilizer rates in pounds N per 1000 square feet and for application timing. All such guidelines recommend somewhat smaller doses of N than often were recommended in the past. Also recommendations are for multiple small doses of N rather than single large doses. UC recommends more frequent, smaller applications to turf on soils having a low water holding capacity (i.e., on sandy soils). In some situations, the use of slow-release fertilizers will allow for reduced frequency of application, while maintaining turf quality; this type of product is in use on professionally managed turfgrass. An incentive for golf course managers and other landscape managers to use conservative N application rates is the less frequent mowing needed and smaller volume of clippings requiring disposal.

Turf N management guidelines suitable for both homeowners and professionally managed turf exist and can be accessed on the internet. Such guidelines are published by the University of California Integrated Pest Management Program (University of California Integrated Pest Management 2011) and by the Oregon Chapter of the Golf Course Superintendents Association of America (Oregon Golf Superintendents Association 2009).

5 Reducing Domestic and Urban Wastewater Nitrate Loading

Prepared by:

Vivian B. Jensen, Jeannie Darby, Nicole De La Mora, Thomas Harter, Aaron M. King

Acknowledgments

This work was funded by the State Water Resources Control Board under agreement number 09-122-250. The authors are grateful to all of the treatment plant employees who participated in surveys and interviews, especially Ron Cole of Salinas Environmental and Maintenance Services, Glenn Holder and Rosa Staggs of Fresno-Clovis Regional Wastewater Reclamation Facilities, Zachary Meyers of the Bakersfield Wastewater Division, and Jim Ross of the City of Visalia Wastewater Treatment Plant. Special thanks to Dr. Yoram Rubin and his team for sharing the Hilmar SEP database, to State and Regional Water Board representatives including Erin Mustain, Daniel Benas, Clay Rodgers, and Matt Keeling, and to Lauren Fondahl from U.S. EPA Region 9. The input from Harold Leverenz and Amelia Holmes regarding septic system improvements is appreciated. The contents of this document are solely the responsibility of the authors and do not necessarily represent the official views of supporting agencies.

5.1 Introduction

As potential nitrogen sources in the Tulare Lake Basin and Salinas Valley, wastewater treatment plants (WWTPs) and food processing facilities (FPs) were examined to:

- Assess their contribution to groundwater nitrate loading,
- Determine the regional and local impacts of nitrogen in discharge,
- Examine nitrogen control measures, and
- Propose solutions for nitrate loading reduction.

It is important to understand the dual nature of this discussion; wastewater treatment and food processing facilities can be sources of nitrogen and they can also be part of the solution. Potential sources of nitrate contamination from these facilities are:

- Sewer leakage due to aging/compromised infrastructure,
- Effluent from WWTPs and FPs discharged for irrigation and/or groundwater recharge, and
- Wasted solids from these facilities that are applied to land as a soil amendment.

A comprehensive assessment of potential nitrate loading from land applied discharge from WWTPs and FPs is provided in Technical Report 2, Section 6.2 (Viers et al. 2012). Also, Technical Report 2, Section 6.3 covers potential nitrate loading from sewer leakage. The below discussion is intended as an overview of options to prevent and reduce N loading from these sources.

Land application of effluent from these facilities can be an effective way to reuse water and nutrients, using natural processes in the soil and irrigated crops as a final stage of treatment. However, with inappropriate land application groundwater can be degraded. When discharges run the risk of negatively impacting groundwater, existing land application processes can be modified or facilities can be improved and potentially expanded to optimize operations and/or treat wastewater to a higher quality.

Septic systems in rural and peri-urban regions of the study areas are locally significant sources of nitrate leaching to groundwater (see Technical Report 2, Section 6.4, Viers et al. 2012). We discuss options for reduction of this source of nitrogen, as well.

5.2 Nitrogen Reduction from Wastewater Treatment and Food Processing Facilities

How can nitrate loading be reduced? How feasible are reduction options? What are the costs?

Land application of effluent from WWTPs and FPs can be an effective way to reuse water and nutrients, using natural processes in the soil and irrigated crops as a final stage of treatment. However, with inappropriate land application, groundwater can be degraded. When discharges run the risk of negatively impacting groundwater, existing land application processes can be modified or facilities can be improved and potentially expanded to optimize operations and/or treat wastewater to a higher quality.

Before considering the implementation of additional treatment processes to minimize nitrate loading to groundwater from land applied discharge, adjustment to land application practices should be considered. With discharge application at appropriate rates, proper onsite storage, and monitoring to avoid groundwater degradation, land application may be the best waste management option available for certain facilities.

As discussed previously (see Technical Report 2, Section 6.2, Viers et al. 2012), land treatment methods can be categorized into three main types: Slow Rate (SR), Overland Flow (OF), and Soil Aquifer Treatment (SAT)/Rapid Infiltration (RI) (Crites, Reed, & Bastian 2000; United States Environmental Protection Agency 2006). SR and SAT/RI are most pertinent to our analysis. For food processing facilities, with the selection of the most appropriate land treatment method based on site and water quality characteristics, the high cost of disposal at publicly-owned treatment works (POTW) can be avoided and the need for onsite treatment systems may be minimized. Low strength wastewaters may only require screening before land application; however, high strength waste streams must be treated prior to discharge. To ensure the protection of drinking water sources, the appropriate measures must be determined and implemented based on the needs and characteristics of individual facilities.

5.2.1 Nitrogen Reduction – Methodology

A brief literature review of available options to reduce nitrate loading to groundwater from WWTPs and FPs was conducted including both treatment and non-treatment options. Cost information was collected from published literature and case studies. Cost information can be used to assess the feasibility of options to reduce nitrate loading from WWTPs and FPs relative to the options available to address more significant sources (e.g., fertilizer). Treatment information was collected from WWTPs in the study area (top 90% of flow based on design flow, see Technical Report 2, Section 6.2 (Viers et al. 2012) for additional information), supplementing a survey of WWTPs performed by the State Water Board across CA (State Water Resources Control Board 2010).

A list of at-risk WWTPs and FPs (i.e., WWTPs which may need to adjust land application practices and/or include nutrient removal in the treatment process) was developed, based on the collected nitrate loading data (Technical Report 2 Section 6.2, Viers et al. 2012). For high demand crops, a rough estimate of required nitrogen is 250 kg/ha/yr (~225 lb/acre/yr), or 500 kg/ha/yr (~450 lb/acre/yr) for double cropping.[42] Facilities exceeding this application rate risk contributing to nitrate contamination of groundwater. This is important both regionally and locally to pinpoint hot-spots and locate facilities that may require additional treatment or altered land application practices. Facilities annually discharging total N greater than 250 kg/ha/yr (~225 lb/acre/yr) to agriculture and/or discharging effluent having total N concentrations greater than the MCL to percolation basins are included in the list. Facilities annually discharging total N greater than 500 kg/ha/yr (~450 lb/acre/yr) were also investigated to account for the possibility of double cropping. Treatment costs for nutrient removal were gathered from U.S. EPA documentation (United States Environmental Protection Agency 2008) and utilized to estimate costs for nitrate loading reduction from at-risk WWTPs and FPs.

5.2.2 Reducing Nitrogen Loading from Wastewater Treatment Plant Discharge – Nutrient Removal

"Conventional biological treatment processes designed to meet secondary treatment effluent standards typically do not remove total nitrogen (TN) or total phosphorus (TP) to an extent sufficient to protect certain receiving waters" (United States Environmental Protection Agency 2008). However, nutrient removal in wastewater treatment has become increasingly prevalent over the past 30 years. Treatment options for nutrient removal from wastewater are thoroughly described in the literature, with an abundance of material in engineering textbooks and state and federal guidance manuals/publications (Metcalf & Eddy 2003; United States Environmental Protection Agency 2008; Water Environment Federation 2010). The U.S. EPA guidance manual (2008) is a comprehensive resource describing available relevant technologies, their reliability, feasibility, and costs, based on case studies of full scale WWTPs.

Nitrogen removal from wastewater can be accomplished using a variety of technologies and configurations; both biological and physical/chemical processes are effective. The selection of the most appropriate treatment option is dependent on many factors including:

- Influent wastewater quality characteristics
- Required capacity
- Effluent discharge limitations
- Financial constraints
- Operations and Maintenance (O & M) demands
- Site limitations (land area, temperature, etc.)
- Electron donor source
- Future need for expansion

With many potential configurations to achieve nitrification or both nitrification and denitrification, biological nutrient removal is typically categorized as tertiary or advanced treatment and can be incorporated into the biological processes of secondary treatment (Metcalf & Eddy 2003). Additional

---

[42] This is a rough estimate for high demand crops and is based on crop nitrogen demand for single and double cropping as discussed in Technical Report 2, Section 3 (Viers et al. 2012).

methods used for nitrogen removal include chemical oxidation, air stripping, and ion exchange (Metcalf & Eddy 2003).

Biological nutrient removal (BNR) is accomplished through the provision of optimal conditions for the activity of various species of bacteria (Table 13). Through biologically mediated transformation processes, influent organic nitrogen and ammonia are converted to nitrate and then to nitrogen gas. Optimal conditions are process dependent and different BNR configurations can be designed to facilitate each stage. For example, nitrification is an aerobic process, requiring sufficient oxygen, while denitrification requires anoxic conditions and an electron donor (wastewater is likely sufficient).

Table 13. Treatment processes and associated bacterial species in wastewater treatment for nitrogen removal (adapted from United States Environmental Protection Agency 2008).

Nitrogen Transformation	Process	Bacteria
Organic nitrogen $\rightarrow NH_4^+$	Ammonification	Various
$NH_4^+ + 3/2O_2 + 2HCO_3^- \rightarrow NO_2^- + 2H_2CO_3 + H_2O$	Nitrification (1)	*Nitrosomonas*
$NO_2^- + ½ O_2 \rightarrow NO_3^-$	Nitrification (2)	*Nitrobacter*
NO_3^- + organic carbon $\rightarrow N_{2(g)} + CO_{2(g)} + H_2O + OH^-$	Denitrification	Denitrifiers

Denitrifying bacteria require an electron donor (substrate) for the reduction of nitrate to nitrogen gas. In conventional wastewater treatment, substrate addition is not typically needed, because the wastewater contains sufficient carbon for denitrification to occur. However, depending on source water, substrate addition may be required. Feed water composition may need to be further augmented with the addition of nutrients required for cell growth (phosphorus for example). Autotrophic bacteria utilize sulfur or hydrogen as an electron donor and inorganic carbon (typically carbon dioxide) as a carbon source for cell growth (Eqns. 14 and 15), while heterotrophic bacteria consume an organic carbon substrate, such as methanol, ethanol, or acetate (Eqn. 16) (Mateju et al. 1992; Kapoor & Viraraghavan 1997).

$$11S^0+0.5CO_2+10NO_3^-+2.54H_2O+1.71NH_4^+\rightarrow0.92C_5H_7O_2N+11SO_4^{2-}+5.4N_2+9.62H^+ \quad \text{(Eqn. 14)}$$

$$H_2 + 0.35\ NO_3^- + 0.35\ H^+ + 0.052\ CO_2 \rightarrow 0.010\ C_5H_7O_2N + 0.17\ N_2 + 1.1\ H_2O \quad \text{(Eqn. 15)}$$

$$1.08\ CH_3OH + NO_3^- + H^+ \rightarrow 0.065\ C_5H_7O_2N + 0.467\ N_2 + 0.76\ CO_2 + 2.44\ H_2O \quad \text{(Eqn. 16)}$$

Various species of bacteria are responsible for denitrification including *Thiobacillis denitrificans, Micrococcus denitrificans, Pseudomonas maltophilia* and *Pseudomonas putrefaciens* (Kapoor & Viraraghavan 1997).

BNR processes fall into three major categories: suspended growth, biofilm, and hybrid systems (Water Environment Federation 2010). In suspended growth systems (e.g., activated sludge), "bacteria are kept in suspension under appropriate conditions to allow them to grow and consume pollutants from the water" (Water Environment Federation 2010 p. 65). In contrast, biofilm systems encourage surface growth of bacteria (e.g., trickling filters and moving bed bioreactors (MBBRs)). Sample configurations of BNR are listed in Table 14 (United States Environmental Protection Agency 2008; Water Environment Federation 2010).

Table 14. Sample configurations and processes for biological nutrient removal in wastewater treatment (United States Environmental Protection Agency 2008; Water Environment Federation 2010).

• Activated Sludge (see cyclical aeration, fixed film)	• MBR (In-tank vs. external tank)
• Moving Bed Bioreactor (MBBR)	• Alt MBBR
• Effluent Filter/Denitrifying Filter	• Fluidized Bed
• Ludzack-Ettinger	• Modified Ludzack-Ettinger
• Four-stage Bardenpho	• Sequencing Batch Reactor (SBR)
• ANAMMOX	• SHARON
• InNitri	• Biodenitro
• BABE	• Oxidation Ditch
• Trickling Filter	• Biologically Activated Filters
• Wuhrman	• Step Feed Activated Sludge
• Simultaneous NDN	• SHARON-ANAMMOX
• Schreiber countercurrent aeration process	• Constructed Wetlands

While there are many configurations and types of systems, all BNR processes for nitrogen removal require an aerobic nitrification zone and an anoxic denitrification zone. The Municipal Nutrient Removal Technologies Reference Document (United States Environmental Protection Agency 2008) includes a decision matrix to facilitate technology selection based on key factors including site, water quality, and operation considerations.

Physico-chemical treatment options (Table 15) include breakpoint chlorination, gas stripping, ion exchange, and membrane processes (reverse osmosis (RO) and electrodialysis reversal (EDR)). While technologically feasible, the high costs of physico-chemical processes generally limit application of these options for nitrogen removal from wastewater (United States Environmental Protection Agency 2008). Also, treatment processes resulting in a brine waste stream can be particularly problematic for inland regions like the Tulare Lake Basin, due to the expense of brine disposal.

Table 15. Physico-chemical technologies for nutrient removal from wastewater (adapted from Water Environment Federation 2010).

Breakpoint Chlorination	Ammonia Stripping
Ion Exchange	Chemical and Catalytic Denitrification
Membrane Processes (RO and EDR)	Various Media (Bauxite/Zeolite)

For details on the WWTPs in the study area, with respect to treatment, including a discussion of treatment costs for facilities with greater contributions to nitrate loading, see Section 5.2.5 *Reduction of Nitrogen Loading from Wastewater Treatment Plants and Food Processors in the Tulare Lake Basin and Salinas Valley*, below.

5.2.3 Reducing Nitrate Loading from Food Processor Discharge

There are several options for avoiding the installation of an on-site treatment system for nitrogen removal at FP facilities:

- Optimization of food processing practices to moderate nitrogen levels in discharge or minimize waste volumes requiring disposal,
- Blending of low and high strength waste streams to meet permit limits,
- Reuse of process water to decrease total waste flow,
- Consideration of alternative disposal options, including deep well injection and POTWs,
- Use of discharge for irrigation of agricultural crops rather than direct groundwater recharge through percolation ponds to reduce nitrate loading to groundwater,
- Implementation of appropriate measures to avoid leaching of groundwater from storage vessels prior to land application (lining of storage ponds),
- Modification of land application practices to limit nitrogen application rates to levels less than or equal to plant uptake rates by decreasing flow rate, decreasing nitrogen levels, or increasing acreage.

When alternative options have been eliminated, treatment options for nitrogen removal from FP wastewater are similar to those described above for WWTPs. Additional information is available in the literature; (Isosaari, Hermanowicz, & Rubin 2010) provide a comprehensive discussion of natural wastewater treatment options pertinent to waste management in food processing facilities. Additionally, the Hilmar SEP report includes a detailed discussion of treatment options for food processing wastewater; the primary focus of the Hilmar analysis is salinity, but nitrate is considered as well (Rubin et al. 2007; Sunding et al. 2007; Sunding & Berkman 2007).

