

To see the full report, contact frep@cdfa.ca.gov.



Final Report

Nitrogen Fertilizer Loading to Groundwater in the Central Valley

FREP Projects 11-0301 and 15-0454

For the period January 2012 through December 2014 and August 2015 through June 2016

Funded by

Fertilizer Research and Education Program, California Department of Food and Agriculture

Prepared by

Thomas Harter, Kristin Dzurella, Giorgos Kourakos, Andy Bell, Aaron King, and Allan Hollander

University of California, Davis

August 2017

Project Information

Project Leaders:

Thomas Harter, Robert M. Hagan Endowed Chair in Water Management and Policy, Department of Land, Air, and Water Resources, (530) 752-2709, ThHarter@ucdavis.edu.

Minghua Zhang, Adjunct Professor, Department of Land, Air and Water Resources, (530) 752-4953, MHZhang@ucdavis.edu.

Thomas P. Tomich, Ph.D., W.K. Kellogg Endowed Chair in Sustainable Food Systems, Professor and Director, Agricultural Sustainability Institute and Sustainable Agriculture Research and Education Program, (530) 752-4563, TPTomich@ucdavis.edu.

G. Stuart Pettygrove, Cooperative Extension Soil Specialist Emeritus, Department of Land, Air, and Water Resources, (530) 752-304-1007, GSPettygrove@ucdavis.edu.

Affiliation of all Project Leaders: University of California; One Shields Ave.; Davis, CA 95616

Collaborating Personnel:

Kristin Dzurella, Research Analyst, Department of Land, Air and Water Resources, UC Davis

Giorgos Kourakos, Visiting Research Scientist, Dept. of Land, Air, and Water Resources, UC Davis

Allan Hollander, Project Scientist, Information Center for the Environment, UC Davis

Andy Bell, Research Analyst, Center for Watershed Sciences, UC Davis

Nicholas Santos, Research Analyst, Center for Watershed Sciences, UC Davis

Quinn Hart, Data Scientist, Shields Library, UC Davis

Aaron King, Graduate Student Researcher, Center for Watershed Sciences, UC Davis

Jim Quinn, Professor Emeritus, Information Center for the Environment, UC Davis

Gail Lampinen, Project Scientist, Center for Watershed Sciences, UC Davis

Daniel Liptzin, Post-doctoral Scholar, Institute of Arctic and Alpine Research, University of Colorado

Todd Rosenstock, Research Scientist, World Agroforestry Centre (ICRAF)

Suggested Citation:

Harter, T., K. Dzurella, G. Kourakos, A. Hollander, A. Bell, N. Santos, Q. Hart, A. King, J. Quinn, G. Lampinen, D. Liptzin, T. Rosenstock, M. Zhang, G.S. Pettygrove, and T. Tomich, 2017. Nitrogen Fertilizer Loading to Groundwater in the Central Valley. Final Report to the Fertilizer Research Education Program, Projects 11-0301 and 15-0454, California Department of Food and Agriculture and University of California Davis, 325p., <http://groundwaternitrate.ucdavis.edu>

Table of Contents

Table of Contents

Executive Summary.....	9
Highlights	9
Introduction	9
Methods/Management.....	9
Findings	10
Project Objectives	12
Introduction	12
Task 1: Develop GIS Database Structure.....	16
1.1 Work Description	16
1.2 Results/Data.....	16
Task 2: Compile landuse data that are available in GIS format; historic and current, by CDWR landuse unit / field (crop classification I)	18
2.1 Digital Landuse Map Representing the 2005 Period: Work Description for CAML 2010	18
2.2 Landuse Map for the 1990 Period: Work Description for CAML 1990	23
Task 3: Fertilizer sales, historic and current, by county.....	26
3.1 Work Description	26
3.2 Results and Discussion	26
Task 4: Compile crop acreage and crop production, historic and current, by county (crop classification II)	32
4.1 Work Description	32
4.2 Results and Discussion	33

Task 5: Compile crop fertilizer practices recommendations, historic and current.....	35
5.1 Work Description	35
5.2 Results and Discussion	36
Task 6: Compile crop nitrogen uptake estimates by major crops from literature review, extension reports; historic and current (crop classification IV)	37
6.1 Work Description	37
6.2 Results and Discussion	39
Task 7: Review literature on atmospheric deposition; historic and current, by air basin	42
7.1 Work Description	42
7.2 Data	42
Task 8: Quantify nitrogen volatilization and denitrification; develop an atmospheric loss rate as a function of major fertilization practices, irrigation practices, and major soil groups; historic and current.	44
8.1 Work Description	44
8.2 Results and Discussion	44
Task 9: Develop a unified crop classification scheme.....	45
9.1 Work Description	45
9.2 Results	45
Task 10: Develop and test simplified methodology to account for year-to-year landuse changes (historic and future) in a GIS framework	47
10.1 Work Description: Data Sources	47
10.2 Work Description: Assembly of Land Cover Data	50
10.3 Work Description: Backcasting Algorithm	52
10.4 Work Description: Extension of Backcasting Methods to Central and Northern Central Valley....	54
10.5 Results: Backcasting Landuse for the 1945, 1960, and 1975 Periods.....	55
Task 11: Implement field nitrogen balance and estimate historic and current potential groundwater nitrate loading.....	60

11.1 Introduction	60
11.2 Work Description: Estimating Potential Nitrogen Loading to Groundwater from Crops and Other Vegetated Non-Urban Landscapes	61
11.2.1 Mass Balance Approach for Vegetated Landscapes	61
11.2.2 Time Period of Interest, Temporal Discretization.....	62
11.2.3 Area of Interest, Spatial Discretization: The Control Volume	64
11.2.4 Landuse Maps	65
11.3 Work Description: Nitrogen Leaching from Leguminous Crops: Alfalfa and Clover	67
11.4 Septic Systems.....	68
11.4.1 Introduction	68
11.4.2 Work Description: Nitrogen in Septic Systems	68
11.4.3 Work Description: Septic System Densities	69
11.4.4 Results and Discussion: Septic System Density and Regional Septic Nitrogen Leaching to Groundwater.....	72
11.4.5 Conclusions from Septic Systems Analysis.....	76
11.5 Nitrogen Leaching from Urban Landuses	77
11.5.1 Introduction: Urban Sources of Nitrogen Leaching to Groundwater	77
11.5.2 Work Description: Mapping of Urban Areas.....	77
11.5.3 Work Description: Urban Sources of Nitrogen Leaching to Groundwater	78
11.5.4 Results and Discussion: Diffuse Urban Sources of Nitrogen Leaching to Groundwater.....	79
11.5.5 Nitrogen in Wastewater Treatment Plants and Food Processors - Introduction	81
11.5.6 Work Description: Accounting for WWTP and FP Nitrogen Disposal to Land and Percolation Basins in the Central Valley.....	83
11.5.7 Results and Discussion: WWTP and FP Nitrogen Disposal to Land and Percolation Basins in the Central Valley.....	88
11.6 Dairy Sources of Nitrogen	98

11.6.1 Groundwater Nitrogen Loading from Dairy Corrals.....	98
11.6.2 Nitrogen Loading Rates from Dairy Lagoons	101
11.6.3 Nitrate Loading Rates in Irrigated Crop Fields with Manure Applications.....	104
11.7 Nitrogen Mass Balance: Crop Group, County, Region, and Central Valley Scale Analysis using Agricultural Commissioner Reports (ACR) Data.....	114
11.7.1 Work Description: Total N applied and N use efficiency (ACR)	114
11.7.2 Results and Discussion: Total N applied and N use efficiency (ACR)	115
11.8: The Groundwater Nitrogen Loading Model for the Central Valley (GNLM-CV) - Raster-Based Nitrogen Mass Balance Analysis at the 50 Meter Scale.....	120
11.8.1 Work Description: GNLM_CV methodology for land application of dairy manure	120
11.8.2 Work Description: GNLM-CV Methodology for Mapping and Simulating WWTP and FP Nitrogen Disposal to Agricultural Land and Percolation Basins.....	126
11.8.3: Work Description: GNLM-CV Simulation	127
11.8.4: Results and Discussion: GNLM-CV Simulation	128
Task 12: Develop a list of prominent alternative management practices in high loading crops.....	153
Task 13. Apply nitrate loading rates to NPS groundwater assessment tool to predict statistical distribution of nitrate in production wells.....	155
13.1 Work Description	155
13.2 Results and Discussion	156
Task 14: Publish all relevant data on web-accessible GIS database	162
Synthesis Discussion and Conclusions	163
References	167
Project Impacts	172
Specific ways in which the work, findings, or products of the project have had an impact during this reporting period:.....	172
How data obtained from the project can be used, what further steps will be needed to make it applicable for growers, how the management practice will be demonstrated to growers, how the research will be applied to impact growers, and how this will impact the grower community:	172

Cost-benefit analysis of adoption of the new technology and a discussion of barriers to adoption: ..	173
Project’s contribution toward advancing the environmentally safe and agronomically sound use of fertilizing materials:	174
Outreach Activities Summary	175
Project-related presentations by the Principal Investigator (Dr. Thomas Harter), 2012-2014	175
Project-related Websites	186
Project-Related Media Interviews:	186
Factsheet.....	187
Nitrogen Fertilizer Loading to Groundwater in the Central Valley	187
Highlights	187
Introduction	187
Methods/Management.....	188
Findings	188
Project Products: Websites, Databases, Publications.....	192
Websites	192
Databases.....	192
Publications.....	192
Appendix Tables.....	194
Appendix Table 1: County ACR analysis – Central Valley crop group nitrogen applied and harvested, and nitrogen use efficiency.....	194
Appendix Table 2: County ACR analysis – County crop area, nitrogen applied and harvested.....	194
Appendix Table 3: County ACR analysis and survey – typical nitrogen applied and typical nitrogen harvested, by crop.	194
Appendix Table 4: Wastewater treatment plant facilities.....	194
Appendix Table 5: Food processing facilities.....	194
Appendix Figures.....	215

