# Nitrogen Fertilizer Loading to Groundwater in the Central Valley

FREP Project 11-0301


**Project Leaders:**

Thomas Harter
Robert M. Hagan Endowed Chair in Water Management and Policy
Department of Land, Air, and Water Resources
University of California; One Shields Ave.
Davis, CA 95616
(530) 752-2709, ThHarter@ucdavis.edu

Minghua Zhang
Adjunct Professor
Department of Land, Air and Water Resources
University of California; One Shields Ave.
Davis, CA 95616
(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
University of California; One Shields Ave.
Davis, CA 95616
(530) 752-4563, TPTomich@ucdavis.edu.

G. Stuart Pettygrove
Cooperative Extension Soils Specialist Emeritus
Department of Land, Air, and Water Resources
University of California; One Shields Ave.
Davis, CA 95616
(530) 304-1007, GSPettygrove@ucdavis.edu

**Collaborating Personnel:**

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

Giorgos Kourakos
Post-doctoral Fellow
Department of Land, Air and Water Resources, UC Davis

Allan Hollander
Research Analyst
Information Center for the Environment (ICE)
Department of Environmental Science and Policy, UC Davis

Aaron King
Graduate Student Researcher
Civil and Environmental Engineering
Center for Watershed Sciences, UC Davis

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

Todd Rosenstock
Post-doctoral Fellow
World Agroforestry Centre (ICRAF)
Nairobi, Kenya

# INTRODUCTION

Nitrate is the most common pollutant found in aquifers of the Central Valley, California. This project will provide the first long-term assessment of past and current nitrate loading to groundwater on irrigated lands across the entire Central Valley of California; assess the long-term implications for groundwater quality in the Central Valley (Sacramento Valley, San Joaquin Valley, and Tulare Lake Basin); and provide a planning tool to better understand local and regional groundwater quality response to specific best management practices and policy/regulatory actions. This assessment will contribute significantly to the scientific framework surrounding the implementation of the salt and nutrient basin plan amendment and of the "irrigated lands regulatory program". The core of this project is an extensive field-scale assessment of the historic and current (1940-2010) crop- and irrigation- method specific nitrogen leaching from irrigated lands in the Central Valley. The primary tool for this assessment is a field-scale nitrogen mass balance. Groundwater loading of nitrogen will be determined, in principle, as the closure term to the mass balance, that is, groundwater loading will be assumed to be the difference between field nitrogen applications (from atmospheric, fertilizer, animal, and human sources) and field nitrogen removal (harvest removal, atmospheric losses).

# 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 NPS assessment tool (currently in development) 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-geared magazines, and in peer-reviewed scientific journals.

# DESCRIPTION

For the first year of this project, the goals included development of 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), and work on the groundwater loading model. Data collection was extensive, including land N applications (from atmospheric, fertilizer, animal, and human sources) and field nitrogen removal (harvest removal, atmospheric losses, surface runoff).

The first 6 months of the second year have focused primarily on the analysis of the cropping data, that is, the annual fluxes into and out of the rootzone of individual fields. This is arguably the largest component of the overall nitrogen flux, as Harter *et al.* (2012) found that nearly 95% of groundwater nitrate in the Tulare Lake Basin and Salinas Valley was directly attributable to croplands, with approximately one half of this nitrogen coming from synthetic fertilizer and another third attributable to land-applied manure used as a fertilizer source or soil amendment. Crop area and production data have been used to determine the median period harvest removal rates of nitrogen by county, by sub-basin, and for the entire Central Valley, as well as by crop. Published N fertilization rates (Viers et al. 2012, Rosenstock et al. 2013) for each period were then used to estimate total synthetic N applications based on reported crop area.

We have begun surveying extension specialists throughout the Valley, regarding their opinion of the published application rates for the 2005 period, for 20 of the most prominent crop species. We are additionally asking for estimated application rate ranges and reasons for their estimates, including varietal and regional differences. Should these experts agree that current fertilization rates for any one crop differ from published data, the application totals for the 2005 period will be adjusted.