Details on the FPs in the study area, with respect to treatment, including a discussion of treatment costs for facilities with greater contributions to nitrate loading, follow in the next section.

5.2.4 Reduction of Nitrate Loading from Wastewater Treatment Plants and Food Processors – Treatment Costs

When options for in-plant optimization and improvements to land application practices have been exhausted, N loading can be reduced through the implementation of additional treatment measures. The Municipal Nutrient Removal Technologies Reference Document (United States Environmental Protection Agency 2008) includes a comprehensive cost analysis of retrofitting and expansion for BNR. Based on case studies developed by the U.S. EPA, "the costs for modification ranged from a low of $0.20 to a high of $5.25 per gpd capacity" (United States Environmental Protection Agency 2008 pp. 4–34). Costs varied based on facility size, water quality parameters, treatment level, and process; overall costs per unit capacity are higher for small systems. Costs were modeled and cost curves were developed based on process and system capacity.

Expansion of facilities refers to "a parallel train and no increase in design flow" while retrofitting facilities includes the adaptation of existing facilities and is therefore less expensive (United States Environmental Protection Agency 2008). Table 16 lists BNR costs for multiple configurations; costs were averaged over three system sizes: 1, 5, and 10 mgd (United States Environmental Protection Agency 2008). Life cycle costs were calculated, "by first annualizing the capital cost at 20 years at 6 percent interest. The annualized capital cost was then added to the annual O&M cost to obtain total cost. This cost was then divided by the annual flow to get the life-cycle cost per million gallons (MG) treated" (United States Environmental Protection Agency 2008 p. ES–17).

Although the Hilmar SEP report includes a detailed cost analysis of treatment options for food processing facilities, the primary focus of that investigation is salinity. The costs and technologies for treating high salinity waters are different from those for nitrate treatment. Salt loading is a significant problem in parts of California and the results of the Hilmar SEP study provide an extensive volume of information. The costs listed for biological treatment are pertinent to this discussion. Costs associated with the discharge of food processor effluent to the Tulare WWTP, provided as an estimate of the costs of biological treatment, are $1,070/MG ($1.07/kgal) (Sunding et al. 2007 p. 571).

Table 16. Costs of BNR for example configurations with design capacity ranging from 1 to 10 mgd (United States Environmental Protection Agency 2008).

Process	Capital Cost ($/gpd capacity)	O&M Cost ($/MG treated)	Life Cycle Cost ($/MG treated)
Retrofit			
Denitrifying Filter[1]	1.00	303	543
Step Feed[2]	0.83	105	303
MLE[3]	0.88	92	275
Extra Basins for PID[4]	0.52	65	190
Expansion			
Denitrifying Filter[1]	1.00	303	543
Step Feed[2]	1.73	383	792
MLE[3]	1.97	408	883
Extra Basins for PID[4]	0.79	145	335
SBR[5]	2.40	398	970

[1] Denitrifying filter with a total N target of 3 mg/L.
[2] Step feed configuration with retrofit taken as 1/3 of step feed, with a total N target of 5 mg/L.
[3] Modified Ludzack-Ettinger process with retrofit taken as 1/3 of MLE and total N target of 5 mg/L.
[4] Extra basins for PID (phased isolation ditch) with a total N target of 5 mg/L.
[5] SBR (Sequencing Batch Reactor), with a total N target of 5 mg/L, provided for comparison with Tulare WWTP.

5.2.5 Reduction of Nitrate Loading from Wastewater Treatment Plants and Food Processors in the Tulare Lake Basin and Salinas Valley

Fifteen percent of the WWTPs included in this study reported the use of some form of nutrient removal to decrease effluent nitrogen levels. For reference, total annual nitrogen levels (including nitrate-N, nitrite-N, ammonia-N, and organic-N) discharged from facilities with treatment for nutrient removal average 12.54 mg/L N, while the average across all other facilities is 16.65 mg/L N. It is important to keep in mind, however, that WWTPs treating to remove nitrogen in effluent are doing so because of high nitrogen levels.

A list of at-risk WWTPs and FPs (i.e., facilities which may need to adjust land application practices and/or include nutrient removal in the treatment process) was developed, based on the collected nitrate loading data (Technical Report 2, Section 6.2, Viers et al. 2012). Facilities discharging an annual total N greater than 250 kg/ha/yr (223 lb/ac/yr) to agriculture and/or discharging effluent having nitrogen concentrations greater than the MCL to percolation basins are included in the list.[43] Facilities discharging an annual total N greater than 500 kg/ha/yr (446 lb/ac/yr) are also listed to account for the possibility of double cropping.[43] It is important to note that this analysis is not suggesting that all of these facilities are contributing to groundwater nitrate contamination; groundwater monitoring data would be necessary to determine the relative impact (if any) of discharges from these facilities on

---

[43] This is a rough estimate for high demand crops and is based on crop nitrogen demand for single cropping as discussed in Technical Report 2, Section 3 (Viers et al. 2012).

groundwater nitrate levels. However, based on the assumptions herein, the facilities included in Table 17 are the top contributors to applied nitrogen of all the facilities included in this investigation.

Table 17. Number of facilities with > 250 kg N/ha/yr and > 500 kg N/ha/yr in discharges to irrigated agriculture and > 10 mg/L N in discharges to percolation basins.

	WWTP Irrigation	**WWTP Percolation**	**FP Irrigation**	**FP Percolation**
By County	# > 250 kg N/ha/yr (# > 500 kg N/ha/yr)*	# > 10 mg/L N	# > 250 kg N/ha/yr (# > 500 kg N/ha/yr)*	# > 10 mg/L N
Fresno	0 (0)	8	6 (2)	11
Kern	4 (2)	2	3 (1)	5
Kings	0 (0)	2	1 (0)	0
Tulare	3 (1)	7	2 (1)	10
Monterey	1 (0)	2	0 (0)	2
By Basin				
TLB	*7 (3)*	*19*	*12 (4)*	*26*
SVB	*1 (0)*	*2*	*0 (0)*	*2*
Overall Count**	**8 (3)**	**21**	**12 (4)**	**28**

Note: Solids not included.
*To allow for double cropping.
**Total # Facilities: 24 WWTP, 39 FP. Some facilities discharge to both irrigated agriculture and percolation ponds.

Based on wastewater flow, capital and O&M costs associated with treatment for nutrient removal for the at-risk facilities listed in Table 17 can be estimated. As mentioned above, wastewater treatment costs vary with numerous factors; these numbers are intended as a rough guide and actual costs may vary significantly from those listed here. These costs have been estimated based on system flow and the above cost information reported for biological nutrient removal in wastewater treatment (Table 16). Available BNR costs (United States Environmental Protection Agency 2008) for 1, 5, and 10 mgd treatment systems are used here as an approximation of actual costs. Many of the food processing facilities have very low wastewater flows (<< 1 mgd); BNR capital costs are therefore expected to be significantly underestimated for these low flow systems lacking economies of scale. In practice, these facilities would likely consider modification of land application practices or in-plant optimization, rather than installation of a small scale BNR system. Similarly, facilities listed above as exceeding application levels for irrigated agriculture are likely to first consider addressing groundwater degradation risk through changes in land application practices. Costs were estimated only for those facilities with land application (irrigation or percolation) of discharges having nitrogen concentrations above 10 mg/L as N. This includes all at-risk facilities listed above (24 WWTPs and 39 FPs) as some facilities discharge to both irrigated agriculture and percolation ponds.

Total capital costs for BNR treatment of all wastewater (FPs and WWTPs) from the above listed at-risk facilities range from \$70 – \$135 million and \$107 – \$266 million, for retrofit and expansion projects, respectively. Associated annual O&M costs range from \$3.2 – \$15 million and \$7.2 – \$20 million, for retrofit and expansion projects, respectively. Table 18 lists estimated cost information for BNR by basin for at-risk WWTPs and FPs.

Table 18. Estimated costs of BNR (U.S. EPA 2008) for at-risk facilities, based on wastewater flow.

# Facilities: 24 WWTP, 39 FP	**WWTP Retrofit**	**WWTP Expansion**	**FP Retrofit**	**FP Expansion**
Total by Basin				
TLB Capital Costs (\$ x10^6)	62.0 – 119.2	94.2 – 234.8	5.5 – 10.6	8.4 – 20.9
TLB Annual O & M (\$ x10^6)	2.8 – 13.2	6.3 – 17.8	0.252 – 1.2	0.561 – 1.6
SVB Capital Costs (\$ x10^6)	2.7 – 5.3	4.2 – 10.4	0.035 – 0.067	0.053 – 0.132
SVB Annual O & M (\$ x10^6)	0.125 – 0.582	0.279 – 0.785	0.002 – 0.007	0.004 – 0.010
Overall Total				
Capital Costs (\$ x10^6)	64.7 – 124.5	98.3 – 245.2	5.6 – 10.7	8.4 – 21.0
Annual O & M (\$ x10^6)	3.0 – 13.8	6.6 – 18.5	0.25 – 1.2	0.57 – 1.6

An additional, more general strategy for the reduction of nitrate loading from these sources is simply to improve management of water quality data. Groundwater monitoring is required for many of these facilities; however, the data are largely unavailable since they are not in a digital format. To improve monitoring, enforcement, and abatement efforts related to these facilities, groundwater data need to be centrally managed and organized digitally.

5.3 Methods and Cost of Sewer Leakage Prevention and Reduction

A comprehensive assessment of potential nitrogen leakage from sewer systems is provided in Technical Report 2, Section 6.3 (Viers et al. 2012). Here we briefly discuss potential prevention and reduction options.

The main causes of sewer exfiltration are outdated and poorly fitted pipes, according to the majority of interviewed county employees. Surveys of city and county personnel indicated that sewage system leakage is generally considered a minor problem within the study area, although some survey participants mentioned particular sources of pipe leakage: Concrete pipes were considered problematic due to corrosion from hydrogen sulfide gas. Old vitrified clay pipes (VCP) pipes are burdened with numerous cracks and leaks, and a U.S. EPA study confirms that the sewers most susceptible to exfiltration are old VCP pipes (Amick & Burgess 2000). Poorly fitted pipes were cited as a potentially greater cause of leakage than any particular piping material. While identifying problematic piping material is important, the age of the piping system is also crucial. The oldest neighborhoods (primarily in the downtown areas) are most likely to exhibit leakage problems. However, proper sewer maintenance is an important process for sewers of all ages in preventing exfiltration.

Replacing outdated or inadequate pipe materials will decrease sewer exfiltration. Although many piping materials are suitable for sewage transport and are adequate replacements for older pipes, the longevity of the chosen replacement piping material is an important consideration. Pipes vary greatly in cost depending on material. Typical costs of some gravity pipes are as follows: $10.30 per linear foot for PVC, $14.50 per linear foot for concrete, $50 – $55 per linear foot for VCP, and $6.85 per linear foot for HDPE (Cutter 2009). Pressure pipes tend to be more expensive, as they are often thicker to withstand greater pressures (Cutter 2009).

Further research is needed to adequately evaluate potential costs associated with addressing sewer leakage in the study area, a source of groundwater nitrate for which few data exist (see Technical Report 2, Section 6.3 in Viers et al. 2012).

5.4 Reducing Nitrogen Leaching from Septic Systems

Septic systems in the study area are shown to have a small but important impact on overall groundwater nitrate loading/leaching. In certain locales, generally near the outskirts of larger cities, these systems are leaching nitrogen at rates similar to that of irrigated agriculture. An important distinction between this source and the agricultural source, is that septic systems do not require high concentrations of dissolved nitrogen to function properly – they merely discharge nitrogen as a byproduct. Therefore, it is possible to take measures to reduce or eliminate this nitrogen source without concern for a negative impact on the local economy. Septic tanks are, in fact, a low-hanging fruit in some areas.

Two methods of nitrogen reduction are presented below: source-separation and post-septic tank biological denitrification.

5.4.1 Source Separation Technology for Nitrogen Reduction

Segregation of urine from wastewater can be accomplished using separating toilet technology or urinal fixtures. Urine-separating toilets divert urine to a storage tank for processing, removing it from the septic (or sewer) waste stream. Urine-separation toilets have been approved for use in California. The California Department of Transportation has recently installed a separate storage tank for diversion of waste from ultra-low flow urinals at a highway safety roadside rest area in Southern California. The urine diversion was implemented to reduce the size and improve the performance of the onsite wastewater treatment system (anoxic treatment wetland). Based on model estimates, the urine diversion is expected to reduce the nitrogen loading to the treatment system by about 50 percent.

Urine separation toilets have been investigated extensively in several European and African countries, both in laboratory and in field (household) settings (Johansson 2000; Vinneras 2001; Jönsson 2004; Muench 2009; Rossi et al. 2009). The urine separation is accomplished generally with a split bowl, with urine collection in the front and fecal and solid wastes collected in the back.

Performance
Around 80% of the nitrogen (as well as 50% of the phosphorus and 90% of the potassium) in human waste is contained in the urine (Vinneras 2001). Given a known loading rate and assuming a 75% recovery rate (Rossi et al. 2009), the leaching rate of a system can be calculated. If one considers, for example, a septic nitrate loading/leaching rate of 66 kg N/ha/yr (59 lb/ac/yr) as seen in some of the areas northeast of Fresno (see Technical Report 2, Viers et al. 2012), the same region with urine-separating toilets would have a nitrate loading/leaching rate of (66 x 0.2) + (0.25 x 0.8 x 66) = 26.4 kg N/ha/yr (23.5 lb/ac/yr).

Pathogens

While urine itself is not generally considered pathogenic (Björklund 1999; Vinneras 2001), cross-contamination with feces poses a risk (Vinneras 2001). However, simply storing urine at 20°C (room temperature) for 6 months is sufficient treatment to produce fertilizer safe for any crop (Höglund 2002). The storage conditions allow for near complete conversion of urea-nitrogen to ammonia, resulting in a product that is sterile. With average soil temperatures below 1-meter depth around 16-18°C in most of the study area, only a small amount of energy would be expended in maintaining the required temperature in these tanks.

Economics

These toilets cost between $150 and $1300 depending on the level of sophistication of the technology (based on review of prices from the following companies: Separett[44] and Ecovita[45]). Some urine-separating toilets are also composting toilets, designed to produce compost from the solids portion. Other urine-separation toilets are designed to send the solids to the sewer or septic waste system, some with reduced flush-water volumes. Other costs associated with the technology include dual plumbing systems downstream of the toilet, storage tank costs, maintenance, pumping, heating, and transport costs (where applicable).

Dual plumbing systems are required from the toilet to the storage tank. A typical cost for such a renovation would range from $2,000 for simple systems with bathrooms already on an outside wall to $15,000 for more complex systems involving multiple stories, multiple bathrooms, or longer transport to storage tanks through existing structure (walls). To properly treat the stored urine, two 6-month storage tanks would be required. Assuming a reasonable value for urine excretion for humans, 0.6 to 1.2 L/day (0.15 to 0.3 gallons per day) (Schouw et al. 2002), and a household size of 3.5 individuals, a 6-month storage tank should be on the order of 800 liters capacity. The cost of two such tanks ($400 each for HDPE) plus excavation for underground emplacement ($500) and a low-power warming system ($500) to maintain 20°C amounts to about $1,800. Assuming an additional $200 per year of maintenance cost (pumping and electrical heating), partially offset by sale of the fertilizer product, total cost for a system, including tank, dual plumbing, toilet, and maintenance, annualized at a 5% discount rate over 20 years is between $525 and $1,650 per year. The cost for new construction could be significantly less than for renovation.