Appendix Figures 1 – 5: Landuse maps of landuses with fixed or facility-specific groundwater nitrate loading rates (“fixed rate lands”) for 1945, 1960, 1975, 1990, and 2005 215

Appendix Figures 6 – 109: 13 nitrogen flux maps for each of 8 simulation periods: 1945, 1960, 1975, 1990, 2005, 2020, 2035, 2050. For each period, the set of maps include:..... 215

- Atmospheric nitrogen deposition 215
- Irrigation nitrogen 215
- Potential synthetic fertilizer application (typically recommended rate) 215
- Synthetic fertilizer application (actual use after accounting for manure or effluent applications) .215
- Land-applied manure, effluent, or biosolids nitrogen 215
- Manure sale 215
- Potential harvest 215
- Actual harvest 215
- Actual runoff 215
- Atmospheric losses 215
- Potential groundwater loading from crops and natural vegetation 215
- Potential groundwater loading from septic systems 215
- Potential groundwater loading from urban areas, golf courses, wastewater lagoons, corrals, and alfalfa/clover 215

Executive Summary

Highlights

- Agricultural lands are the largest contributor of nitrate to Central Valley groundwater. Urban and domestic contributions to potential groundwater nitrogen loading are less than 10%.
- Synthetic fertilizer contributes nearly 60%, dairy manure nearly 20% of nitrogen to croplands.
- New technologies are urgently needed to derive synthetic fertilizer-like materials from dairy manure to address the largest pollution risks.
- A wide range of agricultural practices are available to improve crop nitrogen use efficiency at a region-wide scale.
- Agricultural management improvements will only gradually affect groundwater quality in supply wells, at decadal time-scales.
- New modeling tools can assess future groundwater quality trends including those achievable from broader adoption of currently available or future best agricultural practices.

Introduction

Nitrate-nitrogen is the most common pollutant found in the Central Valley aquifer system of California. This project provides a long-term assessment of past and current potential nitrogen loading to groundwater on irrigated and natural lands across the entire Central Valley of California using a nitrogen mass balance approach; assesses the long-term implications for groundwater quality in the Central Valley (Sacramento Valley, San Joaquin Valley, and Tulare Lake Basin); evaluates potential best management practices to reduce groundwater nitrogen loading from irrigated lands; and provides a planning tool to better understand local and regional groundwater quality response to specific best management practices and policy/regulatory actions. The project complements other work to assess the vulnerability of Central Valley groundwater to nitrate contamination, sources of nitrate in groundwater, and how to reduce source loading.

Methods/Management

The primary tool for this Central Valley assessment are field-scale, crop-scale, crop-group scale, county-scale, groundwater-basin scale, and Central Valley-wide nitrogen mass balance computations that can be linked to groundwater transport models. We developed a GIS framework and a compilation of spatial land use data, collecting and digitizing data for performance of the nitrogen mass balance (historic and current). Data collection included a comprehensive assessment of historic and current nitrogen applications to cropland (from atmospheric, fertilizer, animal, and human sources) and field nitrogen removal (harvest removal, atmospheric losses, surface runoff). Agricultural Commissioner reported crop area and production data have been used to determine the mean period harvest removal rates of nitrogen. We used the tabularized county-by-county crop acreage information and a number of existing geospatial databases to generate digital maps of current and 1990 landuses; and then developed an algorithm that backcasts agricultural crop maps of the Central Valley to the mid-1970s, late 1950s/early 1960s and to the 1940s when fertilizer use in the Central Valley first started to be widespread. Published N fertilization rates (Viers et al. 2012, Rosenstock et al. 2013) were updated through an extensive

interview process and used to estimate total synthetic N applications based on reported crop area. New concepts for handling various components of crop data emerged, and extensive quality control was performed on the data collected.

For comparison of synthetic fertilizer nitrogen loading to that from other sources, we tabularized nitrogen loading from wastewater treatment plants, food processors, and from septic systems. Dairy manure nitrogen amounts and fate were assessed through review of existing research results and by performing dairy nitrogen mass balances.

We also extended the computational performance of groundwater transport modeling software: The groundwater nitrate transport modeling tool developed here allows computation of long-term transport of nitrate to individual domestic/municipal/irrigation wells, based on the spatially distributed, field-by-field, annual nitrogen loading to groundwater. We have developed new solver capacities and the ability to run the software program on parallel computing machines, with initial runs of a highly detailed flow and transport model for several basins in the Central Valley.

Findings

This report updates and expands the 2012 SBX2 1 Report “Addressing Nitrate in Groundwater”, which focused geographically on the Tulare Lake Basin and Salinas Valley. The data presented here confirm the major findings of the earlier report and of information since then submitted by agricultural coalitions and CV-SALTS to the Central Valley Regional Water Quality Control Board:

The largest nitrogen fluxes into the agricultural landscape include synthetic fertilizer (504 Gg N/yr), land application of manure on dairy cropland or exported to other crops and land application of wastewater effluent (220 Gg N/yr), and nitrogen fixation in alfalfa (115 Gg N/yr). The largest nitrogen fluxes out of the agricultural landscape include harvested nitrogen (450 Gg N/yr including alfalfa), potential nitrogen losses to groundwater from cropland (331 Gg N/yr), and atmospheric nitrogen losses (209 Gg N/yr, which includes 131 Gg N/yr of atmospheric N losses from dairy manure prior to land application).

The Tulare Lake Basin accounts for the largest nitrogen fluxes but it also reflects nearly half of the total irrigated cropland area – 1.5 million ha of 3.2 million ha in the Central Valley. Nitrogen flux rates in the Tulare Lake Basin largely mirror those in the San Joaquin Valley, with large amounts and rates of manure land applications.

The Sacramento Valley, in contrast, has only small amounts of dairy cropland with manure land applications and little manure export. Lacking manure nitrogen sources to augment synthetic fertilizer, the Sacramento Valley in turn has a slightly higher rate of synthetic nitrogen application (175 kg N/ha/yr instead of 165 and 158 kg N/ha/yr in the San Joaquin Valley and Tulare Lake Basin, respectively).

To reduce potential groundwater nitrogen loading from cropland across the Central Valley and thus improve the quality of recharge water from the agricultural landscape, there are only few options, dictated by the magnitude of nitrogen fluxes:

- Increase the amount of harvest without also increasing the amount of synthetic or organic fertilizer
- Reduce the nitrogen input to the agricultural landscape. However, of all fluxes into the agricultural landscape, only synthetic fertilizer use can be reduced significantly without significantly changing Central Valley landuse: Cities and particularly dairy farming are generating large amounts of nitrogen that is currently recycled in the agricultural landscape.

A central challenge to improving groundwater quality in the Central Valley is to develop nutrient management practices that make more efficient and effective use of animal derived nutrients to allow growers to increasingly rely on organic fertilizer. This will require the development of new processes to transform manure into a fertilizer product that can be marketed and that performs much like synthetic fertilizer.

In the meantime, a wide range of agricultural practices have been documented, as part of this work, as part of CDFA FREP's work, and elsewhere, that significantly improve crop nitrogen use efficiency at a region-wide scale from today's practices. Extending this knowledge to growers will be a key goal for the agricultural coalitions in the Central Valley that are engaged in the implementation of the Irrigated Lands Regulatory Program and the Dairy Order. Agricultural management improvements are urgently needed to not further degrade groundwater recharge quality, even if improvements of groundwater quality in supply wells will only be felt at decadal time-scales, due to the slow-moving nature of groundwater.

Project Objectives

1. Develop a field-scale nitrogen mass balance for all major irrigated crops and other landuses across the entire Central Valley.
2. Determine nitrogen leaching to groundwater as closure term to the nitrogen mass balance, where possible, and from literature review, where nitrogen mass balance is not possible, e.g., septic systems and other non-cropped areas.
3. Apply the nitrogen loading rates with our non-point source assessment tool to several large pilot areas in the Tulare Lake Basin, the San Joaquin Valley, and the Sacramento Valley for a groundwater nitrate pollution assessment and assess the prediction uncertainty inherent in the approach.
4. Provide results within a GIS atlas that is publishable on the web and also in form of extension and outreach activities including newsletter articles, interviews with news outlets, web-based materials, and publication in California Agriculture and other grower-g geared magazines, and in peer-reviewed scientific journals.

Introduction

An overarching objective of this project is to assess the potential impact of fertilizer use in the Central Valley relative to other sources of nitrogen on groundwater quality. In hydrologic investigations, this type of assessment is sometimes referred to as a vulnerability assessment, impact assessment, or risk analysis. Such assessments can be implemented to various degrees of accuracy using a number of different approaches, at various spatial and temporal scales. The hydrologic literature distinguishes four major categories useful for the assessment of impacts of pollution sources (here: fertilizer applied in agricultural and urban settings) on groundwater quality and the risk for groundwater quality degradation (Harter, 2008):

- Mapping-based index and overlay methods:
 - Single indicator based approach (e.g., crop type or fertilizer application rate)
 - Aggregation of multiple risk factors (e.g., recharge rate, depth to groundwater, soil type, source intensity, landuse/crop)
- Computer-based, numerical water flow and pollutant fate and transport simulation methods:
 - Water and pollutant mass flux based (zero-dimensional) approach
 - Crop and root zone processes modeling (one-, two-, or three-dimensional)
 - Vadose zone process modeling (including the root zone, most commonly one-dimensional, but also two- and three-dimensional)
 - Groundwater flow and transport modeling (two- or three-dimensional)
- Statistical analysis, including regression models relating groundwater quality to potential explanatory factors, including landuse
- Field monitoring approaches
 - Root zone / vadose zone monitoring at selected sites

- Groundwater monitoring at selected sites or across a (regional) monitoring network

Mapping-based index and overlay methods are commonly used for vulnerability or risk assessments (Harter, 2008). In the Central Valley, recent efforts under Irrigated Lands Regulatory Program (ILRP) of the Central Valley Water Quality Control Board (CVRWB, 2017) have provided a vulnerability analysis of nitrate in groundwater across the entire Central Valley: As part of their regulatory compliance under the ILRP, agricultural water quality coalitions prepared a so-called Groundwater Quality Assessment Report (GAR) that provides a baseline understanding of the hydrology, hydrogeology, water quality, and landuse within each coalitions area and the factors potentially leading to groundwater nitrate contamination. As part of the GAR, each coalition developed a vulnerability mapping approach that summed indices related to climate, landuse, geography, soil type, crop type, groundwater quality, urbanization, the presence of groundwater users, especially domestic well and economically disadvantaged public water supply users, and other factors (the GARs can be found under each “Coalition Group” at

http://www.waterboards.ca.gov/centralvalley/water_issues/irrigated_lands/water_quality/coalitions/index.shtml). These and other mapping-based index and overlay methods rely on spatial analysis of multiple maps, each representing certain quantitative or quality indicator variables. The assembly of maps are overlaid and digitally evaluated based on an expert-based or other algorithm that combines indicator values at one location into a final location-based vulnerability score.