Fertilizer sales data were also examined and a preliminary analysis was performed for the 1990 and 2005 periods. Comparison of recorded synthetic sales data with the preliminary application estimates, along with discussions with California fertilizer sales industry representatives, has provided insight into some of the apparent errors in the sales data.

The second half of the project (through 12/2014) will be devoted to the remaining mass balance component analysis and calculation of the nitrogen flux within the Central Valley, to determine the leachable fraction. Kourakos et al. (2012) developed a groundwater nitrate transport modeling tool that 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. Using this software, we are currently developing flow and transport models for the Central Valley. We will apply the nitrogen loading rates obtained from the mass balance assessment and from the literature review with this nitrate transport modeling tool to the Central Valley. The model results will provide long-term (1940 – 2100) statistical predictions of groundwater nitrate in domestic wells, irrigation wells, and municipal wells in several large project areas in the Central Valley. This will allow us to track nitrate travel paths and travel times from recharge zones to the groundwater capture in domestic wells, irrigation wells, and municipal wells. In the final project step, data developed will be published in a web-accessible GIS database.

## RESULTS AND DISCUSSION OF PRELIMINARY FINDINGS

The following discussion is focused on croplands, the largest component of the nitrogen mass balance in the Central Valley. Total harvested nitrogen, total synthetic N applications, and total reported fertilizer N sales are compared. Note that alfalfa and pasture have been excluded from these preliminary analyses, as both typically receive no to very little synthetic N and exceptional quantities of nitrogen are harvested with alfalfa, while pasture "harvest" is often not reported.

**Harvested Nitrogen.** A unified crop classification scheme was developed to rectify crop and crop group naming and categorization differences between the crop data sources, including the Department of Water Resources, the USDA Crop Nutrient Tool, the USDA National Agricultural Statistics Service, and the Agricultural Commissioner Reports. The crop area and yield data were digitized from County Agricultural Commissioner Reports (ACRs) and the yields translated into total nitrogen removal using individual crop nitrogen and moisture percentages as estimated by the USDA Crop Nutrient Tool (http://plants.usda.gov/npk/main).

Harvest rates were then determined separately for each county, each sub-basin (Sacramento, North San Joaquin, Tulare Lake Basin), and the Central Valley as a whole, for each of 5 periods (1945, 1960, 1975, 1990, 2005). To smooth year-to-year fluctuations, median values of the 5 years surrounding each period was used (i.e. the value reported for the 2005 period is the median for the years 2003-2007). Individual crop N removals were also analyzed. Among the sub-basins, overall crop yield is highest in the Tulare Lake Basin counties, followed by the North San Joaquin and the Sacramento Valley. From the 1990 to 2005 period, the amount of N in harvested crops in the Central Valley increased by 20% (Figure 1, red bars). While the total cropped area in the CV has remained relatively stable since 1975, changes in the distribution of individual crop areas (e.g. a general decline in field crops and increase in nuts and other permanent crops) has been responsible for the increases in the total nitrogen harvested and applied. .