Reuse

Urine that is collected by source separation systems is most often stored on-site for use as fertilizer in the immediate environs of the residence, but some installations utilize on-site temporary storage tanks that are periodically serviced by pumping (Berndtsson 2006). The urine from many households can thus be accumulated in a centralized location and used for larger scale application to crops.

As a replacement for conventional fertilizers, urine has several benefits. First, it should be cheaper than chemical fertilizers, being essentially a byproduct of normal household activity. Second, urine requires

---

[44] http://www.separett-usa.com

[45] http://www.ecovita.net

minimal processing prior to use as fertilizer and therefore is more energy efficient over its lifecycle than chemical fertilizers (Jönsson et al. 2004). Third, urine contains less heavy metals than either chemical or manure fertilizers (WHO 2006), and less pharmaceuticals and hormones than manure (Magid 2006; Hammer and Clemens 2007). Farmers surveyed in Sweden reported no negative impact on crop production (Berndtssen 2006).

Urine from a single individual will fertilize about 0.035 hectares (0.086 acres) at agricultural rates (Jönsson et al. 2004). If one assumes that residents of areas with more than one system per hectare will be encouraged to implement source separation, then 29,500 hectares (72,900 acres) of peri-urban and rural residential land, or approximately 77,800 households (roughly 250,000 persons) will be affected (see Technical Report 2, Viers et al. 2012). If all those households implemented urine separation, this amounts to enough urine-N to provide agricultural rates of fertilizer for around 8,750 hectares (21,600 acres) of farmland or landscaping.

Future Outlook

Recent experiences in San Diego, Los Angeles, and San Ramon (Guest et al. 2009) indicate that Californians may not be prepared to implement urine separation, or similar waste-recycling technologies on a wide scale. As further research is conducted and costs of the technology decrease, this option for reduction of nitrate loading/leaching to groundwater will become more attractive, particularly in areas with high septic system densities.

5.4.2 Post-septic Tank Nitrification/Denitrification

Septic systems present an opportunity to intercept and treat water with nitrogen concentrations many times the MCL before it reaches the aquifer. In certain locales of the study area, this can result in sizeable reductions in nitrate loading/leaching to groundwater. In contrast to urine separation systems, treatment does not result in a reusable resource; however, it can reduce the concentration of nitrogen in septic leachate to lower levels than urine separation. Current research on wood-chip bioreactors (WCBRs) indicates great potential for reduction of nitrate (Leverenz et al. 2010; Schipper et al. 2010; Moorman et al. 2010).

Performance

Robertson and Cherry (1995) used an in situ bioreactor to treat septic leachate from around 60 ppm nitrate-N to 2 – 25 ppm nitrate-N. Robertson et al. (2000), in a series of field trials lasting up to 7 years, found that Wood Chip Permeable Reactive Barriers (WCPRBs) treating high-nitrate septic leachate removed between 74 and 91 percent of influent nitrate. These WCPRBs were two horizontal denitrification walls installed below septic leach fields, and a vertical denitrification wall installed to intercept a septic leachate plume. A fourth bioreactor in this study was installed as a sub-surface containerized Wood Chip Bioreactor (WCBR) to treat low-concentration agricultural drainage. The low-concentration WCBR removed 58 percent of influent nitrate.

Economics

A typical septic leach field for a household of four is 400 square meters (0.1 acres), and infiltrates around 300 cubic meters (0.24 acre feet) of water per year. For a WCBR with a 10-day residence time, this would require less than 10 cubic meters of woodchips. A 10 cubic meter (13 cubic yards) denitrification bed under the entire 400 square meters would likely be too thin to produce appropriate hydraulics. In the denitrification bed study by Robertson et al. (2000), a slurry of silt and wood chips was used to increase hydraulic retention time, but in a household setting, a more economical approach would be to install a separate tank for the WCBR between the septic tank and the leach field. The woodchips in this tank could be replaced or serviced easily as needed, whereas a layer of wood chips below the leach field would be expensive and difficult to maintain.

Effluent from the septic tank contains nitrogen in the form of ammonium, requiring nitrification before it can be denitrified in a WCBR. Nitrification is accomplished by passing the septic effluent through an unsaturated media (typically sand) aerobic filter. Two types of systems are typically used, single pass systems that require no dosing tank, and multi-pass systems that require a dosing tank, but use a much smaller filter (Metcalf and Eddy 2003). Single pass systems, 30 m^2 (323 square feet) of surface area and 1 m (3.3 feet) deep, use a pump from the septic tank to spray effluent onto the large surface of the filter at a slow enough rate to maintain unsaturated conditions. Effluent then flows by gravity from the outlet of the filter to the WCBR tank and then to the leach field.

In a multi-pass system, the filter is only 2 m^2 by 1 m (22 square feet by 3.3 feet) deep, but a 500 gallon recirculating tank is required. Effluent flows from the septic tank to the recirculating tank by gravity, is pumped into the filter, and flows by gravity back to the recirculating tank, with a portion flowing to the WCBR and then to the leach field. Mixing of the partially nitrified effluent from the filter with the septic tank effluent accomplishes partial denitrification (up to around 60% removal). In a multi-pass system, the WCBR is a finishing component and could be smaller sized. Such a system would cost between $10,000 and $20,000 to install as a retrofit to an existing septic system (Crites and Tchobanoglous 1998, EPA 2002). Bio-filtration for nitrification is a common technology in wastewater treatment and has been extensively tested. Off the shelf components and systems are available. Monitoring of these systems is easily accomplished due to containerized treatment.

Future Outlook

Based on the analysis presented in Technical Report 2, (Viers et al. 2012), there are roughly 77,800 households using septic systems in areas with septic system densities above one per hectare. These households produce about 1,031 metric tonnes (1,136 short tons) per year of leached nitrogen through their septic systems – about half of the total nitrogen leached by septic systems by our estimation. The reduction of this nitrogen load with nitrification/denitrification systems as described above would be most limited by the implementation coverage, as near 100% removal of nitrate is not difficult to achieve with a properly functioning nitrification/denitrification system. In addition, effluent from these systems can be expected to have reduced presence of pathogens and other constituents due to biological treatment in the bioreactor.

6 Reducing Nitrate Loading from Active Wells, Dry Wells, and Abandoned or Destroyed Wells

Prepared by:

Nicole De La Mora, Thomas Harter

Acknowledgments

In preparation for this report, we corresponded with or interviewed a number of county and state agency personnel and consultants. We gratefully acknowledge the following people for providing us with invaluable information. Their support was critical to our research. This work was funded by the State Water Resources Control Board under agreement number 09-122-250.

Beverly Briano, Kern County Department of Environmental Health
Paul Charpentier, Tulare County Department of Environmental Health
Cindy Fosi, City of Modesto Wastewater Division
Wayne Fox, Fresno County Department of Environmental Health
Tom Hardy, Kern County Department of Environmental Health
Bob Herman, Myers Brothers Well Drilling
Michael Hickey, Tulare County GIS Division
Chris Johnson, Aegis Groundwater Consulting
Dennis Keller, Keller Engineering
Michael McGinnis, Department of Water Resources- South Central Region
Ralph Nix, Nix Robert L Well Drilling
Bob Rhodes, Johnson Drilling Company
Cheryl Sandoval, Monterey County Health Department- Environmental Health Division
Diane Stevenson, Diamond Well Drilling
Kathy Thomasberg, Monterey County Water Resources Agency
John Troiano, California Department of Pesticide Regulations
Darren Verdegaal, Kings County Community Development Agency
David Von Aspern, Sacramento County

6.1 Introduction

Most nitrate is transported from sources to groundwater via soil percolation and recharge. However, dry wells, abandoned wells, or improperly destroyed wells may act as rapid local conduits of nitrate contaminated surface runoff directly into groundwater. In addition, many deep wells may inadvertently act as conduits for deep aquifer contamination from shallow, nitrate-contaminated groundwater (for details, see Section 9 of Technical Report 2, Viers et al., 2012). The role of these wells in aquifer contamination is not limited to nitrate. In urban and industrial areas, many other contaminants may rapidly be leaked into groundwater and across multiple overlying aquifer units into deeper groundwater. Similarly, in agricultural areas, farm chemicals such as pesticides may also be rapidly leaked into groundwater or transferred to deep groundwater along these conduits.

Preventing contamination from leaky or improperly constructed active, abandoned, or dry wells is therefore a significant concern, beyond nitrate impacts. Proper construction and destruction of wells can largely avoid this type of contamination, which affects groundwater quality at the local scale, even if it is not a large source of nitrate at the basin scale. This section discusses potential solutions to remedy these sources and to prevent future groundwater contamination from these direct pathway sources. Specifically, this section discusses options to reduce loading by backflow prevention, options to reduce loading from existing or abandoned wells by retrofitting and proper destruction, and the potential costs of such actions.

Much of the information presented was assembled by informal interviews with hydrogeological professionals to obtain an overall assessment of reduction options, but this section does not provide a formal, extensive review of the available technical literature.

6.2 Reducing Nitrate Loading from Direct Inflow into Active Wells

Nitrate loading to groundwater from this source is best avoided by rigorous backflow prevention programs and by proper well construction, including a functioning annular seal below the surface, proper surface completion, and protection of the well per recommendations from the California Department of Water Resources (DWR 1981; DWR 1990).

6.2.1 Implementation and Cost

Inspection of newly constructed wells by county personnel upon well completion, where not already done, is one possibility for enforcing existing regulations on proper well design (currently an unfunded mandate although funding could be provided through, for example, a well permit fee). Implementing a requirement of having the well construction and especially the seal placement of large municipal and agricultural supply wells supervised and certified by a registered civil engineer, geologist, or hydrogeologist would be a further, more rigorous option that is already exercised for the construction of many monitoring wells and large public water supply wells, but which is an uncommon practice for the construction of irrigation wells. The cost of county inspection (at least \$500 - \$1000 for basic inspection) or professional certification (at least \$2,000, assuming about ten hours of billable consulting hours) would add less than 5% to the cost of intermediate to large production well construction. With an average of 468 large productions wells drilled annually in the TLB and SV basins (see Technical Report 2, Section 9, Viers et al. 2012), the total annual cost of this measure is on the order of at least \$1.5 million. This estimate does not include enforcement for domestic wells. The cost of installation and equipment for backflow prevention varies depending on type. Prevention by air gap requires no additional device. Mechanical devices may cost a few to several hundred dollars per system. Assuming an average cost of \$200 - \$400 per well, annual costs for installing backflow prevention on new wells is on the order of \$1-2 million. It is unknown how many existing agricultural wells would need backflow prevention to prevent fertilizer chemical backflow.

6.2.2 Benefits

Relative to other measures, this reduction option addresses future well construction, but does not address construction problems (other than backflow prevention) at existing wells.

6.3 Reducing Nitrate Loading from Direct Inflow into Abandoned or Dry Wells and from Aquifer-to-Aquifer Leakage in Abandoned Wells

The first step to reduce N loading to groundwater via direct inflow into abandoned and dry wells is a field reconnaissance program that identifies the location of abandoned and dry wells (many of which may have little or no obvious surface structure). The second step is to properly destroy wells and dry wells using developed protocols (California Department of Water Resources 1981, 1990). Proper well destruction requires improved guidelines and county implementation. Currently, many counties in the study area require the destruction of the near-surface portion of the well and the placement of some sort of seal to prevent inflow to wells. However, this does not seal the aquifer-to-aquifer leakage, especially from the most vulnerable shallow aquifer zone. Proper destruction of wells includes removal and pressure grouting of the existing well and well-bore, or, at a minimum, perforation (sometimes referred to as laceration) of the well-casing and pressure-grouting of the gravel pack and casing.

The “Sacramento County Abandoned Well Restoration Project” provides an excellent case study for a county-directed well destruction program (David Von Aspern, personal communication, October 9, 2011). In 2009 and 2010, the county’s Environmental Management Department (EMD) received $1.4 million funding from a Special Environmental Project (SEP) to locate abandoned wells and provide support to well owners for proper destruction of abandoned wells under the county’s water well ordinance. Funding was used for a year-and-a-half of field canvassing and program administration, for an extensive public outreach program, and for providing waivers of the “inactivation permit” fee (normally $426 per inactivated well) to owners of abandoned wells. Approximately 60 wells have been destroyed over a two year period. Roughly 460 illegally abandoned wells have been discovered and processed thus far. Destruction costs encountered (by well owners) in that program vary widely. The lowest price for an agricultural well destruction over the initial two year phase of the project was $4,000. The highest price was $13,000 (including County permit costs). Wells have ranged in depth from less than 200 feet to 300 feet. Costs are a function of (ibid.):

- well depth
- well construction and design
- geology
- availability of a well log, in the absence of which a down-hole camera is needed prior to designing the destruction protocol
- number(s) and sizes of voids and cavities created during well use
- obstruction(s) present in the borehole, such as a “stuck pump”
- whether the well was previously part of a “hand-dug” well or a “pit well.” When this is the case, most often the pit is filled with junk and debris, which must be removed, sometimes using manual labor.

- type of perforation (laceration) used for destruction (blast[46] or mechanical)
- presence of secondary constraints, such as a) newer buildings having been constructed too close to the well, b) powerlines too close, thereby interfering with drill rig, c) newer wells built too close to the old one, d) if the groundwater had become contaminated at some point, necessitating containerization and legal disposal of water coming out of the well as it is grouted from the bottom up, e) proximity to residential subdivision.

Other estimates for proper well destruction that we have obtained typically range from $10,000 for shallower wells (up to 400 ft) to over $50,000 for deep wells, including an example of a consultant estimate of $60,000 for perforating and pressure grouting a deep, 240 m (800 ft) well.

6.3.1 Implementation and Cost

It may be possible to identify abandoned or dry wells with steel casing through remote sensing and on-the-ground validation of the type of well (inactive, abandoned, dry). Without remote sensing, local and state governments will largely rely on information voluntarily provided by landowners or other forms of identifying abandoned and dry wells. Incentives programs by the county and state may motivate private landowners to identify the location of abandoned wells, particularly, if the landowner can avoid some of the financial liability associated with the proper abandonment of wells or dry wells. Dry wells may be operated by public entities (cities) and therefore more forthcoming in the identification. Depending on the methods used, the (partial) identification of abandoned and dry wells (not including the cost of proper well abandonment itself) may vary widely (from $1 million to $10 million per county).

Proper well destruction (including that of dry wells) typically includes sealing the borehole simultaneously with pulling the existing piping out of the borehole. Often, the latter cannot be accomplished and requires the overdrilling of the existing borehole, an operation that is as expensive as the construction of a new well. Alternatively, the well casing is lacerated and then pressure-grouted. Conservatively, assuming that the average cost of proper well destruction is on the order of $20,000 and that approximately 1,233 wells (see Technical Report 2, Section 9, Viers et al. 2012) need proper destruction due to their potential exposure to large amounts of surface run-on with nitrate-laden water, the one-time cost for this measure is on the order of $25 million for the TLB and SV basins.

Further, assuming that the number of wells newly abandoned each year is 94 wells per year, 20% of the number of newly constructed agricultural and municipal wells (468 wells per year, see Technical Report 2, Section 9, Viers et al. 2012), and that the proper destruction of these newly abandoned wells (not including newly abandoned domestic wells) can be done at an average cost of $20,000/well, the total ongoing cost of proper well destruction is on the order of $2 million per year for the TLB and SV basins.

---

[46] This method has a significant potential to lead to ineffective abandonment in some cases.

6.3.2 Benefits

Relative to other measures, this reduction permanently prevents a significant amount of nitrate loading to groundwater, some from direct inflow of stormwater and irrigation water into wells. But more importantly, this measure would primarily prevent large amounts of aquifer to aquifer nitrate leakage (estimated to be as much as 2,600 Mg N/year). Perhaps more importantly, this measure prevents the leakage of other harmful contaminants into groundwater.