Computer-based, numerical simulation models range from lumped mass flux based models to process-based models that may encompass crop, atmosphere, root zone, vadose zone (below the root zone), and groundwater processes of water movement and pollutant fate and transport. These methods use detailed spatio-temporal information about a site or region – the distribution of climate, soil, landuse, and hydrogeologic properties – to predict the flow of water and the associated fate and transport of pollutants in the subsurface. Numerical simulation models are commonly used in the site assessment and evaluation of point sources of groundwater contamination (e.g., groundwater contamination from leaky underground storage tanks at gas stations, discharge of industrial solvents from leaky waste impoundments). Numerical methods have also been commonly used in assessing nutrient and pesticide fate and transport in the root zone of agricultural crops. To date, such methods have been less commonly used to assess pollutant fluxes from nonpoint sources to groundwater (Harter, 2008).

Statistical approaches have been used to relate the presence of potential pollutants in the source area of groundwater to measured groundwater quality data, where the transport pathway via the crop root zone and vadose zone to groundwater and subsequently through the aquifer to a well, spring, or stream is represented in a “black box” approach via a statistical model. For example, Nolan et al. (2014, 2015) developed and compared three advanced, machine-learning based statistical approaches to relate groundwater nitrate measurements to a large number of potential factors influencing groundwater nitrate concentration. Similarly, Nolan et al. (2002), used a statistical regression technique to relate measured groundwater nitrate to a number of factors thought to influence groundwater nitrate concentrations, at the national scale. Statistical methods, once developed from existing data are then commonly employed to make predictions at unmeasured locations, e.g., to predict nitrate concentration

at locations with the Central Valley (Nolan et al., 2014, 2015; Ransom et al., 2017) or within the US (Nolan et al., 2002), where data currently do not exist. The information is also used to delineate regions with higher pollution risk for a particular contaminant: the California Department of Pesticide Regulation used statistical regression to identify regions that are vulnerable to groundwater pesticide contamination (so-called “groundwater protection zone”) based on information about depth to groundwater, soil texture, and the presence of soil hardpans (Troiano et al., 1992).

Monitoring of pollutants in the environment is used to obtain direct observations of groundwater quality impacts. Properly designed monitoring networks (of the root zone, unsaturated zone, or groundwater) ideally provide information on groundwater quality impacts from specific sources. Often, significant uncertainty exists about the exact source locations that contribute to the water quality in a particular well. Monitoring wells, constructed with relatively short screens (up to 25 feet) in the uppermost groundwater zone typically provide the most constraint on the uncertainty about the source location of water measured in the well. Source area location of domestic wells is much more uncertain and even larger for large production wells used for municipal or agricultural water supplies. Often, monitoring methods are used in conjunction with computer-based methods and statistical methods of pollution source assessments.

In this project, our goal has been to better assess the role of synthetic fertilizer in contributing to groundwater nitrate pollution in California’s Central Valley, relative to the many other sources. We map the potential for groundwater nitrate pollution based on the information obtained on nitrogen fluxes associated with urban areas, golf courses, wastewater treatment plants, food processing plants, septic systems, dairies, and 58 agricultural crops, using mapping and mass balance simulation tools. This report steps through the various tasks designed to assemble the mapping and simulation data layers, including literature surveys, extensive data collection from over a half century of agricultural commissioner reports on crop acreage and crop harvest, from fertilizer sales reports, from interviews with fertilizer application experts, and through the development of mapping and simulation tools. This final report follows the originally proposed project Task schedule. Work description, data and results, and discussion are provided within each Task chapter. A synthesis discussion is provided at the end of the report.

Task 1 describes the overall database architecture, the spatial extent of the study, and the temporal extent of the study. Tasks 2, 4, 9, and 10 describe the development of Central Valley landuse layers with 50 m resolution using existing digital information (Task 2), existing county-level agricultural crop acreage information (Task 4), and through back-simulation for historic periods (Task 10) based on a unified crop classification scheme with 58 individual crops and crop classes (Task 9).

Tasks 3 and Tasks 5 through 8 describe the data collection associated with various components of the agricultural nitrogen cycle: historic and current fertilizer sales data (Task 3), historic and current fertilizer practice recommendations (Task 5), historic and current crop harvest rates and associated nitrogen removed (Task 6), atmospheric nitrogen deposition (Task 7), and nitrogen losses to the atmosphere (Task 8).

The data and information discovery described in Tasks 1 through 10 is employed in Task 11. Task 11 describes the methodology and additional data sources used to perform a Central Valley-wide, detailed historic and current nitrogen mass balance, at the county-level and at the 50 m field scale, to estimate the potential groundwater nitrogen loading from key urban and agricultural nitrogen sources. Task 13 describes the development of a groundwater flow and transport modeling tool that can be used in conjunction with the estimated potential groundwater nitrogen loading maps (historic and current) to assess long-term impacts on groundwater quality.

Finally, alternative agricultural management practices available to address potential high groundwater nitrogen loading rates are summarized in Task 12.

Task 1: Develop GIS Database Structure

1.1 Work Description

The study area includes the California Central Valley floor, roughly following the CV aquifer as defined in the USGS Central Valley Hydrological Model (CVHM, Faunt 2009). Crop area and crop production statistics were compiled from annual county agricultural commissioner offices for 20 Central Valley Counties. These include counties in three regions:

- Sacramento Valley (SCV): Butte, Colusa, Glenn, Placer, Sacramento, Shasta, Solano, Sutter, Tehama, Yolo, Yuba
- (Northern) San Joaquin Valley (NSJV): Contra Costa, Madera, Merced, San Joaquin, Stanislaus
- Tulare Lake Basin (TLB): Fresno, Kings, Kern, Tulare

To enable running the GNLM on the full Central Valley study region, it is necessary to create historical land cover layers to initialize the model at prior times. As current and future groundwater nitrate concentrations are the results of a long history of nitrate loading, the annual mass balance is performed in 15 year intervals from 1945 to 2005 requiring landuse data back to 1945. For improved accuracy, needed data collection for this task (e.g. harvest statistics from Agricultural Commissioner Reports, see Task 4) includes not only each interval year (1945, 1960, 1975, 1990, 2005), but 2 years prior to and after the individual interval year, for a total of 25 years:

1943 – 1947 for the period year “1945”

1958 – 1962 for the period year “1960”

1973 – 1977 for the period year “1975”

1988 – 1992 for the period year “1990”

2003 – 2007 for the period year “2005”

The approach to generating landuse maps for these five periods was two-fold: the “1990” and “2005” periods are compiled from existing county-level landuse surveys, compiled digitally by the California Department of Water Resources and others. Digital landuse maps for the earlier periods (“1975”, “1960”, and “1945”) are obtained by back-simulating landuse using information available on the extent of agricultural landuse from county agricultural commissioner’s crop acreage data, other available land classification sources, and known spatial landuse distribution in 1990.

1.2 Results/Data

Using ArcGIS® as the GIS platform, a spatial framework for data compilation and model simulation has been developed. All spatial data and maps are converted into a uniform coordinate system using California Albers projection. Base maps include 1:24,000 scale National Elevation Dataset (NED),

1:100,000 scale National Hydrography Dataset (NHD), and 1:24,000 scale Soil Survey Geographic (SSURGO) database, landuse and weather data (CIMIS) from California Department of Water Resources. GIS databases have been developed for the San Joaquin Valley watershed, with details documented in Zhang and Luo, 2007; and for the Tulare Lake Basin as documented in Viers et. al., 2012.

Task 2: Compile landuse data that are available in GIS format; historic and current, by CDWR landuse unit / field (crop classification I)

2.1 Digital Landuse Map Representing the 2005 Period: Work Description for CAML 2010

A map of current land use was developed to provide a statewide view of land cover using the most recent data sources as of 2010 (Figure 2.1). In the context of this project, the statewide view was necessary because it served as an input for a parallel project developing a nitrogen budget for the entire state of California. This map was based upon the earlier California Augmented Multisource Landcover (CAML) raster layer (Hollander, 2007), developed at ICE in 2007. This 2007 map augmented the earlier 2002 Multi-Source Land Cover (MSLC) map from the California Department of Forestry and Fire Protection by dividing its single agricultural class into the 8 agricultural classes used in the California Wildlife Habitat Relationships classification system (California Department of Fish and Game, 1999), the primary focus of the MSLC map being on natural vegetation. The differences of the current map (henceforth CAML 2010) from the 2007 map include the following: 1) the data sources are up-to-date (the most recent being 2008); 2) given the agricultural focus of this project, the number of agricultural classes have been expanded drastically, to a fairly large subset of the agricultural classes used in the landuse mapping efforts by the California Department of Water Resources (DWR)(about 120 classes). The raster cell resolution has been increased from 100 meters to 50 meters (see <http://cain.ice.ucdavis.edu/caml>).

The initial base layer for this product was the MSLC layer from 2002. This layer pools the best regional vegetation maps into a single statewide raster map, at 100 meter resolution. The land cover classes use the California Wildlife Habitat Relationships system, which is organized around differentiating habitat types for wildlife. The MSLC layer is used for the natural vegetation component of CAML 2010.

The DWR land use maps were the main input for the agricultural component of the map. DWR has been mapping land cover types on a county-by-county basis on a rotation of about every 7 years. We used the most recent maps for each county, specifically 1997 for Monterey, 1999 for Tulare, 2000 for Fresno, 2003 for Kings, and 2006 for Kern County. The GIS workflow was to load the shapefiles for each county into a single table in the spatial database PostGIS (Refractions Research, 2008). We then associated each polygon with a single land cover classification type using a two-column lookup table which referred to the fields labeled class1 and subclass1 in the DWR shapefile. We then exported this table via spatial analysis to another shapefile. The shapefile was then rasterized at 50 meter resolution raster using the raster centroid landuse and retaining a single integer coded value for the land cover classification within the raster cell.

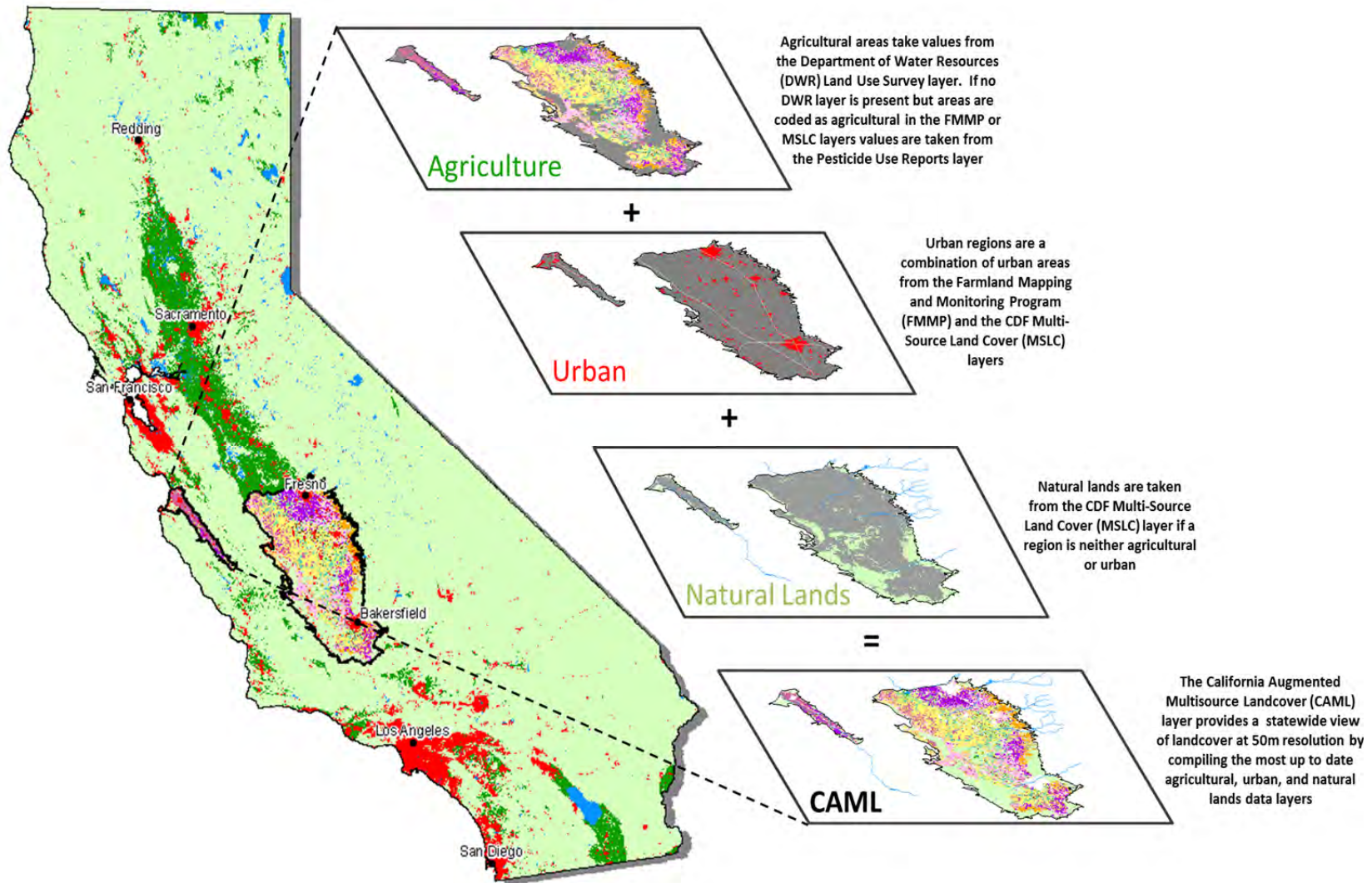


Figure 2.1: The input layers for the final 2010 raster layer with insets illustrating the SBX2 1 study area portion of the Central Valley. (Viers et al. 2012, used with permission)

Another input to the CAML 2010 map were the Farmland Mapping and Monitoring Program (FMMP) maps produced by the California Department of Conservation. These identify prime farmlands, locally important farmlands, grazing lands and so on for most counties in the state. FMMP has been mapping these in two-year intervals since 1984. Most importantly, FMMP has mapped conversion of farmlands to developed lands. We use the FMMP layer from 2008 as a source for urban boundaries. Equivalent to the processing of the DWR shapefiles, we add all of the FMMP maps to a single table in PostGIS and then export that to a shapefile which was subsequently rasterized at 50 meter resolution. This raster layer had 15 distinct categories in it (Table 2.1)

Table 2.1 - FMMP Land use categories

Land Use Categories for FMMP
Confined Animal Agriculture (CI)
Urban and Built-up Land (D)
Grazing Land (G)
Farmland of Local Importance (L)
Farmland of Local Potential (LP)
Natural Vegetation (nv)
Prime Farmland (P)
Rural Residential Land (R)
Farmland of Statewide Importance (S)
Semi-Agricultural and Rural Commercial Land (sAC)
Unique Farmland (U)
Vacant or Disturbed Land (V)
Water (W)
Other Land (X)
Area Not Mapped (Z)

One issue was that not all agricultural areas of the state had been mapped by DWR at any point, even once, one example of this being southern Santa Clara County. Yet these areas show up as agricultural regions in the MSLC map or the FMMP mapping. We need to populate these areas with agricultural land classes, so we need an alternative source for these. This is provided by the Pesticide Use Reporting available from the California Department of Pesticide Regulation (PUR) (California Department of Pesticide Regulation, 2000). When farmers apply pesticides they document this with their county agricultural commissioner, who in turn reports these data to the DPR. These data include amounts and types of pesticides applied spatially located to the nearest one square mile section. Significantly, these pesticide use reports also include the crop type of application. We converted the list of crop types in the PUR database to the lookup table used with the DWR maps and summed up the crop types by area for each square mile section, the rule being to assign each section the crop with the greatest total by area. The table was referenced spatially to a public land survey system layer for the state. The township-range-section map was then rasterized with the values for each pixel being the crop code for the majority crop type within each section according to the PUR data.

These 4 inputs to CAML 2010 were then all put together (Figure 2.2). The urban regions are a combination of the urban areas from the MSLC and FMMP maps. The agricultural areas took values from the DWR layer where that was present. If no DWR layer was present but the area was coded as agricultural in MSLC or FMMP, we took the values from nearest PUR square-mile section, using a raster-based region growing algorithm to determine the crop type of the nearest section). If the region was neither urban nor agricultural, it is natural vegetation, so these values were taken from the MSLC layer.