6.4 Reducing Nitrate Loading from Aquifer-to-Aquifer Leakage in Active Wells

In seasonally active, inactive, abandoned, or improperly destroyed wells with screens across multiple aquifer systems, the task of reducing N loading from a shallower to a deeper aquifer system requires measuring and/or estimating the amount of vertical leakage under pumping and under non-pumping conditions. A measurement program would be designed to also assess seasonal fluctuations. Vertical leakage estimates could include measurement of a vertical velocity profile under pumping conditions as well as non-pumping conditions inside the well screen. If downward flow exists, the nitrate concentration would need to be monitored, possibly at a regular interval (e.g., annually, every 3 years) to determine whether the downward flow is associated with a transfer of nitrate into deeper aquifer layers. Shallow wells would not be subject to these guidelines except for extending the surface seal to near the top of the screen.

In wells that are found likely to be transferring nitrate into deeper aquifer layers, the following options prevent/reduce the nitrate loading to the deeper layers:

- Well retro-fitting (lining sections of screen, cementing portions of well, blocking casing flow with packers), which is most appropriate in newer wells with large diameter existing casing.
- Destruction of the existing well and new construction. The cost of destruction and new construction may not be significantly higher than retrofitting, especially in smaller diameter wells; it is sometimes easier to identify and target high quality, high producing aquifer formations in a new borehole than in an already existing well. The decision between retrofitting and new construction needs to be done on a case by case basis.

In newly constructed wells, the following are recommended measures to help prevent the leakage of nitrate-laden groundwater into deeper layers or the occurrence of natural contaminants in well water. These measures require good test hole information on both aquifer yields and water quality, collected prior to actual well construction:

- Where possible (favorable water quality, aquifer productivity), construction of irrigation well screens in nitrate-contaminated aquifer horizons with no screen sections extending into deeper, cleaner aquifer horizons. This may limit the amount of water that can be pumped from an individual well and require construction of multiple smaller-production irrigation wells.
- Construction of well screens below contaminated zones with proper annular sanitary seal around a blank casing from the surface to near the top of the (first) well screen; use of high quality screen material (e.g., stainless steel) with large open area (e.g., continuous wire-wrap type screens), use of high quality inert filter pack materials (e.g., well-rounded quartz gravel), and proper well development, all of which provide the basis for a well yielding high quality water from limited thickness, high-yielding aquifer layer.
- Construction of a proper annular seal around blank casing between aquifer layers (across aquitards) and simultaneous installation of well-packers inside the well casing that prevent the

leakage of groundwater across aquifer horizons during or after groundwater pumping operations.

- Minimization of well screen length and number of screen segments by using screens with a high open area ratio (e.g., continuous wire-wrap screens) that are placed only against the most permeable aquifer horizons and that do not span contaminated aquifer horizons (would lead to cross-aquifer contamination within the well). This may limit the amount of well-production and require construction of a larger number of smaller-production wells.
- Regional programs (such as Kern County's) and guidelines that prevent construction of well screens across multiple aquifer systems.

6.4.1 Implementation and Cost

The implementation of these measures will require establishing new incentive programs or implementing new regulatory programs that control the design and construction of large production wells in nitrate-contaminated groundwater basins, or both. As a principal policy objective, agricultural pumping would largely occur from wells in shallower groundwater - up to 150 m (500 ft) depth – and be sealed off against deeper, uncontaminated groundwater, where water quality, hydrogeology, and other potential constraints are favorable. Domestic, small community, and large community groundwater supplies could be pumped from deeper groundwater, with design, assessment, and construction ensuring complete seals to the depth of the screen, and with screen placement at depth focusing on avoiding other natural contaminants or undesirable constituents (see above, also see Technical Report 5, King et al. 2012). These programs can be developed, for example, as part of a regional Groundwater Management Plan, a county ordinance, or as part of an Integrated Regional Water Management Plan.

Proper design and construction of new wells according to the guidelines above may increase the cost of large irrigation well construction. On the other hand, proper construction and well development may provide some long-term savings in pumping costs due to energy savings (reduced hydraulic well losses) and decreased well maintenance costs (absence of suspended sediments that cause wear and tear on pumping equipment). Over the life-time of the well (many decades), the above measures may actually decrease the overall cost of well installation and maintenance. Current irrigation well construction tends to be with long screens, low open screen areas (slotted well screens rather than continuous wire-wrap or louvered screens), and poor well development, leading to poor well efficiency. For large drinking water wells that are properly constructed and developed (proper well design with necessary pilot hole testing and assessment, deep sanitary seals, targeted short screen sections at desired depths, proper well development), the costs are on the order of at least $1 – 2 million per well (depth: 800 feet or more).

The cost of testing existing deep wells for the potential of cross-aquifer nitrate leakage is estimated to be on the order of a few thousand dollars per well, if a rigorous regional program were implemented that provides economies of scale. Assuming, for illustration purposes, that most of the estimated 20,000 existing irrigation wells in the TLB and SV are tested, the total one-time expense for the reconnaissance program would be at least $100 million.

Costs for retrofitting with packers and sealing off contaminated aquifer horizons, redrilling new wells and abandoning leaky wells, or other methods, may vary widely from well to well. Assuming an average cost of $30,000 for retrofitting one-third of the 20,000 irrigation wells, leads to a total one-time cost on the order of **$200 million**, which does not include the cost for drilling additional wells due to potentially reduced yields in retrofitted wells.

6.4.2 Benefits

Relative to other measures, this reduction option prevents a significant amount of nitrate loading to groundwater (estimated to be as much as 4,000 Mg N/year, currently, and significantly more in future nitrate pollution avoidance).

6.5 Discussion and Promising Actions

A long history of inadequate well design and well construction that was – and often continues to be – largely not focused on reducing the potential for contamination, has led to two major nitrate contamination related impacts:

1. Short-circuiting of contaminants directly from the surface into the well or short-circuiting of contaminants in the shallowmost aquifer (near the water table) into the well.
2. Cross-aquifer contamination between aquifers through borehole leakage, either in the filter pack or in the well via the well screen, or both.

The well construction issues that lead to either one of these two conditions can be summarized into the following categories:

1. improper or poor construction of the mandatory sanitary surface seal in the annulus around the well casing;
2. mandatory sanitary seal depths (15 m (50 ft), except in Monterey County: 30 m (100 ft)) are insufficient and do not prevent movement of contaminated shallow groundwater through the filter pack into a well screened in a deeper, higher quality aquifer;
3. long intake screens that span multiple aquifer and aquitard horizons with highly variable water quality;
4. improper pump location in the upper screened section of the well possibly leading to preferential pumping of predominantly shallow, often more nitrate-contaminated water;
5. poor well design due to a lack of proper assessment of the hydrogeology by a trained professional using the appropriate geophysical and geochemical probing tools;
6. poor choice of well construction material leading to a perceived need for long screens and to poor sanitary/annular seal construction;
7. lack of backflow prevention devices on wells used to mix water with agricultural fertilizer.

The above issues are particularly widespread in the construction of private domestic and irrigation wells. Well owners are often poorly informed or misinformed about trade-offs between up-front construction costs (which can be significantly higher in properly constructed wells), long-term energy, well and pump maintenance, and water treatment costs (which may quickly reach levels much higher than the additional construction investment for a properly constructed and developed well).

Policy measures to address these issues include:

- providing appropriate informative materials for (future) well owners
- improved well construction standards/guidelines and appropriate, regular enforcement, possibly funded through, for example, well construction fees or energy incentives programs
- proper continuing education and training programs for well drilling and consulting professionals

- improved licensing requirements/training for drilling and consulting professionals involved in the design of groundwater wells
- well and backflow prevention inspection programs.

Table 19, below, summarizes the N reduction measures described above, the associated costs, and the associated estimated reduction in annual N loading to groundwater. The least cost measure, and one that has a large potential for future increased N loading avoidance is the implementation of a backflow prevention program and of rigorous well construction standards for wells that penetrate more than the shallow-most aquifer layer.

Rigorous well construction standards can avoid both surface inflow into the well casing or annulus and – much more importantly from an aquifer management perspective – they may avoid the silent and unseen leakage of shallow contaminated groundwater into deeper, uncontaminated horizons. Relative to the cost of other measures, implementation of more rigorous well construction standards may in many cases be nearly cost-neutral given that proper well construction, while initially more expensive, may be offset by significant reduction in long-term energy and maintenance/well rehabilitation cost. This should therefore be a high priority measure. However, it does require more rigorous enforcement by the counties of their well construction permit regulations (additional funding may be possible through increased permit fees for certain well types (e.g., deep wells), or through incentive programs by energy providers).

Table 19. Summary of the estimated potential costs and benefits of N loading reduction measures associated with wells. The categorization of "benefits" as significant is not meant to be interpreted as a recommended measure. The benefit indicates merely whether the overall impact on groundwater nitrate in the study area is thought to be measureable and beneficial in the long run. Public policy debate must decide whether the avoided impact is worth the cost of these measures.

Reduction Measure	Cost for Entire Study Area (one-time or annually)	Benefit to Overall TLB & SV N Load Reduction
Backflow prevention program	$1-2M per year (on new wells)	Significant to avoid local hot spots
Enforcement of proper well construction	$1.5M per year (on new wells)	Significant in the future – several 1,000 Mg N/yr
Identification of abandoned/dry wells	$1M to $10M once	
Proper abandonment of abandoned/dry wells	$25M once + $2M per year	Significant - less than 1,000 Mg N/yr
Testing existing deep wells for leakage	$100M once	
Retrofitting existing deep wells for leakage avoidance	$200M once	Significant - 4,000 Mg N/yr

Retrofitting existing wells to avoid cross-aquifer leakage is a potentially expensive option, but may avoid significant deeper aquifer contamination that is out of sight and typically ignored. A least-cost alternative may be the sealing of existing screens in the uppermost, most nitrate contaminated aquifer horizons (or the opposite – sealing off all deeper, uncontaminated aquifer horizons).

Identifying and properly destroying inactive/abandoned or dry wells may be difficult and costly to implement. It does not necessarily have a significant impact on groundwater nitrate loading from surface inflow, but it could avoid significant N loading from cross-aquifer leakage in deep abandoned wells. For those, a potentially lower-cost alternative to casing removal or overdrilling is to perforate the screen and casing and to fill the casing and gravel pack by pressure-grouting. Sacramento County is an example of a recent program to address this issue.

We note that costs provided in this section are based on numerous assumptions, are order-of-magnitude estimates, and are intended for illustration purposes only. Costs do not reflect any actual survey of well drilling or retrofitting costs. Further assessment of the extent of well leakage and of technologies and costs to addressing well leakage is needed.

7 Overall Conclusions: Source Reduction

Technologies are available for reducing the rates of nitrate leaching to well below those that historically have contaminated groundwater. Generally, reduction of nitrate leaching involves changes in management and upgrading of infrastructure. Costs for doing this vary widely. We have considered the methods and associated costs for reduction of nitrate leaching losses from the major anthropogenic sources of N loading to groundwater in the two study regions. These include irrigated cropland, livestock operations, turfgrass and other urban landscaping, wastewater treatment plants and food processing plants, septic systems, and abandoned wells.

Reduction of agricultural nitrate leaching from cropland and livestock and poultry operations is primarily dependent upon changes in farm management and improving crop nitrogen use efficiency (NUE). NUE can be increased by the correct timing and rates of applied fertilizer N, animal manures, and irrigation water, and to a lesser extent by modification of crop rotations. Improving the storage and handling of manures, livestock facility wastewaters, and fertilizers also plays a role in nitrate leaching reduction. Tandem implementation of improved management practices, chosen in relation to each unique farm situation, is the best approach to reducing nitrate leaching from agricultural fields.

While improvements in N use efficiency are possible, a practical upper limit is set by unpredictable rainfall, difficulty in predicting the rate of mineralization of organic N, and most especially, soil spatial variability and the need to leach salt from the crop rootzone. It is estimated that by implementing recommended practices, crop N recovery can reach 60-80% of N inputs. While improved management will lead to a reduction in the mass of nitrate lost by leaching, it is unlikely that the concentration of nitrate can be reduced to the MCL, especially where the sole or main source of aquifer recharge is percolate from irrigated crop fields.

Based only on inherent characteristics of the soil, crop species grown, and irrigation systems in use, we conclude that approximately 52% of irrigated cropland in the Salinas Valley and 35% of such land in the Tulare Lake Basin is susceptible to significant nitrate leaching losses. Improved management in these more highly vulnerable areas is expected to have the most impact on nitrate leaching reduction. A number of the practices known to reduce cropland nitrate leaching have been adopted in recent years by farmers in the study area. Those management options that are less utilized are generally associated with multiple barriers to adoption by farmers. These include higher operating or capital costs, risks to crop quality or yield, and conflicting farm logistics. Additional significant barriers include inadequate education and inadequate adaptation of practices to local conditions and research to this end.

Expanded efforts to promote the adoption of nitrogen efficient practices are clearly needed. The educational barriers that are associated with many of the identified practices highlight the importance of expanded funding of research, education, and outreach activities to better assist farmers in applying best management strategies. For example, Cooperative Extension, the USDA Natural Resources Conservation Service, and independent crop advisors play important roles in delivering such educational information. More on-farm research is required to demonstrate the impact of practices on NUE and N leaching for specific crops and soils. Development of crop-specific nitrogen application metrics that relate, for example, total N applied to total N harvested in the crop, needs to be further explored and supported. To allow for identification of the areas in which improved management is needed most, a task force charged with fine-tuning existing options for spatial nitrate leaching risk assessment methods is recommended. Such a method would need to include consideration of the spatial soil characteristics, as well as probable monitoring requirements.

Finally, as the recently instituted Central Valley dairy regulations[47] restrict on-farm cropland applications of manure, the volume of off-dairy transfer of animal waste to unregulated fields has increased. It is not known which crop species and soils are receiving this manure or how the receiving farmers have integrated the manure into their N fertilization practices. We recommend development of adaptive research and education programs that will promote conversion of solid and liquid dairy manure into forms that meet the food safety and production requirements for a wider range of crop species. Providing guidance to non-dairy farms in co-managing organic and conventional N sources is necessary to help ensure the nutrient value of manure is properly accounted for in fertilization regimes.

The cost of improving crop NUE is difficult to define quantitatively and there is wide uncertainty in the marginal costs of such improvements. Therefore it is not possible to assign a cost (incurred for on-farm improvements) to a defined or quantitative lowering of cropland nitrate leaching. Our model suggests that modest reductions in N fertilizer application rates and increased adoption of related improved practices will increase production costs slightly, assuming adequate levels of education. Thus, modest reductions are concluded to be economically feasible in the general sense. As larger load reduction strategies are undertaken, the model predicts production costs to increase enough to result in larger reductions in irrigated cropland within the study area, or to decrease the area of land used for lower revenue crops such as grain, hay, and other field crops. A simulated nitrogen sales tax revealed that it could initiate additional grower motivation to adopt practices that contribute to NUE.

Studies confirm that leaching from urban turfgrass areas, including golf courses, are often negligible due to the dense plant canopy and perennial root system that allows for continuous N uptake over a large portion of the year. Additionally, often any excess N above plant need will still be taken up and utilized by the turf, increasing vegetative growth. However, poor management can lead to a discontinuous canopy and weed presence, wherein nitrate leaching risk increases, especially if growing on permeable soils, if over-irrigated, or if fertilized at high rates during dormant periods. The best leaching reduction strategy from this source then is to simply follow recommended guidelines of fertilizer application rate and timing. The UCCE and UCIPM publish such guidelines. The practice of keeping fertilization rates and timing concordant with plant need has the added benefit to professional turfgrass managers of requiring less frequent mowing and reducing the volume of clippings requiring disposal.