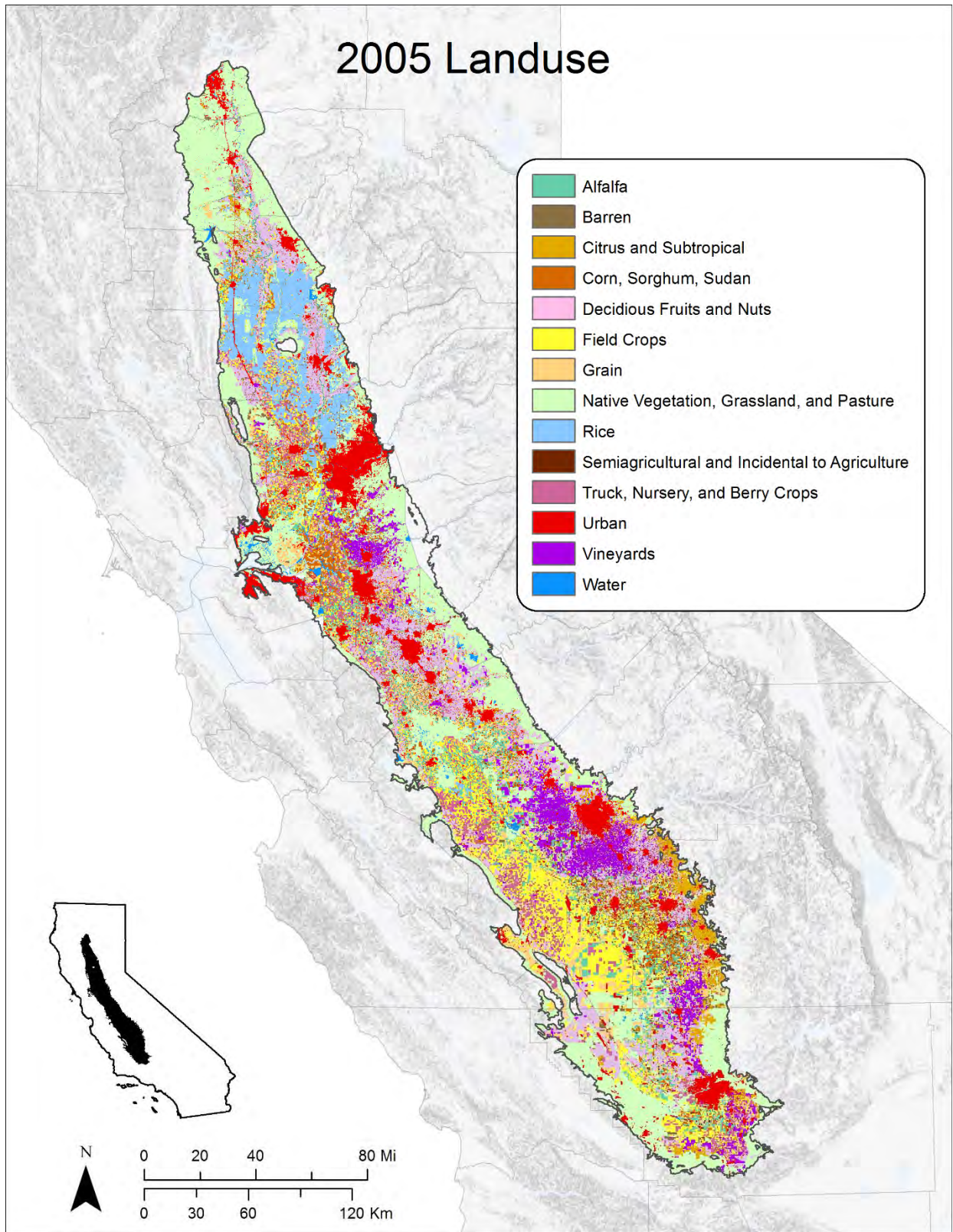


Figure 2.2: California Augmented Multisource Landcover (CAML) landuse map for the 2005 period.

2.2 Landuse Map for the 1990 Period: Work Description for CAML 1990

The time period of the 1990 era is the furthest back when there is digital mapping available that provide details on the spatial distribution of crop patterns, the data coming from the DWR Land Use Survey.

Construction of the 1990-era land cover map for the Central Valley proceeded in three stages. The first was a map of the 4 Tulare Lake Basin counties (Fresno, Tulare, Kings, and Kern) produced in 2011 for the SB2X 1 nitrate project. The second stage, completed in spring of 2013, extended this collation to the other counties in the San Joaquin Valley as part of the San Joaquin Valley Greenprint project. The final stage, completed in summer of 2014, added the Sacramento Valley counties to the set as well.

Three input layers went into the processing for the 1990 land cover map. First, the 1992 NLCD, a raster layer at 30 meter resolution, was used to distinguish between agricultural, natural vegetation, and urban land cover areas. Second, the 2002 Multi-Source Land Cover (MSLC) map from the California Department of Forestry and Fire Protection (California Department of Forestry and Fire Protection 2002), a raster map with 100 m resolution, was used as a source of information on natural vegetation. Areas of natural vegetation in the NLCD map were assigned land cover classes from pixels in the MSLC map. Third, areas marked as agriculture in NLCD were assigned land cover classes from the DWR land cover mapping. The DWR map for each county was selected from the one closest in time to 1990 from the list of all maps for each county; these ranged from 1989 for Yolo County to 1998 for Sutter County, with the median year being 1994. The output for this processing was a set of raster layers by county at a 50 meter pixel resolution. These layers were then patched together to form a single 1990-era raster land cover map for the Central Valley counties.

We have assembled a circa 1990 land cover layer for the entire Central Valley, using a combination of Department of Water Resources land cover layers, the 1992 National Land Cover Dataset, and the California Department of Forestry and Fire Protection Multi-Source Land Cover dataset. An image of this 1990 land cover dataset is provided in Figures 2.3 and 2.4.

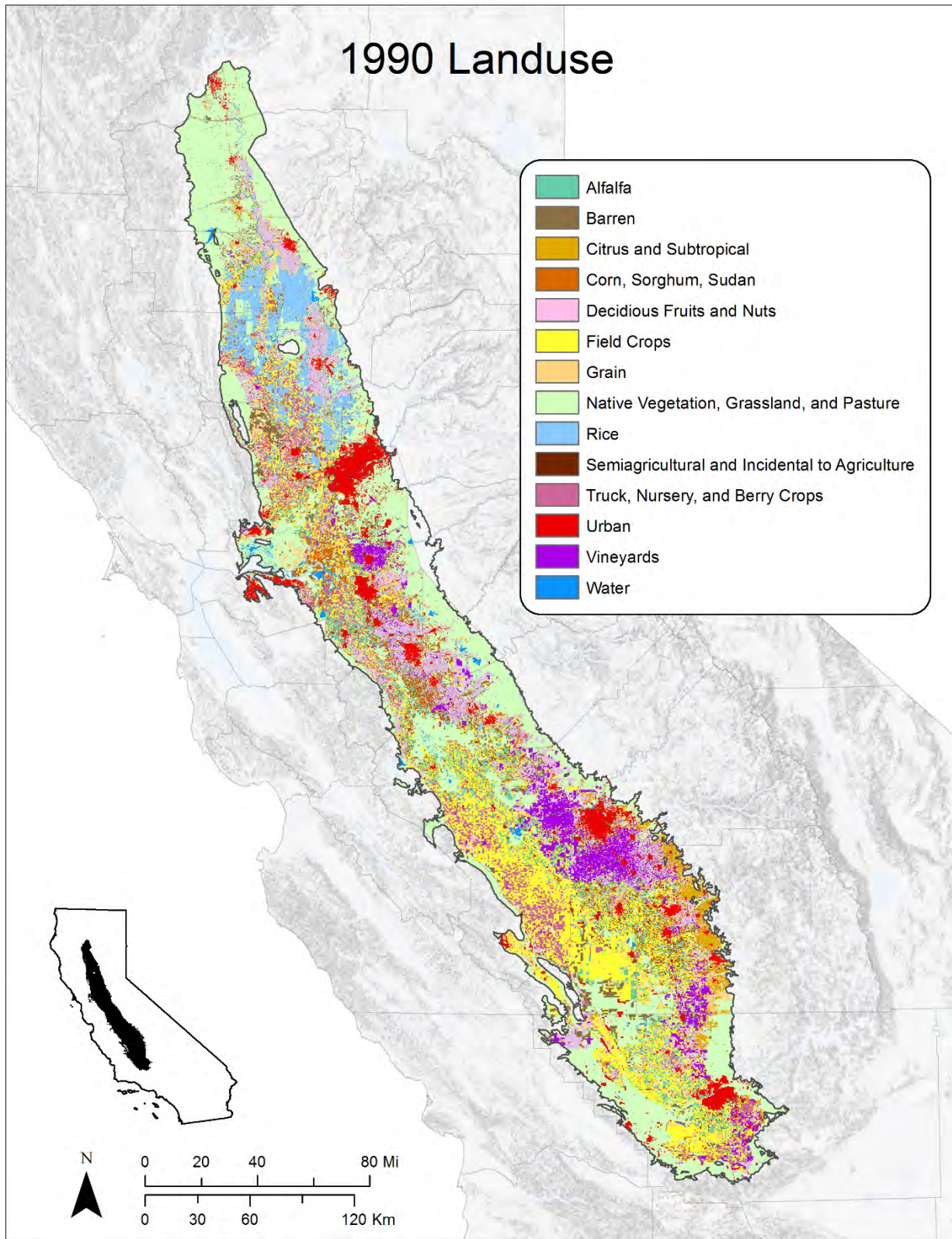


Figure 2.3: Reconstructed 1990 land use and cropping systems map for the Central Valley with over sixty landuse classes grouped here into 14 landuse groups.

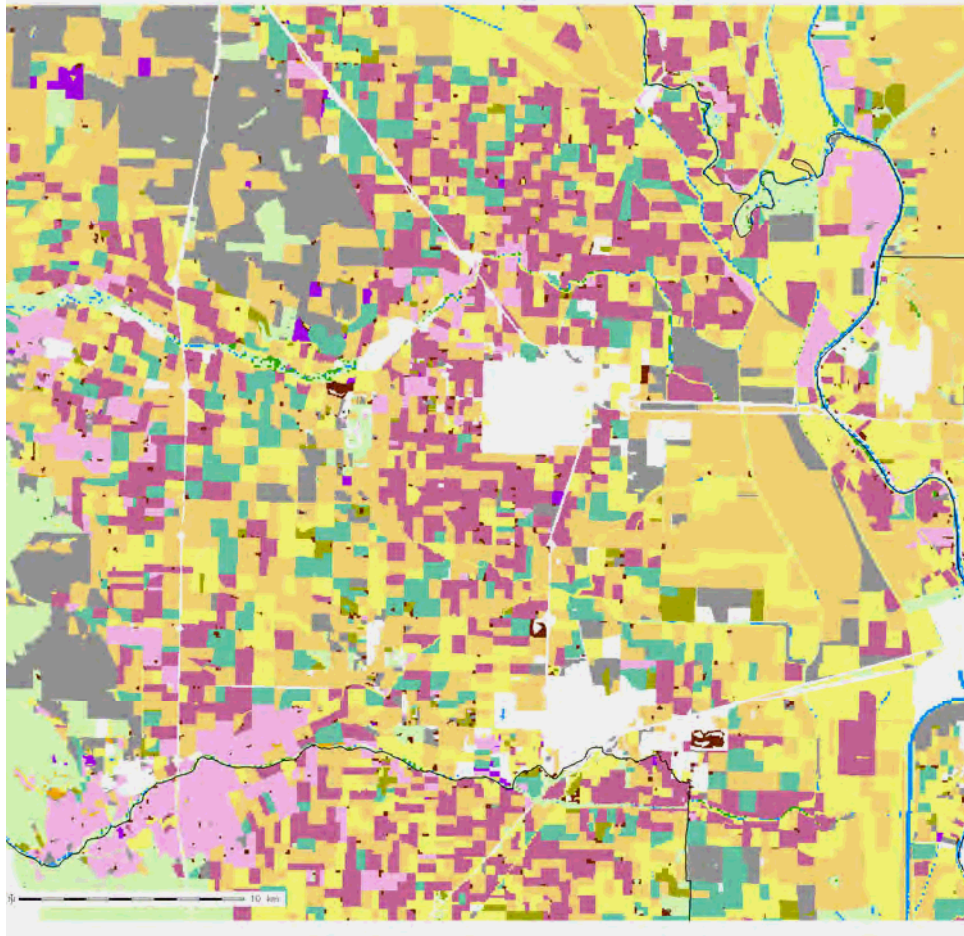


Figure 2.4: Detail of the Central Valley 1990 landuse map , showing Yolo County with Woodland and Davis in the center of the map (white: urban areas).

Task 3: Fertilizer sales, historic and current, by county

3.1 Work Description

California Department of Food and Agriculture publishes fertilizer sales reports bi-annually, in which the second report for the year lists annual total N by county (appearing after individual product totals), under a column variously named “All Nutrients Tons, N”; or “All N” (https://www.cdfa.ca.gov/is/ffldrs/Fertilizer_Tonnage.html). We digitized these reports for the years 1988-2011 and processed average sales for the 1990 and 2005 periods (1988-1992, 2003-2007) to compare to synthetic N application totals. Additionally, the decadal averages prior to and after 2002 were analyzed, and significant outliers were removed.

3.2 Results and Discussion

Statewide nitrogen fertilizer sales vary from less than 500,000 tons in 1991 to over 900,000 tons reported for 2002. Significant variability is observed in statewide fertilizer sales. By 2011, reported nitrogen fertilizer sales had decreased from 2002 levels to less than 750,000 tons. Counties in the Central Valley account for a significant amount of state-wide fertilizer sales. In 1991, sales in the Central Valley counties were nearly 300,000 tons. By 2011, fertilizer sales in the Central Valley had doubled to nearly 600,000 tons. These counties make up between two-thirds and three-quarters of statewide fertilizer sales, depending on the year. Annual variations largely follow those of the statewide fertilizer sales.

A significant increase in reported N sales occurred in 2002, with high sales continuing thereafter. While it may be expected that such a sudden rise in fertilizer demand is driven by sudden landuse or landuse practice changes, our analysis shows that statewide nitrogen demand does not significantly change in 2002 (Figure 3.1). Instead, the bulk of the reported sales increases in 2002 are attributable specifically to reported sales of anhydrous ammonia in San Joaquin County, and to a lesser degree, to reported sales of aqua ammonia sales in Colusa County. In 2002, 97% of the reported statewide anhydrous ammonia sales took place in two counties. San Joaquin county accounts for 56% of that year’s reported sales, with the remainder reported in San Luis Obispo County, which in all other years reports zero sales of anhydrous ammonia. In 2008, 90% of the statewide anhydrous ammonia sales were reported in San Joaquin County, accounting for over 35% of statewide total N sales.

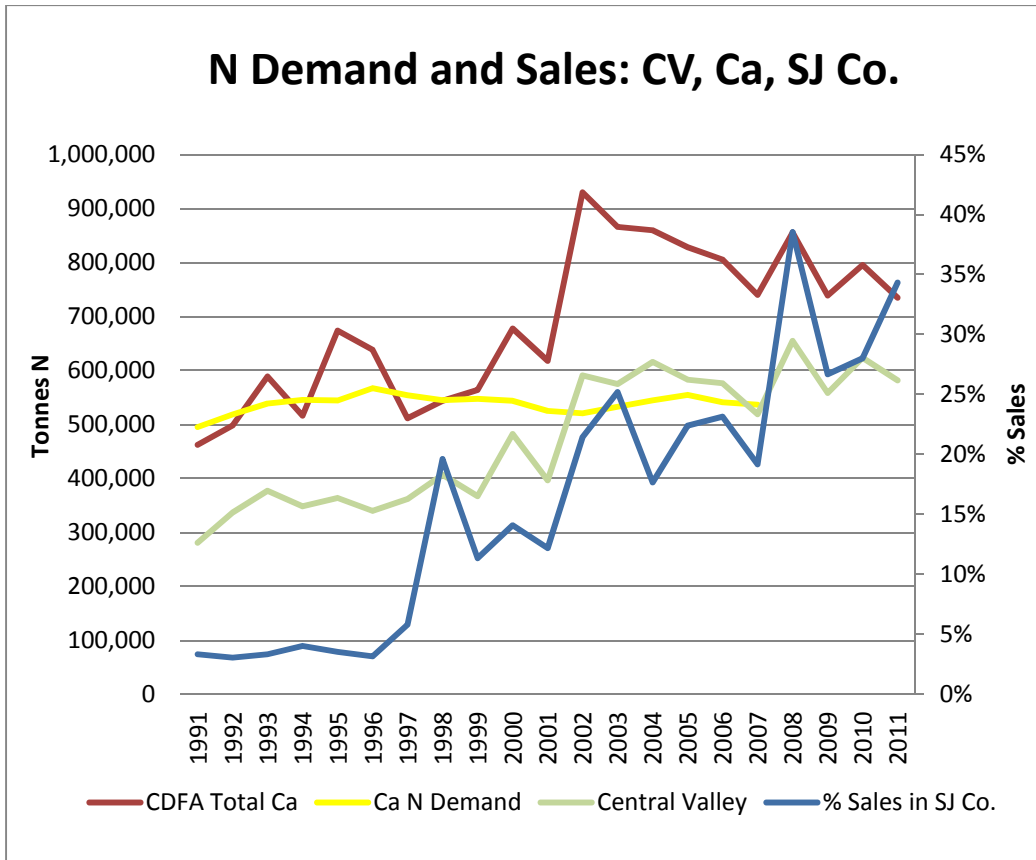


Figure 3.1: Statewide and Central Valley N sales as reported in CDFA tonnage reports. Statewide N demand, based on yields, does not show a similar increase, highlighting a sales reporting anomaly. The CV accounts for ~65-75% of statewide sales while the sales in San Joaquin County have been increasingly and disproportionately high, accounting for up to 38% of statewide sales.

While fertilizer sales should be reported by the dealer who sells to the end-user only (from a licensed dealer to an unlicensed buyer), products may change hands several times before being purchased by the end-user. A possible explanation for over-reporting could occur if a company reports sales to “middlemen,” who then also report sales to the end-user. Such double reporting by one prominent company was verified by a California fertilizer industry expert whom we interviewed. According to this anonymous source, this error has affected reliability of reported values for anhydrous ammonia in San Joaquin County and aqua ammonia in Colusa County “for at least 10 years”. These are the counties and N materials that show the largest anomalies in the sales reports. Nationally, the relationship between an individual state’s N fertilizer sales data and reported crop acreage do not vary as dramatically from year to year as shown here. While transcription errors, unit conversion errors, and other anomalies may contribute to reported sales anomalies, we conclude that double reporting is the main factor in the inaccurate sales data since 2002. The differences in decadal average N sales within each county before and after the 2002 sales jump are shown in Table 3.1.

Table 3.1: Central Valley county synthetic nitrogen fertilizer sales; averages for the decade prior to and after the 2002 jump in statewide sales. Differences > 10,000 tons highlighted in bold. Outliers were removed from the analysis on 3 occasions as noted, and are assumed reporting errors. N sales occurring in county “unknown” average 35K per year, ranging 1k-100k.

County	Avg. 1991-2001	Avg. 2002-2012	(tons N)
Butte	18,362*		<i>*removed 1995 outlier of 43,000 tons</i>
Colusa	22,932	38,549*	<i>*large increase in aqua ammonia</i>
Contra Costa	2,262		
Fresno	64,784	67,342	
Glenn	13,545		
Kern	44,304	50,509	
Kings	28,091		<i>*spike in 2006</i>
Madera	10,148	9,413	
Merced	17,130		
Placer	850	1,363	
Sacramento	13,525		
San Joaquin	44,265	208,549*	<i>*large increase in anhydrous ammonia</i>
Shasta	1,566		<i>*removed 2002 outlier of 15,000 tons</i>
Solano	9,142	9,633	
Stanislaus	18,867*		<i>*removed 1995 outlier of 66,000 tons</i>
Sutter	17,482	14,397	
Tehama	1,345		
Tulare	24,589	26,808	
Yolo	16,472		
Yuba	3,262	2,781	
Central Valley	369,333		<i>Above outliers excluded</i>
California Total	572,042	815,416	<i>Outliers and county ‘unknown’ included</i>

Estimating more realistic sales figures for the 2005 period based on the relationship between application and sales or harvest estimates in the 1990 period, is not possible with any reasonable certainty. But it is helpful to compare the reported fertilizer sales figures to estimated synthetic fertilizer application rates and estimated harvest rates for nitrogen. In Task 11 we describe two approaches to estimate county

level synthetic fertilizer applications: one is based on county agricultural commissioner reports of land area harvested (Section 11.7); the second is based on the detailed CAML 2010 landuse map (Task 2) with detailed spatial accounting for manure utilization that may affect synthetic fertilizer use (Section 11.8). Tasks 4-10 describe further details behind these approaches. Here we use county reported crop land area as the basis of computing synthetic fertilizer use, by county (Section 11.7):

Figure 1 shows fertilizer sales records, estimated synthetic N application and estimated N harvests (see tasks 4, 5, and 11) for the 1990 and 2005 periods, based on mean crop acreages reported by county agricultural commissioners for those periods. Estimated synthetic N applications increased by 7% from 1990 to 2005 while estimated harvest increases by 27% indicating significant improvements in overall synthetic nitrogen fertilizer use efficiency. However, reported Central Valley fertilizer sales of 306 Gg N/yr are 40 Gg N/yr less than estimated synthetic N applications in the 1990 period. In the Sacramento Valley and San Joaquin Valley, estimated synthetic N applications exceed reported synthetic N fertilizer sales in those regions by 11% and 37%, respectively. In the Tulare Lake Basin, the difference is less than 5%.