Discharges from municipal wastewater and food processing treatment facilities, while not as regionally significant as agriculture, do have locally important impacts. Implementation of control options for these sources is feasible and an important part of a multi-pronged approach.

---

[47] The General Order for Waste Discharge from Existing Dairies in the San Joaquin Valley, see http://www.waterboards.ca.gov/centralvalley/water_issues/dairies/dairy_program_regs_requirements/index.shtml

For locations where discharges from WWTPs and FPs may be detrimental to groundwater quality, reduction strategies include transfer of food processing waste to publically owned treatment works and modification or addition of treatment (e.g., biological nutrient removal). The most cost effective solutions for management of N loading from WWTP and FP discharges may be an adjustment to the current practices to limit N application to levels that can be accommodated by irrigated crops and soil degradation. As such, the discharge should be managed in an agronomic manner such that the nutrients, especially nitrogen present in the wastes, are included in the overall nitrogen management plan for the receiving crops.

Another primary consideration is the optimization of operations; limiting nitrogen and total discharge volume through in-plant process modifications may be sufficient for some facilities. Lastly, the technology for nutrient removal is proven and can be implemented where other options are not sufficient to limit N loading to groundwater. Costs of implementing reduction strategies are widely variable and generally facility dependent. Evaluation of nitrate loading due to waste discharges and impacts of operational changes is difficult at some facilities due to recordkeeping shortcomings. Groundwater monitoring is required for many of these facilities; however, the data are largely unavailable since they are not in a digital format. To improve monitoring, enforcement, and abatement efforts related to these facilities, groundwater data need to be centrally managed and organized digitally.

The need to replace aging infrastructure is a concern across the US; while leaking sewer pipes can lead to nitrate contamination of groundwater, this poses a smaller threat to public health than pathogen contamination. Choice of pipe material determines the cost of sewer retrofits. Septic system contributions to groundwater N are another locally significant source. At a reasonable cost, these sources can be reduced or eliminated using existing technology, including local reuse of nitrogen through source-separation and post-septic tank biological denitrification. Urine separation technology, in particular, has the potential to reduce the use of chemical fertilizer, representing possible cost savings for farmers and reducing energy expenditure.

Contributions to aquifer and deep aquifer nitrate contamination from wells (permanently or seasonally inactive, abandoned, or dry wells) are best addressed through development and implementation of rigorous well construction standards for future wells. Reconnaissance of abandoned and improperly destroyed wells and their proper destruction is another step toward avoiding aquifer contamination from either surface inflow to wells or cross-aquifer flow within wells. Expenditures on retrofitting of existing wells are high and should be selected based on their individual contamination risks.

Literature Cited

Section 2 Reducing Agricultural Nitrate Loading

Adriano, D.C., Takatori, F.H., Pratt, P.F. & Lorenz, O.A. (1972) Soil nitrogen balance in selected row-crop sites in southern California. *Journal of Environmental Quality*, **1**, 279–283.

Allaire-Leung, S.E., Wu, L., Mitchell, J.P. & Sanden, B.L. (2001) Nitrate leaching and soil nitrate content as affected by irrigation uniformity in a carrot field. *Agricultural Water Management*, **48**, 37–50.

Alva, A.K., Paramasivam, S., Graham, W.D. & Wheaton, T.A. (2003) Best nitrogen and irrigation management practices for citrus production in sandy soils. *Water, Air, & Soil Pollution*, **143**, 139–154.

Animal Manure Management - Handling and Storage Options for Manure. (2011) http://www.extension.org/animal_manure_management

Bassil, E.S., Kafka, S.R. & Hutmacher, R.A. (2002) Response of safflower (Carthamus Tinctorius L.) to residual soil N following cotton (Gossypium Spp.) in rotation in the San Joaquin Valley of California. *The Journal of Agricultural Science*, **138**, 395–402.

Beaudoin, N., Saad, J., Vanlaethem, C., Machet, J., Maucorps, J. & Mary, B. (2005) Nitrate leaching in intensive agriculture in Northern France: effect of farming practices, soils and crop rotations. *Agriculture, Ecosystems & Environment*, **111**, 292–310.

Boldt, A.L., Watts, D.G., Eisenhauer, D.E. & Schepers, J.S. (1994) Simulation of water applied nitrogen distribution under surge irrigation. *Transactions of the ASAE*, **37**, 1157–1165.

Brandi-Dohrn, F.M., Dick, R.P., Hess, M., Kauffman, S.M., Hemphill, D.D. & Selker, J.S. (1997) Nitrate leaching under a cereal rye cover crop. *Journal of Environmental Quality*, **26**, 181–188.

Breschini, S.J. & Hartz, T.K. (2002) Presidedress soil nitrate testing reduces nitrogen fertilizer use and nitrate leaching hazard in lettuce production. *HortScience*, **37**, 1061–1064.

Brodt, S., Klonsky, K. & Tourte, L. (2006) Farmer goals and management styles: Implications for advancing biologically based agriculture. *Agricultural systems*, **89**, 90–105.

Burt, C.M. (2004) Rapid field evaluation of drip and microspray distribution uniformity. *Irrigation and Drainage Systems*, **18**, 275–297.

Cameron, K.C. & Di, H.J. (2002) The use of a nitrification inhibitor, dicyandiamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland. *Soil Use and Management*, **18**, 395–403.

Carneiro, J., Cardenas, L.M., Hatch, D.J., Trindade, H., Scholefield, D., Clegg, C.D. & Hobbs, P. (2009) Effect of the nitrification inhibitor dicyandiamide on microbial communities and N2O from an arable soil fertilized with ammonium sulphate. *Environmental Chemistry Letters*, **8**, 237–246.

Cavero, J., Plant, R.E., Shennan, C., Friedman, D.B., Williams, J.R., Kiniry, J.R. & Benson, V.W. (1999) Modeling nitrogen cycling in tomato-safflower and tomato-wheat rotations. *Agricultural Systems*, **60**, 123–135.

Central Valley Regional Water Quality Control Board. (2007) *Waste Discharge Requirements General Order for Existing Milk Cow Dairies. General Order R5-2007-0035*. Central Valley Regional Water Quality Control Board.

Chapman, H.D. (1951) Nitrogen needs of citrus: losses caused by leaching and volatilization can be reduced by management and irrigation practices. *California Agriculture*, **5**, 6–6.

Chen, D., Suter, H., Islam, A., Edis, R., Freney, J.R. & Walker, C.N. (2008) Prospects of improving efficiency of fertiliser nitrogen in Australian agriculture: a review of enhanced efficiency fertilisers. *Australian Journal of Soil Research*, **46**, 289–301.

Chen, D. & Wallender, W.W. (1984) Economic sprinkler selection, spacing, and orientation. *Transactions of the ASAE*, **27**, 737–743.

Christensen, P.L., Bianchi, M.L., Peacock, W.L. & Hirschfelt, D.J. (1994) Effect of nitrogen fertilizer timing and rate on inorganic nitrogen status, fruit composition, and yield of grapevines. *American Journal of Enology and Viticulture*, **45**, 377–387.

Coupal, R.H. & Wilson, P.N. (1990) Adopting water-conserving irrigation technology: The case of surge irrigation in Arizona. *Agricultural Water Management*, **18**, 15–28.

Crews, T.E. & Peoples, M.B. (2005) Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A Review. *Nutrient Cycling in Agroecosystems*, **72**, 101–120.

Dawar, K., Zaman, M., Rowarth, J.S., Blennerhassett, J. & Turnbull, M.H. (2010a) The impact of urease inhibitor on the bioavailability of nitrogen in urea and in comparison with other nitrogen sources in ryegrass (Lolium perenne L.). *Crop and Pasture Science*, **61**, 214.

Dawar, K., Zaman, M., Rowarth, J.S., Blennerhassett, J. & Turnbull, M.H. (2010b) Urea hydrolysis and lateral and vertical movement in the soil: effects of urease inhibitor and irrigation. *Biology and Fertility of Soils*, **47**, 139–146.

Dear, B.S., Cocks, P.S., Peoples, M.B. & Swan, A.D. (2001) The nitrate scavenging ability of phalaris and lucerne in subterranean swards. *Proceedings of the 10th Australian Agronomy Conference*. The Regional Institute, Hobart, Tasmania.

Delgado, J.A. (1998) Sequential NLEAP simulations to examine effect of early and late planted winter cover crops on nitrogen dynamics. *Journal of soil and water conservation*, **53**, 241–244.

Delgado, J.A. & Mosier, A.R. (1996) Mitigation alternatives to decrease nitrous oxides emissions and urea-nitrogen loss and their effect on methane flux. *Journal of Environment Quality*, **25**, 1105–1111.

Delgado, J.A., Shaffer, M., Hu, C., Lavado, R., Cueto-Wong, J., Joosse, P., Sotomayor, D., Colon, W., Follett, R., DelGrosso, S. & others. (2008) An index approach to assess nitrogen losses to the environment. *Ecological Engineering*, **32**, 108–120.

Di, H.J. & Cameron, K.C. (2002) Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems*, **46**, 237–256.

Di, H.J. & Cameron, K.C. (2004) Treating grazed pasture soil with a nitrification inhibitor, eco-n (TM), to decrease nitrate leaching in a deep sandy soil under spray irrigation—a lysimeter study. *New Zealand Journal of Agricultural Research*, **47**, 351–361.

Diez, J.A., Caballero, R., Bustos, A., Roman, R., Cartagena, M.C. & Vallejo, A. (1995) Control of nitrate pollution by application of controlled release fertilizer (CRF), compost and an optimized irrigation system. *Nutrient Cycling in Agroecosystems*, **43**, 191–195.

Dillon, J., Edinger-Marshall, S. & Letey, J. (1999) Farmers adopt new irrigation and fertilizer techniques: changes could help growers maintain yields, protect water quality. *California Agriculture*, **53**, 24–31.

Dittert, K., Bol, R., King, R., Chadwick, D. & Hatch, D. (2001) Use of a novel nitrification inhibitor to reduce nitrous oxide emission from15N-labelled dairy slurry injected into soil. *Rapid Communications in Mass Spectrometry*, **15**, 1291–1296.

Dong, S., Neilsen, D., Neilsen, G.H. & Fuchigami, L.H. (2005) Foliar N application reduces soil NO3-N leaching loss in apple orchards. *Plant and Soil*, **268**, 357–366.

Drury, C.F., Tan, C.S., Reynolds, W.D., Welacky, T.W., Oloya, T.O. & Gaynor, J.D. (2009) Managing tile drainage, subirrigation, and nitrogen fertilization to enhance crop yields and reduce nitrate loss. *Journal of Environmental Quality*, **38**, 1193–1204.

Edinger-Marshall, S. & Letey, J. (1997) Irrigation shifts toward sprinklers, drip and microsprinklers. *California Agriculture*, **51**, 38–40.

Entz, M., Bullied, J.W., Forster, D.A., Gulden, R. & Vessey, J.V. (2001) Extraction of subsoil nitrogren by Alfalfa, Alfalfa-Wheat and perennial grass systems. *Agronomy Journal*, **93**, 495–503.

Esser, B., Hudson, B., Moran, J., Beller, H., Carlsen, T., Dooher, B., Krauter, P., McNab, W., Madrid, V., Rice, D. & Verce, M. (2002) *Nitrate contamination in California groundwater: An integrated* *approach to basin assessment and resource protection (Draft)*. Lawrence Livermore National Laboratory (LLNL), Livermore, CA.

Evans, R.G. (1977) Improved Semi-Automatic Gates for Cut-Back Surface Irrigation Systems. *Transactions of the American Society of Agricultural Engineers*, **20**, 105–108.

Feaga, J.B., Selker, J.S., Dick, R.P. & Hemphill, D.D. (2010) Long-Term Nitrate Leaching Under Vegetable Production with Cover Crops in the Pacific Northwest. *Soil Science Society of America Journal*, **74**, 186–195.

Fereres, E., Martinich, D.A., Aldrich, T.M., Castel, J.R., Holzapfel, E. & Schulbach, H. (1982) Drip irrigation saves money in young almond orchards. *California Agriculture*, **36**, 12–13.

Fessehazion, M.K., Stirzaker, R.J., Annandale, J.G. & Everson, C.S. (2011) Improving nitrogen and irrigation water use efficiency through adaptive management: A case study using annual ryegrass. *Agriculture, Ecosystems & Environment*, **141**, 350–358.

Fixen, P. (2011) Nutrient Balance in Arable Lands. A global Challenge for the Fertilizer Industry. *International Plant Nutrition Institute 17th ANA Annual Forum and Exhibition*. Cairo, Egypt.

Fulton, A., Buchner, R., Goldhamer, D., Hanson, B., Lampinen, B., Prichard, T., Schwankl, L. & Shackel, K. (2008) UC Drought Management Plant-based Irrigation Scheduling - UC Drought Management, http://ucanr.org/sites/Drought/Agriculture/Irrigation_Scheduling/Plant-based_Irrigation_Scheduling/

Gardenas, A., Hopmans, J., Hanson, B. & Simunek, J. (2005) Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agricultural Water Management*, **74**, 219–242.

Gaudi, F., Howes, D. & Ton, D. (2007) Center pivot design for effluent irrigation of agricultural forage crops. ITRC Paper No. P 07-002. p. 16. Irrigation Training and Research Program, California Polytechnic State University, San Luis Obispo, San Diego, CA.

Gehl, R.J., Schmidt, J.P., Stone, L.R., Schlegel, A.J. & Clark, G.A. (2005) In situ measurements of nitrate leaching implicate poor nitrogen and irrigation management on sandy soils. *Journal of Environmental Quality*, **34**, 2243–2254.

Gheysari, M., Mirlatifi, S.M., Homaee, M., Asadi, M.E. & Hoogenboom, G. (2009) Nitrate leaching in a silage maize field under different irrigation and nitrogen fertilizer rates. *Agricultural Water Management*, **96**, 946–954.

Gioacchini, P., Nastri, A., Marzadori, C., Giovannini, C., Vittori Antisari, L. & Gessa, C. (2002) Influence of urease and nitrification inhibitors on N losses from soils fertilized with urea. *Biology and Fertility of Soils*, **36**, 129–135.

Goldhamer, D.A. & Peterson, C.M. (1984) *Comparison of Furrow and Linear Move Sprinkler Irrigation on Cotton - Case Study. Land, Air and Water Resources Paper No. 10012*. Department of Land and Water Resources, Univ. of Calif. Davis, Davis, CA.

Gonzalez, C., Zheng, Y. & Lovatt, C.J. (2010) Properly Timed Foliar Fertilization Can and Should Result in a Yield Benefit and Net Increase in Grower Income. *Proceedings of the VI International Symposium on Mineral Nutrition of Fruit Crops* pp. 273–286. Acta Horticulturae (ISHS).

Goodhue, R.E., Klonsky, K. & Mohapatra, S. (2010) Can an Education Program Be a Substitute for a Regulatory Program That Bans Pesticides? Evidence from a Panel Selection Model. *American Journal of Agricultural Economics*, **92**, 956–971.

Hanson, B.R. (1989) A systems approach to drainage reduction in the San Joaquin Valley. *Agricultural water management*, **16**, 97–108.

Hanson, B.R. (1995) Practical potential irrigation efficiencies. *Proceedings of the Aug 14-18 First International Conference on Water Resources Engineering*. San Antonio, TX.

Hanson, B.R. & Ayars, J.E. (2002) Strategies for reducing subsurface drainage in irrigated agriculture through improved irrigation. *Irrigation and Drainage Systems*, **16**, 261–277.

Hanson, B.R., Bali, K.M. & Sanden, B.L. (2008) Irrigating alfalfa in arid regions. *Irrigated alfalfa management in Mediterranean and Desertzones. Chapter 16* p. University of California Agriculture and Natural Resources Publication 8293, Oakland CA.