The difference between estimated synthetic N application and reported synthetic N sales in the 1990 period may be due to significant imports of synthetic N fertilizer to the Central Valley from counties outside of the Central Valley. Actual estimates for synthetic fertilizer movement into or out of the Central Valley are not available. Statewide sales for synthetic fertilizer N averages 499 Gg N/yr during the 1990 periods. Given that more than 70% of California irrigated cropland is in the Central Valley, the estimated synthetic N application (345 Gg N/yr, Figure 3.2) is not unreasonable and may indicate that fertilizer was indeed imported to the Central Valley during the 1990 period.

In contrast to the 1990 period, the average reported N fertilizer sales for the 2005 period (2003-2007) exceed the estimated synthetic N application in all three Central Valley regions: estimated synthetic N applications in the Central Valley rise by 7% to 370 Gg N/yr, while the reported N sales rise by 40% to 520 Gg N/yr. The average reported state-wide synthetic N sale for the 2005 period is 761 Gg N/yr. These numbers would indicate significant net export of nitrogen fertilizer from the Central Valley to other California counties – on the order of 150 Gg N/yr. Net exports on that order of magnitude seem unlikely. These numbers instead appear to be consistent with the observation that some double-counting of sales occurred for the reported synthetic N fertilizer sales in the 2005 period. Tomich et al. (2016) estimate 2005 statewide synthetic N use to be 590 Gg N/yr. Urban areas and industrial horticulture account for 53 Gg N/yr, chemical production use is 71 Gg N/yr, and California cropland application accounts for 466 Gg N/yr, i.e., 79% of statewide synthetic fertilizer N application is on cropland. Tomich et al. (2016) used mostly the same estimated synthetic N application rates as those used here (without our updates described under Task 5), assuming 3.66 Mha of cropland (including 0.46 Mha of alfalfa). For comparison, the county agricultural commissioners in the Central Valley reported an average cropland area of 2.73 Mha (including 0.32 Mha of alfalfa) for the 2005 period, 75% of the statewide cropland area (see Task 4).

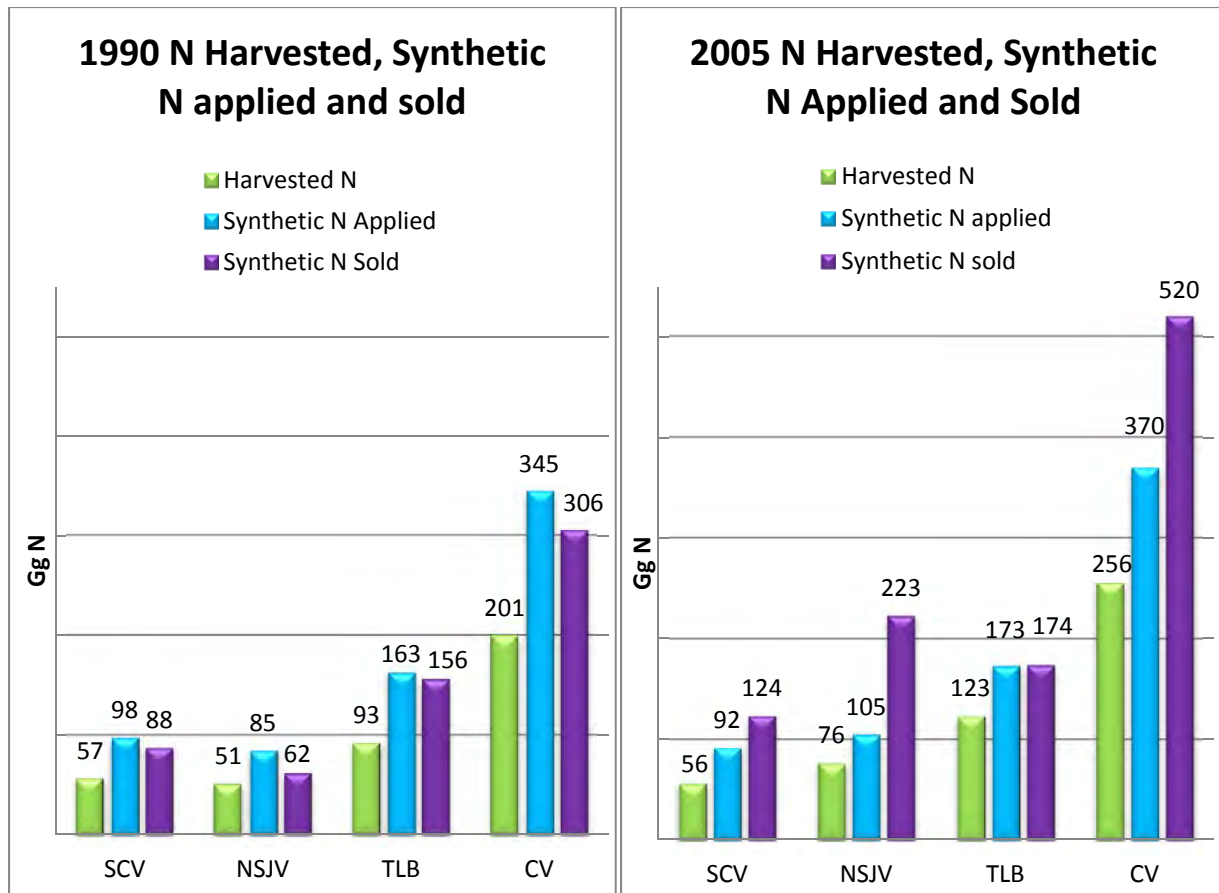


Figure 1.2. Estimated nitrogen harvested based on county agricultural commissioner reports, estimated synthetic N applied based on crop areas reported by county agricultural commissioners and typical N application rates for each of 59 crops, and synthetic nitrogen reported by CDFA as sold for the 1990 (left) and 2005 (right) periods in the respective county regions. The reported sales in the 2005 period are known to be inaccurate due to double reporting in San Joaquin and Colusa counties.

At the county level, the change in reported synthetic N sales (from 1990 to 2005) do not correlate with synthetic N applied, N harvested, or area (Figure 3.2; Table 3.2). This is not restricted to Colusa and San Joaquin counties: Sacramento and Placer counties' production and N applications dropped while reported N sales increased dramatically. Merced, Tehama, Shasta, and Butte counties also report dramatically higher reported N sales in the 2005 period than would be expected given changes in harvested and applied N from 1990 and 2005. However, because some counties are significant importers or exporters of product, the expectation that sales on the county level would match fertilizer needs is unfounded.

The apparent export of nitrogen fertilizer from one county to other counties is concentrated in the NSJV and TLB counties in both periods (Table 1). It would be expected that the port of Stockton would contribute to higher sales than crop N need in the San Joaquin County as is the case in the 1990 period (along with the highly abnormal 2005 period in that county). Similarly, exporting behavior would be expected in counties in which N fertilizer is produced (such as Fresno). However, adjusting 2005 data based on net N-exporting and N-importing behavior is not possible with any degree of certainty. For example, while Madera, Merced, Kern and Tulare counties (among others) reported less N sales than

total synthetic N application for both periods, the majority of the remaining counties do not share a relationship between the two periods. Accounting of cross-county N sales is further complicated by the fact that there are many different individual nitrogen products and formulations sold, each of which may be more or less regionally important and/or with more or less local dealer representation. While one county may import more of one N product, they may export more of another with a different percentage of total N in the formulation. Additionally, fertilizer sales made across state lines (or across counties that are not within the study area) may contribute to differences between sales records and application estimates.

While we are able to provide an explanation for the largest reported nitrogen sales anomalies, no attempt was made to adjust sales figures for the 2005 period (and beyond) or estimate importing and exporting habits of individual counties, due to lack of consistent data and county relationships.

Table 3.2: County percent sales of total state-wide N fertilizer sales, and percent change between the 1990 and 2005 periods for: reported synthetic N sales, cropped area, N harvest, and synthetic N applied. Highlighted in bold are significant county anomalies in reported N sales, given estimated total N harvest and synthetic N applications. Sorted by percent sales in the 1990 period.

County	1990 % sales	2005 % sales	% Change synthetic N sales	% Change area	% Change N harvest	% Change synthetic N applied
Fresno	12.9%	12.8%	3%	0%	21%	-4%
Kern	8.3%	9.6%	20%	0%	35%	11%
Kings	5.5%	6.4%	17%	-2%	27%	4%
San Joaquin	5.5%	30.8%	740%	38%	51%	38%
Colusa	5.4%	6.9%	109%	9%	21%	8%
Yolo	4.5%	2.0%	-34%	-5%	-17%	-15%
Glenn	4.1%	2.4%	-11%	14%	26%	17%
Tulare	4.0%	4.6%	15%	12%	55%	22%
Stanislaus	3.6%	5.6%	63%	13%	52%	25%
Merced	3.5%	4.4%	94%	18%	50%	24%
Madera	3.3%	1.6%	-26%	4%	45%	7%
Butte	3.1%	3.5%	93%	5%	12%	6%
Sutter	3.0%	2.4%	18%	5%	13%	4%
Solano	2.4%	1.4%	-11%	-43%	-53%	-43%
Sacramento	2.3%	3.5%	138%	-8%	-20%	-38%
Yuba	0.7%	0.4%	-12%	9%	0%	9%
Contra Costa	0.6%	0.4%	2%	-28%	10%	-26%
Shasta	0.3%	0.6%	162%	18%	19%	20%
Tehama	0.3%	0.4%	150%	2%	24%	5%
Placer	0.2%	0.3%	135%	-19%	-13%	-26%

Task 4: Compile crop acreage and crop production, historic and current, by county (crop classification II)

4.1 Work Description

Crop area and production statistics were compiled from annual county agricultural commissioner offices for 20 Central Valley Counties in 3 Regions (see Task 1).