Hanson, B., Fulton, A. & Goldhamer, D. (1998) Cracks affect infiltration of furrow crop irrigation. *California Agriculture*, **52**, 38–42.

Hanson, B. & May, D. (2003) Drip irrigation increases tomato yields in salt-affected soil of San Joaquin Valley. *California Agriculture*, **57**, 132–137.

Hanson, B. & May, D. (2011) *Drip irrigation salinity management for row crops*. University of California Division of Agriculture and Natural Resources Publication 8447, Richmond, Ca.

Hanson, B.R., Schwankl, L.J., Schulbach, K.F. & Pettygrove, G.S. (1997) A comparison of furrow, surface drip, and subsurface drip irrigation on lettuce yield and applied water. *Agricultural Water Management*, **33**, 139–157.

Hanson, B.R., Trout, T.J., Ritter, W.F. & Shirmohammadi, A. (2001) Irrigated agriculture and water quality impacts. *Agricultural Nonpoint Source Pollution Watershed Management and Pollution.* pp. 169–206. Lewis Publishers, Boca Raton, FL.

Hartz, T.K. (2006) Vegetable production best management practices to minimize nutrient loss. *HortTechnology*, **16**, 398–403.

Hartz, T.K., Bendixen, W.E. & Wierdsma, L. (2000) The Value of Presidedress Soil Nitrate Testing as a Nitrogen Management Tool in Irrigated Vegetable Production. *HortScience*, **35**, 651–656.

Hartz, T.K. & Bottoms, T.G. (2009) Nitrogen requirements of drip-irrigated processing tomatoes. *HortScience*, **44**, 1988–1993.

Hartz, T.K., LeStrange, M. & May, D.M. (1994) Tomatoes respond to simple drip irrigation schedule and moderate nitrogen inputs. *California Agriculture*, **48**, 28–31.

Hartz, T.K., Mitchell, J.P. & Giannini, C. (2000) Nitrogen and carbon mineralization dynamics of manures and composts. *HortScience*, **35**, 209–212.

Hartz, T.K. & Smith, R.F. (2009) Controlled-release fertilizer for vegetable production: the California experience. *Hort Technology*, **19**, 20–22.

Hartz, T., Smith, R., Schulbach, K.F. & LeStrange, M. (1994) On-farm nitrogen tests improve fertilizer efficiency, protect groundwater. *California Agriculture*, **48**, 29–32.

Hatch, D., Trindade, H., Cardenas, L., Carneiro, J., Hawkins, J., Scholefield, D. & Chadwick, D. (2005) Laboratory study of the effects of two nitrification inhibitors on greenhouse gas emissions from a slurry-treated arable soil: impact of diurnal temperature cycle. *Biology and Fertility of Soils*, **41**, 225–232.

Heckman, J.R., Sims, J.T., Beegle, D.B., Coale, F.J., Herbert, S.J., Bruulsema, T.W. & Bamka, W.J. (2003) Nutrient removal by corn grain harvest. *Agronomy Journal*, **95**, 587–591.

Hutmacher, R.B., Rains, D.W., Travis, R.L., Roberts, B.A., Keeley, M.P. & Degado, R. (2005) *Residual soil nitrogen and nitrogen management for acala cotton*. CDFA Fertilizer Research and Education Program (FREP) Summary Report.

Ingels, C., Van Horn, M., Bugg, R. & Miller, P.R. (1994) Selecting the right cover crop gives multiple benefits. *California Agriculture*, **48**, 43–48.

Irrigated Agriculture Technical Advisory Committee. (1994) Irrigated agriculture: Technical Advisory Committee Report to the California State Water Resources Control Board.

Jackson, L.E. (2000) Fates and losses of nitrogen from a nitrogen-15-labeled cover crop in an intensively managed vegetable system. *Soil Science Society of America Journal*, **64**, 1404.

Jackson, L.E., Stivers, L.J., Warden, B.T. & Tanji, K.K. (1994) Crop nitrogen utilization and soil nitrate loss in lettuce field. *Fertilizer Research*, **37**, 93–105.

Jackson, L.E., Wyland, L.J., Klein, J.A., Smith, R., Chaney, W.E. & Koike, S.T. (1993) In lettuce production, winter cover crops can decrease soil nitrate, leaching potential. *California Agriculture*, **47**, 12–15.

Johnson, R.S., Rosecrance, R., Weinbaum, S., Andris, H. & Wang, J. (2001) Can we approach complete dependence on foliar-applied urea nitrogen in an early-maturing peach? *Journal of the American Society for Horticultural Science*, **126**, 364–370.

Jones, H.G. (2004) Irrigation scheduling: advantages and pitfalls of plant-based methods. *Journal of Experimental Botany*, **55**, 2427–2436.

Kasapligil, D. (1990) *Row crop sprinkler distribution uniformity in field conditions. A special project for Westlands Water District*. California Polytechnic State University, San Luis Obispo, San Luis Obispo, CA.

Kemper, W.D., Olsen, J. & Hodgdon, A. (1975) Fertilizer or Salt Leaching as Affected by Surface Shaping and Placement of Fertilizer and Irrigation Water. *Soil Science Society American Journal*, **39**, 115–119.

Khosla, R., Fleming, K., Delgado, J.A., Shaver, T.M. & Westfall, D.G. (2002) Use of site-specific management zones to improve nitrogen management for precision agriculture. *Journal of Soil and Water Conservation*, **57**, 513–518.

Khosla, R., Inman, D., Westfall, D.G., Reich, R.M., Frasier, M., Mzuku, M., Koch, B. & Hornung, A. (2008) A synthesis of multi-disciplinary research in precision agriculture: site-specific management zones in the semi-arid western Great Plains of the USA. *Precision Agriculture*, **9**, 85–100.

Kincaid, D.C. (1982) *Reducing Energy Requirements for Sprinkler Systems*. USDA Agricultural Research Service, Kimberly, ID.

King, A. & Berry, A. (2005) Vineyard δN, nitrogen and water status in perennial clover and bunch grass cover crop systems of California’s central valley. *Agriculture, Ecosystems & Environment*, **109**, 262–272.

King, A., Boyle, D., Jensen, V., Fogg, G.E. & Harter, T. (2012) *Groundwater Remediation and Management for Nitrate. Technical Report 5 in Addressing Nitrate in California’s Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature.* Center for Watershed Sciences, University of California, Davis.

Kirchmann, H. & Bergström, L. (2001) Do organic farming practices reduce nitrate leaching? *Communications in Soil Science and Plant Analysis*, **32**, 997–1028.

Krusekopf, H.H., Mitchell, J.P. & Hartz, T.K. (2002) Pre-sidedress soil nitrate testing identifies processing tomato fields not requiring sidedress N fertilizer. *HortScience*, **37**, 520–524.

Lehrsch, G.A., Sojka, R.E. & Westermann, D.T. (2000) Nitrogen placement, row spacing, and furrow irrigation water positioning effects on corn yield. *Agronomy Journal*, **92**, 1266–1275.

Letey, J., Blair, J.W., Devitt, D., Lund, L.J. & Nash, P. (1977) Nitrate-Nitrogen in effluent from agricultural tile drains in California. *Hilgardia*, **45**, 289–319.

Li, X., Hu, C., Delgado, J., Zhang, Y. & Ouyang, Z. (2007) Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in North China Plain. *Agricultural Water Management*, **89**, 137–147.

Lopus, S.E., Santibanez, M.P., Beede, R.H., Duncan, R.A., Edstrom, J., Niederholzer, F.J.A., Trexler, C.J. & Brown, P.H. (2010) Survey examines the adoption of perceived best management practices for almond nutrition. *California Agriculture*, **64**, 149–154.

Lovatt, C.J. (1999) Timing citrus and avocado foliar nutrient applications to increase fruit set and size. *HortTechnology*, **9**, 607–612.

Malone, R.W., Jaynes, D.B., Ma, L., Nolan, B.T., Meek, D.W. & Karlen, D.L. (2010) Soil-test N recommendations augmented with PEST-optimized RZWQM simulations. *Journal of Environmental Quality*, **39**, 1711–1723.

Malusa, E., Buffa, G. & Ciesielska, J. (2001) Effect of different fertilisation management on photosynthesis, yield and fruit quality of peach. *Plant Nutrition--Food security and sustainability of agro-ecosystems* pp. 332–333. Kluwer Academic Publishers, Dordrecht, Netherlands.

Mann, K.K., Schumann, A.W., Obreza, T.A., Harris, W.G. & Shukla, S. (2010) Spatial Variability of Soil Physical Properties Affecting Florida Citrus Production. *Soil Science*, **175**, 487–499.

Martin, D.L., Gilley, J.R. & Skaggs, R.W. (1991) Soil water balance and management. *Managing nitrogen for groundwater quality and farm profitability : proceedings of a symposium* pp. 199–235. Soil Science Society of America, Madison, Wisconson.

Meisinger, J.J. & Delgado, J.A. (2002) Principles for managing nitrogen leaching. *Journal of Soil and Water Conservation*, **57**, 485–498.

Meisinger, J.J., Delgado, J.A. & Alva, A. (2006) Nitrate Leaching Management. *Encyclopedia of Soil Science: Second Edition*, **1**, 1122–1124.

Mohammed, H.I., El Ramlawi, H.R., Mohammed, A.E.E.A. & Abbass, O.M. (2006) Use of inflow cutback concept for improving furrow irrigation. *Journal of Science and Technology (SUST)*, **7**, 1–15.

Monteiro, A. & Lopes, C.M. (2007) Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. *Agriculture, Ecosystems & Environment*, **121**, 336–342.

Monterey County Water Resources Agency. (2009) *2008 Ground Water Summary Report*. Monterey County Water Resources Agency, Salinas, California.

Monterey County Water Resources Agency. (2011) *2010 Ground Water Summary Report*. Monterey County Water Resources Agency, Salinas, California.

Mosley, L.M. & Fleming, N. (2009) Reductions in water use following rehabilitation of a flood-irrigated area on the Murray River in South Australia. *Agricultural Water Management*, **96**, 1679–1682.

Musick, J.T., Pringle, F.B. & Johnson, P.N. (1985) Furrow compaction for controlling excessive irrigation water intake. *Transactions of the ASAE*, **28**, 502–506.

Neetson, J.J., Booij, R. & Whitmore, A.P. (1999) A review on sustainable nitrogen management in intensive vegetable production systems. *Acta Hort. (ISHS)*, **506**, 17–28.

Newman, J. (2008) *Greenhouse and Nursery Management Practices to Protect Water Quality*. University of California Agriculture and Natural Resources Publication 3508, Oakland CA.

Niederholzer, F.J.A., DeJong, T.M., Saenz, J.L., Muraoka, T.T. & Weinbaum, S.A. (2001) Effectiveness of fall versus spring soil fertilization of field-grown peach trees. *Journal of the American Society for Horticultural Science*, **125**, 644–648.

Orang, M.N., Matyac, J.S. & Snyder, R.L. (2008) Survey of irrigation methods in California in 2001. *Journal of Irrigation and Drainage Engineering*, **134**, 96–100.

Osterli, P.P. & Meyer, J.L. (1977) Crop rotation improves nitrogen utilization. *California Agriculture*, **31**, 7–7.

Pang, X.P., Letey, J. & Wu, L. (1997) Irrigation quanitity and uniformity and nitrogen application effects on crop yield and nitrogen leaching. *Soil Science Society American Journal*, **61**, 257–261.

Peacock, W.L., Christensen, L.P. & Hirschfelt, D.J. (1991) Influence of timing of nitrogen fertilizer application on grapevines in the San Joaquin Valley. *American Journal of Enology and Viticulture*, **42**, 322–326.

Pence, R.A. & Grieshop, J.I. (2001) Mapping the road for voluntary change: partnerships in agricultural extension. *Agriculture and Human Values*, **18**, 209–217.

Peters, R.T. & Evett, S.R. (2008) Automation of a center pivot using the terperature-time-threshold method of irrigation scheduling. *Journal of Irrigation and Drainage Engineering*, **134**, 286–291.

Pettygrove, G.S., Hartz, T.K., Jackson, L.E., Lockhart, T.R., Schulbach, K.F. & Smith, R. (1998) *Production Guide: Nitrogen and Water Management for Coastal Cool Season Vegetables*. University of California Division of Agriculture and Natural Resources.

Pettygrove, G.S. & Putnam, D.H. (2009) *Legume N credit for crops following alfalfa*. University of California Cooperative Extension Manure Technical Guide Series for Crop Management Professionals.

Pettygrove, S., Schwankl, L.J., Frate, C.A. & Brittan, K.L. (2007) Improving water-run nitrogen fertilizer practices in furrow- and border check-irrigated crops. *15th Annual Fertilizer Research &*

Education Program Conference Proceedings pp. 50–53. California Department of Agriculture Fertilizer Research and Education Program (CDFA FREP), Tulare, Ca.

Power, J.F., Wiese, R. & Flowerday, D. (2001) Managing farming systems for nitrate control: a research review from management systems evaluation areas. *Journal of Environmental Quality*, **30**, 1866–1880.

Quiñones, A., Bañuls, J., Primo-Millo, E. & Legaz, F. (2005) Recovery of the 15N-labelled fertiliser in citrus trees in relation with timing of application and irrigation system. *Plant and Soil*, **268**, 367–376.

Quiñones, A., Martínez-Alcántara, B., Chi-Bacab, U. & Legaz, F. (2009) Improvement of N fertilization by using the nitrification inhibitor DMPP in drip-irrigated citrus trees. *Spanish Journal of Agricultural Research*, **7**, 190–199.

Ramos, M.E., Benítez, E., García, P.A. & Robles, A.B. (2010) Cover crops under different managements vs. frequent tillage in almond orchards in semiarid conditions: effects on soil quality. *Applied Soil Ecology*, **44**, 6–14.

Rodríguez, J., Díaz, A., Reyes, J. & Pujols, R. (2004) Comparison between surge irrigation and conventional furrow irrigation for covered black tobacco cultivation in a Ferralsol soil. *Spanish Journal of Agricultural Research*, **2**, 445–458.

Rotz, C.A. (2004) Management to reduce nitrogen losses in animal production. *Journal of Animal Science*, **82**, E119–137.

Russelle, M.P., Deibert, E.J., Hauck, R.D., Stevanovic, M. & Olson, R.A. (1981) Effects of Water and Nitrogen Management on Yield and 15N-Depleted Fertilizer Use Efficiency of Irrigated Corn1. *Soil Science Society of America Journal*, **45**, 553.

Sanden, B., Mitchell, J. & Wu, L. (1999) *Effects of irrigation nonuniformity on nitrogen and water use efficiencies in shallow-rooted vegetable cropping systems*. CDFA Fertilizer Research and Education Program (FREP).

Sanz-Cobena, A., Misselbrook, T.H., Arce, A., Mingot, J.I., Diez, J.A. & Vallejo, A. (2008) An inhibitor of urease activity effectively reduces ammonia emissions from soil treated with urea under Mediterranean conditions. *Agriculture, Ecosystems & Environment*, **126**, 243–249.

Sanz-Cobena, A., Misselbrook, T., Camp, V. & Vallejo, A. (2011) Effect of water addition and the urease inhibitor NBPT on the abatement of ammonia emission from surface applied urea. *Atmospheric Environment*, **45**, 1517–1524.

Schepers, J.S., Varvel, G.E. & Watts, D.G. (1995) Nitrogen and water management strategies to reduce nitrate leaching under irrigated maize. *Journal of Contaminant Hydrology*, **20**, 227–239.

Schipper, L.A., Cameron, S.C. & Warneke, S. (2010) Nitrate removal from three different effluents using large-scale denitrification beds. *Ecological Engineering*, **36**, 1552–1557.

Schipper, L.A., Robertson, W.D., Gold, A.J., Jaynes, D.B. & Cameron, S.C. (2010) Denitrifying bioreactors—An approach for reducing nitrate loads to receiving waters. *Ecological Engineering*, **36**, 1532–1543.

Schwankl, L. & Frate, C. (2004) Alternative techniques improve irrigation and nutrient management on dairies. *California Agriculture*, **58**, 159–163.

Schwankl, L., Hanson, B., Panoras, A. & others. (1992) Furrow torpedoes improve irrigation water advance. *California Agriculture*, **46**, 15–17.

Schwankl, L.J. & Prichard, T.L. (1990) Clogging of buried drip irrigation systems. *California Agriculture*, **44**, 16–17.

Serna, M.D., Legaz, F. & Primo-Millo, E. (1994) Efficacy of dicyandiamide as a soil nitrification inhibitor in citrus production. *Soil Science Society of America Journal*, **58**, 1817–1824.

Sheenan, C. (1992) Cover crops, nitrogen cycling and soil properties in semi-arid irrigated vegetable production systems. *HortScience*, **27**, 749–754.

Shi, W. & Norton, J.M. (2000) Effect of long-term, biennial, fall-applied anhydrous ammonia and nitrapyrin on soil nitrification. *Soil Science Society of America Journal*, **64**, 228–234.

Smajstrla, A.G., Boman, G.J., Clark, G.A., Haman, D.Z., Pitts, D.J. & Zazueta, F.S. (1997) *Bulletin 266/AE384: Field Evaluations of Irrigation Systems: Solid Set or Portable Sprinkler Systems*. University of Florida Cooperative Extension Service.

Smith, R. & Cahn, M. (2010) Impact of low-residue winter cover crops on sediment and nutrient loss. *CDFA Fertilizer Research & Education Program Conference 20th Anniversary Program Edition* pp. 129–131. CDFA, Fresno, Ca.

Smith, R. & Cahn, M. (2011) Improving nitrogen efficiency in lettuce production. *2011 Conference Proceedings, Agricultural Certification Programs-Opportunities and Challenges* pp. 41–46. American Society of Agronomy, Piccadilly Inn University, Fresno, Ca.

Smith, S.J. & Cassel, D.K. (1991) Estimating nitrate leaching in soil materials. *Managing nitrogen for groundwater quality and farm profitability : proceedings of a symposium* (eds R.F. Follett, D.R. Keeney & R.M. Cruse), pp. 165–188. Soil Science Society of America, Madison WI.

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J. & O'Neil, K. (2005) Cover Crops for Benefits, Costs and Performance within Cropping System Niches. *Agronomy Journal*, **97**, 322–332.

Spalding, R.F., Watts, D.G., Schepers, J.S., Burbach, M.E., Exner, M.E., Poreda, R.J. & Martin, G.E. (2001) Controlling nitrate leaching in irrigated agriculture. *Journal of Environment Quality*, **30**, 1184–1194.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R. & Polasky, S. (2002) Agricultural sustainability and intensive production practices. *Nature*, **418**, 671–677.

Tonitto, C., David, M.B. & Drinkwater, L.E. (2006) Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: a meta-analysis of crop yield and N dynamics. *Agriculture, Ecosystems and Environment*, **112**, 58–72.

Toth, J.D. & Fox, R.H. (1998) Nitrate Losses from a corn-alfalfa rotation: Lysimeter measurement of nitrate leaching. *Journal of Environmental Quality*, **27**, 1027–1033.

Trimmer, W.L. & Hanson, H.J. (1986) *Offsets for stationary sprinkler systems.* Oregon State University Pacific Northwest Extension Service Publication PNW 286.

U.S. Geological Survey. (1999) *USGS: The Quality of Our Nation's Waters-- Nutrients and Pesticides*.

USDA (United States Department of Agriculture) (2008) *2008 Farm and Ranch Irrigation Survey, Volume 3, Special Studies, Part 1. 2007 Census of Agriculture*.

United States Environmental Protection Agency Science Advisory Board. (2011) *Reactive Nitrogen in the United States: An analysis of inputs, flows, consequences, and management options*.

Vázquez, N., Pardo, A., Suso, M.L. & Quemada, M. (2005) A methodology for measuring drainage and nitrate leaching in unevenly irrigated vegetable crops. *Plant and Soil*, **269**, 297–308.

Vázquez, N., Pardo, A., Suso, M.L. & Quemada, M. (2006) Drainage and nitrate leaching under processing tomato growth with drip irrigation and plastic mulching. *Agriculture, Ecosystems & Environment*, **112**, 313–323.

Viers, J.H., Liptzin, D., Rosenstock, T.S., Jensen, V.B., Hollander, A.D., McNally, A., King, A.M., Kourakos, G., Lopez, E.M., De La Mora, N., Fryjoff-Hung, A., Dzurella, K.N., Canada, H.E., Laybourne, S., McKenney, C., Darby, J., Quinn, J.F. & Harter, T. (2012) Nitrogen Sources and Loading to Groundwater. Technical Report 2 in: *Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature.* Center for Watershed Sciences, University of California, Davis.

Wagner Weick, C. (2001) Agribusiness technology in 2010: directions and challenges. *Technology in Society*, **23**, 59–72.

Watson, C.J., Akhonzada, N.A., Hamilton, J.T.G. & Matthews, D.I. (2008) Rate and mode of application of the urease inhibitor *N* -(n-butyl) thiophosphoric triamide on ammonia volatilization from surface-applied urea. *Soil Use and Management*, **24**, 246–253.

Watson, C.J., Poland, P., Miller, H., Allen, M.B.D., Garrett, M.K. & Christianson, C.B. (1994) Agronomic assessment and 15N recovery of urea amended with the urease inhibitor nBTPT (N-(n-butyl) thiophosphoric triamide) for temperate grassland. *Plant and Soil*, **161**, 167–177.

Williams, J.R. & Kissel, D.E. (1991) Water percolation: An indicator of nitrogen-leaching potential. *Follet R.F. et al. [Eds.] Managing nitrogen for groundwater quality and farm profitability: proceedings of a symposium* pp. 59–83. Soil Science Society of America, Inc, Wisconson.

Woli, K.P., David, M.B., Cooke, R.A., McIsaac, G.F. & Mitchell, C.A. (2010) Nitrogen balance in and export from agricultural fields associated with controlled drainage systems and denitrifying bioreactors. *Ecological Engineering*, **36**, 1558–1566.

Wolt, J.D. (2004) A meta-evaluation of nitrapyrin agronomic and environmental effectiveness with emphasis on corn production in the Midwestern USA. *Nutrient Cycling in Agroecosystems*, **69**, 23–41.

Wu, L., Letey, J., French, C., Wood, Y. & Birkle, D. (2005) Nitrate leaching hazard index developed for irrigated agriculture. *Journal of soil and water conservation*, **60**, 90–95.

Wyland, L. (1996) Winter cover crops in a vegetable cropping system: Impacts on nitrate leaching, soil water, crop yield, pests and management costs. *Agriculture, Ecosystems & Environment*, **59**, 1–17.

Yonts, C.D., Eisenhauer, D.E. & Fekersillassie, D. (1996) Impact of surge irrigation on furrow water advance. *Transactions of the ASABE*, **39**, 973–979.

Zaman, M., Nguyen, M.L. & Blennerhas, J.D. (2010) The Effect of Different Rates of Urea with or without Urease Inhibitor (NBPT) on Wheat Yield and Quality. *Agricultural Journal*, **5**, 309–312.

Zhou, S.-L., Wu, Y.-C., Wang, Z.-M., Lu, L.-Q. & Wang, R.-Z. (2008) The nitrate leached below maize root zone is available for deep-rooted wheat in winter wheat–summer maize rotation in the North China Plain. *Environmental Pollution*, **152**, 723–730.

Zoldoske, D.F. (2002) *San Joaquin Valley grower irrigation survey*. The Center for Irrigation Technology California State University, Fresno, Fresno, Ca.

Zvomuya, F.R., Russelle, C.J., Gupta, M.P. & Satish, C. (2003) Nitrate leaching and nitrogen recovery following application of polyolefin-coated urea to potato. *Journal of Environmental Quality*, **32**, 480.

Section 3 Agro-economic Analysis of Nitrogen Source Reductions

Ali, A.G., & Lovatt, C.J. (1994). Winter application of low-biuret urea to the foliage of “Washington” navel orange increased yield. *Journal of American Society for Horticultural Science*, **119**, 1144–1150.

Allaire-Leung, S.E., Wu, L., Mitchell, J.P. & Sanden, B.L. (2001) Nitrate leaching and soil nitrate content as affected by irrigation uniformity in a carrot field. *Agricultural Water Management*, **48**, 37–50.

Bendixon, W. (1995) Strawberry Fruit Yields as Affected by Various Control Release Fertilizers. University of California Cooperative Extension, Santa Maria, Santa Maria, CA, http://www.calstrawberry.com/research_library/95-18.pdf

Broadbent, F.E. & Carlton, A.B. (1978) Field trials with isotopically labeled nitrogen fertilizer. *Nitrogen in the environment* (eds. Nielson, D.R. & MacDonald, J.G.), pp. 1-42. Academic Press, NY.

Burrow K., Stork S.V., Dubrovsy N.M. (1998) Nitrate and pesticide in ground water in the Eastern San Joaquin Valley, California: Occuance and trends. United States Geological Survey. Report Water Resources Investigation Report 98-4040a. 33p.

Christensen, L., Bianchi, M., Peacock, W. & Hirschfelt, D. (1994) Effect of nitrogen fertilizer timing and rate on inorganic nitrogen status, fruit composition, and yield of grapevines. *American Journal of Enology and Viticulture*, **45**, 377–387.

Daberkow, S., Ribaudo, M. & Doering, O. (2008) Economic implications of public policies to change agricultural nitrogen use and management. *Nitrogen in Agricultural Systems* (eds. Schepers, J.S. & Raun, W.R.). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI.

Dasberg, S. (1987) Nitrogen fertilization in citrus orchards. *Plant and Soil*, **100**, 1–9.

DWR (Department of Water Resources). (2009) California Water Plan Update 2009. California Department of Water Resources, Sacramento, CA, http://www.waterplan.water.ca.gov/cwpu2009

DWR (Department of Water Resources). (2003) California's Groundwater Bulletin 118, Update 2003. California Department of Water Resources, Sacramento, CA.

Frate, C.A., Marsh, B.H., Klonsky, K.M. & DeMoura, R.L. (2008). Sample Costs to Produce Grain Corn: San Joaquin Valley South. University of California Cooperative Extension CO-VS-08-2.

Fritschi, F.B., Roberts, B.A., Rains, D.W., Travis, R. L. & Hutmacher, R.B. (2005) Recovery of residual fertilizer-N and cotton residue-N by Acala and Pima cotton. *Soil Science Society of America Journal*, **69**, 718–728.

Hartz, T.K. (1993) Drip irrigation scheduling for fresh market tomato production. *Hortscience*, **28**, 35–37.

Hartz, T.K. (1994) A quick test procedure for soil nitrate-nitrogen. *Communications in Soil Science and Plant Analysis*, **25**, 511–515.

Hartz, T.K., Bendixen, W.E. & Wierdsma, L. (2000) The value of presidedress soil nitrate testing as a nitrogen management tool in irrigated vegetable production. *Hortscience*, **35**, 651–656.

Hartz, T.K. & Bottoms, T.G. (2010) Humic substances generally ineffective in improving vegetable crop nutrient uptake or productivity. *Hortscience*, **45**, 906–910.

Helfand, G.E. & House, B.W. (1995) Regulating nonpoint-source pollution under heterogeneous conditions. *American Journal of Agricultural Economics,* **77**, 1024–1032.

Howitt, R.E. (1995) Positive mathematical programming. *American Journal of Agricultural Economics*, **77**, 329–342.

Jaynes, E.T. (1957) Information theory and statistical mechanics. *Physical Reiew*, **106**, 620–630.

Johnson, R.S., Rosecrance, R., Weinbaum, S., Andris, H. & Wang, J. (2001) Can we approach complete dependence on foliar-applied urea nitrogen in an early-maturing peach? *Journal of the American Society for Horticultural Science*, **126**, 364–370.

Knapp, K.C. & Schwabe, K.A. (2008) Spatial dynamics of water and nitrogen management in irrigated agriculture. *American Journal of Agricultural Economics*, **90**, 524–539.

Larson, D.M., Helfand, G.E. & House, B.W. (1996) Second-best tax policies to reduce nonpoint source pollution. *American Journal of Agricultural Economics*, **78**, 1108–1117.

LeStrange, M., Mayberry, K.S., Kaike, S.T. & Valencia, J. (1996) Broccoli production in California. Publ. 7211, University of California, Agricultural and Natural Resources, Oakland, CA, ucanr.org/freepubs/docs/7211.pdf

Letey, J., Jarrell, W.M. & Valoras, N. (1982) Nitrogen and water-uptake patterns and growth of plants at various minimum solution nitrate concentrations. *Journal of Plant Nutrition*, **5**, 73–89.

Loague, K., Bernknopf, R.L., Green, R.E. & Giambelluca, T.W. (1996) Uncertainty of groundwater vulnerability assessments for agricultural regions in Hawaii: Review. *Journal of Environmental Quality*, **25**, 475–490.

Medellín-Azuara, J., Howitt, R. & Harou, J. (2012) Predicting farmer responses to water pricing, rationing and subsidies assuming profit maximizing investment in irrigation technology. *Agricultural Water Management*, **108**, 73-82

Medellín-Azuara, J., Howitt, R.E., MacEwan, D. & Lund, J.R. (2012) Economic impacts of climate-related yield changes in California. *Climatic Change*, **109**, 387–405.

Meyer, R. & Marcum, D. (1998) Potato yield, petiole nitrogen, and soil nitrogen response to water and nitrogen. *Agronomy journal*, **90**, 420–429.

Peacock, W.L., Christensen, L.P. & Hirschfelt, D.J. (1991) Influence of timing of nitrogen fertilizer application on grapevines in the San Joaquin Valley. *American Journal of Enology and Viticulture*, **42**, 322–326.

Perloff, J.M. (2004) *Microeconomics.* Pearson Addison-Wesley, Boston, MA.

Richardson, W.F. & Meyer, R.D. (1990) Spring and summer nitrogen applications to Vina walnuts. *California Agriculture*, **44**, 30–32.

Rosenstock, T.S., Liptzin, D., Six, J., Tomich, T.P. (In Review) A primer on nitrogen fertilizer use in California. *California Agriculture*.

Saenz, J., DeJong, T. & Weinbaum, S. (1997) Nitrogen stimulated increases in peach yields are associated with extended fruit development period and increased fruit sink capacity. *American Society for Horticultural Science*, **122**, 772–777.

Shannon, C.E. (1948) A mathematical theory of communication. *Bell System Technical Journal*, **27**, 379–423.

Southwick, S., Rupert, M., Yeager, J., Lampinen, B., DeJong, T. & Weis, K. (1999) Effects of nitrogen fertigation on fruit yield and quality of young 'French' prune trees. *Journal of Horticultural Science and Biotechnology*, **74**, 187–195.

Southwick, L.M., Willis, G.H., Johnson, D.C. & Selim, H.M. (1995) Water-quality – Leaching of nitrate, atrazine, and metribuzin from sugarcane in southern Louisiana. *Journal of Environmental Quality*, **24**, 684–690.

Stephany, P.W., Pettygrove, S., Butler, L.J., Ririe, D., Lowry, P., Rush, D., Letey, J., Millaway, R., Miller, J., Schnaible, D., Shaffer, S. & Stoddard, P. (1989) *Nitrate and California Agriculture*. Nitrate Working Group, California Department of Food and Agriculture.