We digitized tabularized data, including area and harvest weights, for each of the Central Valley counties, for each of the 5 years representing the 5 periods in this study (1945, 1960, 1975, 1990, 2005-- see Task 1). Thus, a total of 500 annual county reports have been compiled into digital spreadsheets. The crop classification used in these reports have been aligned via cross-walk tables with the crop classification scheme utilized by the DWR (see Task 9), keeping with the latter's spatial resolution of cropping patterns.

Several complications arose in the effort to create a comprehensive database of crops, their land area in each county, and their harvest amount in each county: It is common for the county reports to indicate total area of, for example, corn, while separating the yield associated with that reported total area into corn grain and corn silage. Therefore, subtotaling the two N harvests into a single total that can be compared to the reported total land acreage for "corn" is required for accurate representation of the harvest rate (where "rate" refers to the harvested amount per hectare or per acre). If area is reported separately for two sub-crops, but yield for only one, subtotaling will result in inaccurate representation of total yield, as was found and corrected for in the database. In other cases, many crops may be categorized together in the reports (e.g. miscellaneous field crops), in which area is reported but individual yields are not. In some cases, the area reported in such miscellaneous categories by the Agricultural Commissioners is large, but without corresponding yield data. These data cannot be incorporated into the mass balance work, representing a source of uncertainty.

Area and production results are reported by county and individual crops, but also by county and region in aggregated crop groups:

- Alfalfa and clover (pasture)
- Pasture (other than natural pasture) was considered but has highly unreliable harvest figures. If harvests are reported at all it is often only seed. If there was no harvest reported, then the area was excluded from the dataset, as in all other crops.
- Corn, sorghum, and sudan
- Cotton
- Field crops – safflower, sugar beets, sunflower, dry beans, and miscellaneous field crops
- Grain and Hay – barley, wheat, oats, and miscellaneous grain and hay
- Nuts – almonds, walnuts, and pistachios
- Olives
- Subtropical Tree Fruit – oranges, lemons, grapefruit, avocado, kiwi, pomegranates, and miscellaneous citrus

- Deciduous Tree Fruit – apples, apricots, cherries, peaches, nectarines, pears, plums, prunes, figs and miscellaneous tree fruit
- Grapes – raisin, table and wine grapes
- Vegetables and Berries – artichokes, asparagus, green beans, carrots, celery, lettuce, melons and squash, garlic and onions, green peas, potatoes, sweet potatoes, spinach, processed tomatoes, berries, strawberries, peppers, broccoli, cabbage, cauliflower, Brussels sprouts, and miscellaneous truck crops

4.2 Results and Discussion

In 1945, reported cropland area in the 20 Central Valley counties encompassed 1.7 Mha. Fifteen years later, that number had increased by 44% to nearly 2.5 Mha, close to the modern-day extent of cropland (2.7 Mha). Table 4.1 shows the historical development of crop area for the various crop groups. Area dedicated to woody perennials, which includes grapes, tree fruits, and nuts, has increased substantially and rapidly since 1945, from 291,000 to 851,000 hectares. Nut crops alone account for nearly half of this increase. Rice, vegetables and berries have seen modest increase in production area over the time period. The area in alfalfa, field crops, and grain and hay has seen a general decline since 1975, while corn, sorghum and sudan have fluctuated only slightly since 1960 (despite an increase in dairy operations that typically grow many of these crops as animal forage).

In the 2005 period in the CV, woody perennials (grapes, fruit and nut trees) account for 31% of the cropped area, field crops (including cotton, corn, and other field crops) for 22% of cropped area, grain and hay crops account for 17%, vegetables and berries 10% and rice 8% of the total cropped area. Approximately half the cropped area is located in the 4 TLB counties, while the SJV and SCV regions each account for about 25% of the CV cropping area. The majority of the state's rice production takes place in the SCV, where 35% of the cropped area in the 2005 period was devoted to that crop alone. Table 11.16 (Task 11) includes crop areas by region.

Table 4.1: Total harvested area (ha), by crop group, periods 1945-2005. Each period is the mean of five annual years. Reported pasture area is much higher than that shown here due the lack of reported harvests in much of the area. One hectare is approximately 2.5 acres. Essentially all of the re

Crop Group	1945	1960	1975	1990	2005
Alfalfa	249,547	360,745	296,419	281,463	319,880
Pasture	1,018	17,341	6,038	3,098	930
Corn, Sorghum, Sudan	55,073	206,395	242,069	149,465	256,940
Cotton	145,305	312,253	426,868	484,958	259,669
Field Crops	88,905	206,788	184,291	181,722	81,437
Grain and Hay	650,483	771,576	617,912	400,855	466,463
Rice	96,164	119,101	174,511	171,852	229,803
Nuts	33,870	64,194	151,016	251,717	390,478
Subtropical Tree Fruit	18,694	17,159	54,421	63,116	84,602
Olives	7,064	10,022	11,230	12,102	11,485
Deciduous Tree Fruit	76,488	81,234	94,986	109,919	126,260
Grapes	154,808	140,335	178,741	210,990	237,830
Vegetables and Berries	132,890	162,059	184,135	251,892	265,001
TOTAL	1,710,309	2,469,202	2,622,637	2,573,149	2,730,778

Task 5: Compile crop fertilizer practices recommendations, historic and current

5.1 Work Description

The most recently published nitrogen fertilization practices for the major crops in California (Viers et al. 2012, Rosenstock et al., 2013), are based on the average of UC Davis ARE agricultural cost and return studies and USDA Chemical Usage Reports for the 1990 and 2005 periods, and on a 1973 survey of extension specialists (Rauschkolb & Mikkelsen 1978) for the 1945-1975 periods.

We corrected for a transcription error between the historic rates reported by Rauschkolb & Mikkelsen (1978) and these same rates published in more recent research (Viers et al 2012, Rosenstock et al 2013, Rosenstock et.al. 2014). These changes most significantly affected the historical nut, grape and orange application rates. Additionally, the 1990 and 2005 period rates have also changed slightly from the original database (Viers et al., 2012) to ensure that significant digits used to convert pounds per acre to kilograms per hectare remained consistent for all periods.

To vet published application rates for the 2005 period, we designed a survey of UCCE crop advisors. Of the 56 DWR defined crop/crop-group categories within the Central Valley, and as shown in Table , we chose 22 crops of high nitrogen yields and application totals¹. In the fall of 2013, for each of these 22 crops, we consulted UCCE crop advisors chosen for their expertise on the crop in question in high area locales.

Table 5.1: Crops included in N application rate survey, chosen based on study area N harvest and application totals.

Field and Grain Crops	Woody Perennials	Vegetables
Corn (grain and silage)	Almonds	Garlic and onions
Cotton (lint and seed)	Walnuts	Processing tomatoes
Safflower	Pistachios	Potatoes
Sudan	Prunes	Melons and squash
Barley	Oranges	Lettuce
Wheat	Peaches and nectarines	Broccoli
Oats	Olives	
Rice	Grapes (all)	

We interviewed a total of 33 advisors, many of whom commented on multiple crops, so that an average of 2 advisors were consulted per crop. We requested opinions of published rates, rate range speculations, and commentary on any regional differences in application rates and micro-regional influence on growers' rate decisions (soil texture for example):

¹ Note that two broad DWR crop groups, "Miscellaneous Truck Crops" and "Miscellaneous Grain, Hay, and Straw" have very high total N harvest and total N applied, but being a "miscellaneous" category inclusive of multiple crops, could not be included in the survey.

1. What is the typical or average N rate applied to [CROP] in Central Valley or in the geographic area you are comfortable commenting on? Viers (2012) and Rosenstock (2013) report [RATE] lb N/acre. Does that sound about right for an average value?
2. What is the range of N rates applied in the Central Valley (or area you have experience in)? Consider the “range” to encompass rates that would not be surprising to you – not necessarily the very most extreme values.
3. What are the factors contributing to the range of values, i.e., that will lead growers to use different annual total N applications?
4. Are you aware of any industry surveys of grower N rates applied? Any other surveys or reliable values? Do processors track or have knowledge fertilization rates? What about the commodity board?
5. Can you comment on average yields?
6. How is the crop residue and (for orchards/vineyards) the middles and floor managed? How are prunings and leaf litter managed?
7. Are there experts besides yourself in UC and industry who likely have knowledge of this? Anyone you could recommend that we contact for this survey?

5.2 Results and Discussion

UCCE advisors included in our telephone survey consistently disagreed with the 2005 published nitrogen application rates for 5 crops, including wheat, potatoes, and three tree crops (oranges, walnuts, and almonds). Experts considered the application rates to be too low for each of these crops, with the exception of potatoes. While geography (generally north-south within the valley) was implied in application rate ranges in some crops (e.g. wheat, rice), the specific variety grown, yield goals, and method of irrigation were also considered central to growers’ differing application rate decisions for many crops. We updated our database to use the average of the range estimates provided by extension staff for these 5 crops for both the 1990 and 2005 periods (Table 5.2). The application rates for the other 17 crops subject of the survey were not adjusted as there was no significant disagreement with those rates (as published in Viers et al., 2012, Rosenstock et. al., 2013), although we note an advisor familiar with carrots (a minor crop that was not specifically questioned but that shows an abnormally high efficiency in our analyses) suggested the application rates are typically much lower than our figures, (90-120 lbs/acre, approximately 118 kg/ha compared to 242 kg/ha in our database) and that furthermore the harvest rates were in his experience much higher than reported in the ACRs.

Appendix Table 3 includes application rates for all 56 DWR crops for each period.

Table 5.2: Disputed published nitrogen application rates (Rosenstock et al. 2013) and updated figures based on 2013 UCCE expert opinion.

	Almonds	Walnuts	Oranges	Wheat	Potatoes
Published application rates kg/ha	196	151	104	194	272
Updated application rates kg/ha	246	196	146	231*	202

*average of 3 regional rates: SCV:179, NSJV:235, TLB:280