Stark, J.C., Jarrell, W.M., Letey, J. & Valoras, N. (1983) Nitrogen use efficiency of trickle-irrigated tomatoes receiving continuous injection of Nitrogen. *Agronomy Journal*, **75**, 672–676.

USBR (United States Bureau of Reclamation). (1997) Central Valley Project Improvement Act: Draft Programmatic Environmental Impact Statement. Documents and Model Runs (2 CD-ROMs). U.S. Department of the Interiof, Bureau of Reclamation, Sacramento, Ca

USDA (United States Department of Agriculture). (2011) USDA National Agricultural Statistics Services Quick Stats, USDA-NASS, Washington, DC, http://www.nass.usda.gov/data_and_statistics/quick_stats/index.

USDA (United States Department of Agriculture) (2011) USDA National Resource Conservation Service Crop Nutrient Tool, USDA-NRCS, Washington, DC, http://plants.usda.gov/npk/main

Vickner, S.S., Hoag, D.L., Frasier, W.M. & Li, J.C.A. (1998) A dynamic economic analysis of nitrate leaching in corn production under nonuniform irrigation conditions. *American Journal of Agricultural Economics*, **80**, 397–408.

Viers, J.H., Liptzin, D., Rosenstock, T.S., Jensen, V.B., Hollander, A.D., McNally, A., King, A.M., Kourakos, G., Lopez, E.M., De La Mora, N., Fryjoff-Hung, A., Dzurella, K.N., Canada, H.E., Laybourne, S., McKenney, C., Darby, J., Quinn, J.F. & Harter, T. (2012) Nitrogen Sources and Loading to Groundwater. Technical Report 2 in: *Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater*. Report for the State Water

Resources Control Board Report to the Legislature. Center for Watershed Sciences, University of California, Davis.

Zhang, M.H., Geng, S. & Smallwood, K.S. (1998) Assessing groundwater nitrate contamination for resource and landscape management. *Ambio*, **27**, 170–174

Section 4 Reducing Urban Landscape Nitrogen Loading

OGCSA (Oregon Golf Course Superintendents Association of America). (2009) 2nd Edition Oregon Chapter GCSAA Environmental Stewardship Guidelines. EnviroLogic Resources, Inc. and Oregon Golf Course Superintendents' Association, Portland, OR.

UC IPM (University of California Integrated Pest Management). (2011) The UC Guide to Healthy Lawns, http://www.ipm.ucdavis.edu/tools/turf

Wu, L., Green, R., Grant, K., Janet, H.S. & Burger, D.W. (2010) Nitrogen source and rate influence on tall fescue quality and nitrate leaching in a southern California lawn on Environmental Expert. *Agronomy Journal*, **102**, 31–38.

Wu, L., Green, R., Yates, M.V., Pacheco, P. & Klein, G. (2007) Nitrate leaching in overseeded bermudagrass fairways. *Crop Science*, **47**, 2521–2528.

Section 5 Reducing Domestic and Urban Wastewater Nitrogen Loading

Amick, R. S. & Burgess, E. H. (2000) Exfiltration in sewer systems. US Environmental Protection Agency, National Risk Management Research Laboratory, New Jersey. <http://www.epa.gov/nrmrl/pubs/600r01034/600r01034.pdf>.

Berndtssen, J.C. (2006) Experiences from the implementation of a urine separation system: Goals, planning, reality. *Building and Environment,* **41**, 427–437.

Björklund, A., Bjuggren, C., Dalemo, M. & Sonesson, U. (1999) Planning biodegradable waste management in Stockholm. *Journal of Industrial Ecology*, **3**, 43–58.

Crites, R., Reed, S., Bastian, R. (2000) *Land Treatment Systems for Municipal and Industrial Wastes*, 1st ed. McGraw-Hill Professional.

Crites, R.W. & Tchobanoglous, G. (1998) *Small and Decentralized Wastewater Management Systems*. McGraw-Hill, NY.

Cutter, J. (2009) What Type of Pipe Do You Want Lying in Your Bedding? Part 1 of 2. PACE: An Engineering Services Company. Accessed 1 August 2011 via <http://www.paceengrs.com/Publications/What%20type%20of%20pipe%20do%20you%20want%20lying%20in%20your%20bedding.pdf>

Guest, J.S., Skerlos, S.J., Barnard, J.L., Beck, M.G., Daigger, G.T., Hilger, H., Jackson, S.J., Karvazy, K., Kelly, L., MacPherson, L., Mihelcic, J.R., Pramanik, A., Raskin, L., Van Loosdrecht, M.C.M., Yeh, D. & Love, N.G. (2009) A new planning and design paradigm to achieve sustainable resource recovery from wastewater. *Environmental Science and Technology*, **43**, 6126–6130.

Hammer, M. & Clemens, J. (2007) A tool to evaluate the fertilizer value and the environmental impact of substrates from wastewater treatment. *Water Science and Technology*, **56**, 201–209

Höglund, C., Ashbolt, N., Stenström, T.A. & Svensson, L. (2002) Viral persistence in source-separated human urine. *Advances in Environmental Research*, **6**, 265–275.

Isosaari, P., Hermanowicz, S.W. & Rubin, Y. (2010) Sustainable natural systems for treatment and disposal of food processing wastewater. *Critical Reviews in Environmental Science and Technology*, **40**, 662–697.

Johansson, M. (2000) Urine Separation – Closing the Nutrient Cycle. Final Report of the R&D Project: Source-Separated Human Urine – A Future Source of Fertilizer for Agriculture in the Stockholm Region. Stockholm: Stockholm Vatten, Stockholmshem & HSB National Federation.

Jönsson, H., Stintzing, A.R., Vinnerås, B. & Salomon, E. (2004) Guidelines on the use of urine and faeces in crop production. EcoSanRes Publications Series. Stockholm Environment Institute.

Leverenz, H.L., Haunschild, K., Hopes, G., Tchobanoglous, G. & Darby, J.L. (2010) Anoxic treatment wetlands for denitrification. *Ecological Engineering*, **36**, 1544–1551.

Lienert, J. & Larsen, T.A. (2007). Soft paths in wastewater management – The pros and cons of urine source separation. *Gaia*, **16**, 280–288.

Kapoor, A. & Viraraghavan, T. (1997) Nitrate removal from drinking water – Review. *Journal of Environmental Engineering*, **123**, 371–380.

Magid, J. (2006) Estrogen in the Environment. *Blackwater Systems: Nordic Inventory and proposals for Research and Development*. Full report in Swedish, English summary in Appendix 2.

Mateju, V., Cizinska, S., Krejci, J. & Janoch, T. (1992) Biological water denitrification – A review. *Enzyme and Microbial Technology*, **14**, 170–183.

Metcalf and Eddy, Inc., revised by Tchobanoglous, G., Burton, F.L. & Stensel, H.D. (2003) *Wastewater Engineering: Treatment and Reuse*, 4th Ed. McGraw-Hill, Boston, MA.

Muench, E. & Winker, M. (2011) *Technology Review of Urine Diversion Components*. Gesellschaft für Internationale Zusammenarbeit, Eschborn, Germany.

Moorman, T.B., Parkin, T.B., Kaspar, T.C. & Jaynes, D.B. (2010) Denitrification activity, wood loss, and N_2O emissions over 9 years from a wood chip bioreactor. *Ecological Engineering*, **36**, 1567–1574.

Robertson, W.D. & Cherry, J.A. (1995) In situ denitrification of septic-system nitrate using reactive porous media barriers: Field trials. *Ground Water*, **33,** 99–111.

Robertson, W.D., Blowes, D.W., Ptacek, C.J. & Cherry, J.A. (2000) Long-term performance of in situ reactive barriers for nitrate remediation. *Ground Water*, **38**, 689–695.

Rossi, L., Lienert, J. & Larsen, T.A. (2009) Real-life efficiency of urine source separation. *Journal of Environmental Management*, **90**, 1909–1917.

Rubin, Y., Sunding, D. & Berkman, M. (2007a) Hilmar Supplemental Environmental Project: Volume 1. Hydrogeophysics, Inc.

Rubin, Y., Sunding, D. & Berkman, M. (2007b) Hilmar Supplemental Environmental Project: Volume 2. Hydrogeophysics, Inc.

Rubin, Y., Sunding, D. & Berkman, M. (2007c) Hilmar Supplemental Environmental Project: Volume 3. Hydrogeophysics, Inc.

Schipper, L.A., Robertson, W.D., Gold, A.J., Jaynes, D.B. & Cameron, S.C. (2010) Denitrifying bioreactors – An approach for reducing nitrate loads to receiving waters. *Ecological Engineering*, **36**, 1532–1543.

Schouw, N.L., Danteravanich, S., Mosbaek, H. & J.C. Tjell. (2002) Composition of human excreta – A case study from southern Thailand. *Science of the Total Environment*, **286**, 155–166.

State Water Resources Control Board. (2010) File: WWTP_Survey_05_10_2010.mdb. Sent by Erin Mustain, SWRCB, Office of Information Management and Analysis.

United States Environmental Protection Agency. (2006) Process Design Manual: Land Treatment of Municipal Wastewater Effluents. EPA 625-R-06-016.

United States Environmental Protection Agency. (2008) Municipal Nutrient Removal Technologies. EPA 832-R-08-006.

United States Environmental Protection Agency. (2002) Onsite Wastewater Treatment Systems Manual. EPA-625-R-00-008.

Viers, J.H., Liptzin, D., Rosenstock, T.S., Jensen, V.B., Hollander, A.D., McNally, A., King, A.M., Kourakos, G., Lopez, E.M., De La Mora, N., Fryjoff-Hung, A., Dzurella, K.N., Canada, H.E., Laybourne, S., McKenney, C., Darby, J., Quinn, J.F. & Harter, T. (2012) Nitrogen Sources and Loading to Groundwater. Technical Report 2 in: *Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Report for the State Water Resources Control Board Report to the Legislature.* Center for Watershed Sciences, University of California, Davis.

Vinneras, B. (2001) Faecal Separation and Urine Diversion for Nutrient Management of Household Biodegradable Waste and Wastewater. Dissertation. Swedish University of Agricultural Sciences, Uppsala, Sweden.

Water Environment Federation. (2010) *Nutrient Removal, WEF MOP 34*, 1st Ed. McGraw-Hill Professional.

World Health Organization (WHO). (2006) Guidelines for the Safe Use of Wastewater, Excreta and Greywater Use in Agriculture and Aquaculture: Socio Cultural, Environmental and Economic Aspects. WHO Press, Geneva, Switzerland.

Section 6 Reducing Nitrogen Loading from Active, Dry, and Abandoned or Destroyed Wells

Braun, A.L. & Hawkins, L.S. (1991) Presence of Bromacil, Diuron, and Simazine in Surface Water Runoff from Agricultural Fields and Non-Crop Sites in Tulare County, California PM 91-1. California Department of Food and Agriculture, Sacramento, CA.

Bryant, D. (2002) Salinas Valley survey sets nitrate practices baseline. *Western Farm Press*, http://westernfarmpress.com/salinas-valley-survey-sets-nitrate-practices-baseline

California Department of Water Resources. California Well Standards, Bulletin 74-81 and 74-90, http://www.water.ca.gov/groundwater/well_info_and_other/california_well_standards/well_standards_content.html

Christman, M.C., Benson, C.H. & Tuncer, B.E. (2002) Geophysical study of annular well seals. *Ground Water Monitoring & Remediation*, **22**, 104–112.

Cleaning, Maintenance & Rejuvenation, City of Modesto's Rockwells. City of Modesto, Modesto, CA.

Creedon, P.C. (2008) Monitoring and Reporting Program No. R5-2008-0092. City of Modesto, Modesto, CA.

DeMartinis, J. & Royce, K. (1990) Identification of Direct-Entry Pathways by which Agricultural Chemicals Enter Ground Water. *Proceedings of the 1990 National Water Works Association Cluster of Conferences*, pp. 51–65.

Edil, T.B., Chang, M.M.K., Lan, L.T. & Riewe, T.V. (1992) Sealing characteristics of selected grouts for water wells. *Ground Water*, **30**, 351–61.

Fresno County, California – Code of Ordinances (2011) http://library.municode.com/index.aspx?clientid=14972&stateid=5&statename=california

Holden, P.W. (1986) Pesticides and ground water quality, issues and problems in four states. National Academy Press, Washington, D.C.

Kern County, California – Code of Ordinances (2010) http://library.municode.com/index.aspx?clientid=16251&stateid=5&statename=california

Kings County, California – Code of Ordinances (2011) http://library.municode.com/index.aspx?clientid=12257&stateid=5&statename=california

Monterey County, California – Code of Ordinances (2011) http://library.municode.com/index.aspx?clientid=16111&stateid=5&statename=california

MPWMD (Monterey Peninsula Water Management District). (2007) Requirements for New Water Wells within the MPWMD, http://www.mpwmd.dst.ca.us/pae/wds/requirements/requirements_20070524.pdf

Paulsen, S. (2001) Chemigation Safety Devices: Pesticide Label Requirements and Allowable Alternative Equipment. Department of Pesticide Regulation, Sacramento, CA, www.cdpr.ca.gov/docs/county/cacltrs/penfltrs/penf2001/2001028.pdf

Pesticide Registration (PR) Notice 87-1 (1987) Label Improvement Program for Pesticides Applied through Irrigation Systems (Chemigation) . United States Environmental Protection Agency, http://www.epa.gov/pr_notices/pr87-1.html

Pickett, C.H., Hawkins, L.S., Pehrson, J.E. & O'Connell, N.V. (1990) Herbicide Use in Citrus Production and Ground Water Contamination in Tulare County. California Department of Food and Agriculture, Pest Management Analysis and Planning Program Safety, Sacramento, CA.

Ross, J. (2010) The Nebraska grout study. *Water Well Journal*, November 2010, 25–31.

Stormwater Pollution Prevention. (2011) City of Modesto, California, Modesto, CA, http://www.modestogov.com/pwd/utilities/wastewater/pollution

Storm Drain System Map. (2008) City of Modesto, California, Modesto, CA, http://www.modestogov.com/pwd/utilities/wastewater/drain_map.asp

Troiano, J.J. & Segawa, R.T. (1987) Survey for Herbicides in Well Water in Tulare County. Environmental Hazards Assessment Program, California Department of Food and Agriculture, Division of Pest Management, Sacramento, CA.

Tulare County, California – Code of Ordinances. (1997) Tulare County Ordinance Code Part IV. Health, Safety and Sanitation.

Underground Injection Control Program. (2011) United States Environmental Protection Agency, http://water.epa.gov/type/groundwater/uic

When are Strom Water Discharges Regulated as Class V Wells? (2003) United States Environmental Protection Agency, http://www.epa.gov/npdes/pubs/sw_class_v_wells_fs.pdf

Viers, J.H., Liptzin, D., Rosenstock, T.S., Jensen, V.B., Hollander, A.D., McNally, A., King, A.M., Kourakos, G., Lopez, E.M., De La Mora, N., Fryjoff-Hung, A., Dzurella, K.N., Canada, H.E., Laybourne, S., McKenney, C., Darby, J., Quinn, J.F. & Harter, T. (2012) Nitrogen Sources and Loading to Groundwater. Technical Report 2 in: *Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater*. Report for the State Water Resources Control Board Report to the Legislature. Center for Watershed Sciences, University of California, Davis.

Zoldoske, D., Jacobsen, T. & Norum, E.M. (2004) Grower Training Manual for Backflow Prevention in Chemigation of Pesticides. The Center for Irrigation Technology, California State University, Fresno, Fresno, CA, http://www.cdpr.ca.gov/docs/emon/grndwtr/chem/grower_manual.pdf