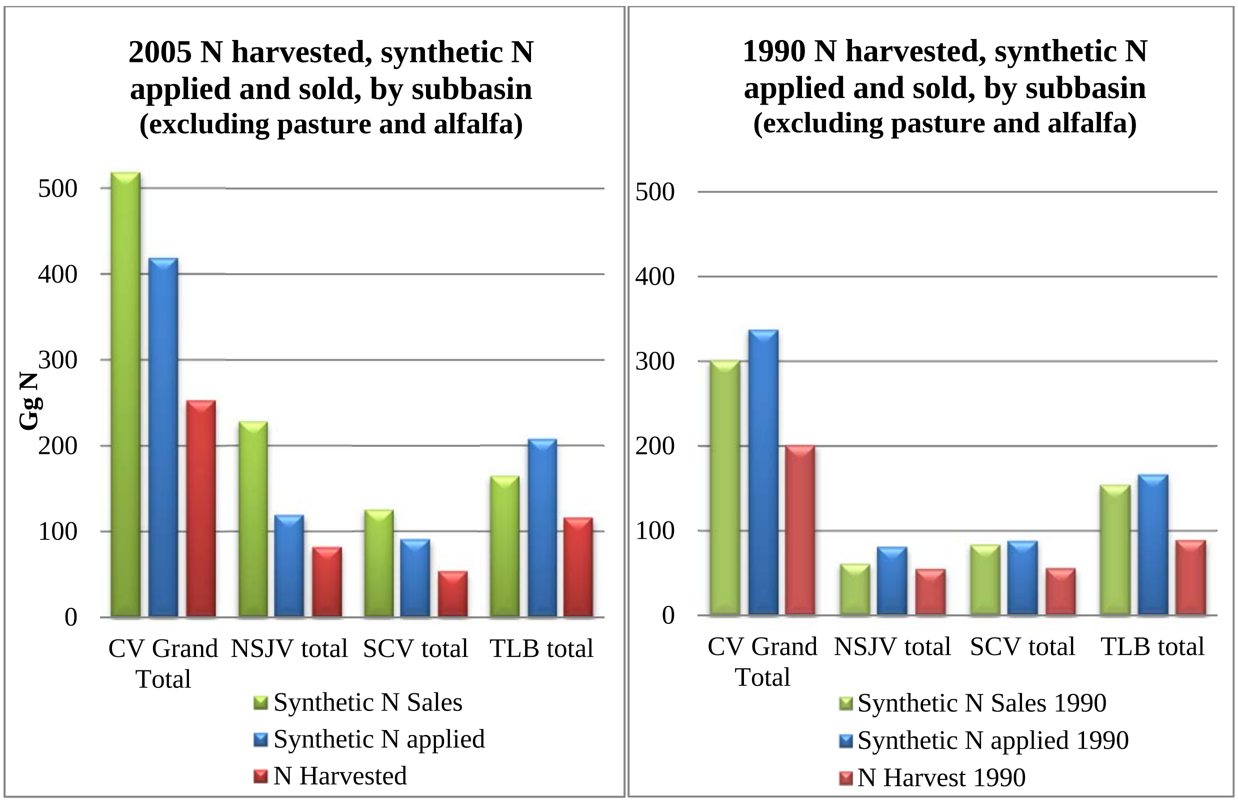


**Figure 1. 2005 and 1990 period median reported synthetic N sales, estimated synthetic N applications and estimated N harvest totals for each sub-basin and for the entire Central Valley. The reported sales in the 2005 period are known to be inaccurate due especially to double reporting of ammonia products in San Joaquin and Colusa counties, affecting the NSJV and SCV sales totals. Both harvested N and applied synthetic N increased by 20% from the 1990 to 2005 period.**

**Estimated Synthetic N Application. Published synthetic N application rates for the 1990 and 2005 period (Viers et al. 2012, Rosenstock et al. 2013) are based on averages of UC crop cost and return studies and USDA grower surveys. The published rates were applied to the median period area of each individual crop to estimate the total synthetic N application in each period. Similar to the estimated harvested N quantities, estimated application of synthetic fertilizer also rose 20% between 1990 and 2005 (Figure 1, blue bars). Again, our final report may include minor adjustments to some of the current N application rates, as we are currently in the process of vetting published rates for key crops by surveying experts familiar with fertilization practices and harvest rates in the Central Valley. Note that the total nitrogen**

**harvest removal is not directly comparable to the synthetic N application estimates, as many forage crops receive substantial amounts of N from manure applications. In crops that typically receive little or no manure, the nitrogen use efficiency (NUE, defined as total N harvested divided by N applied, expressed as a percentage) ranges from 21% in deciduous tree fruit to 75% in rice for the 2005 period (**

Table 1). Grapes have a relatively low NUE, but their typical application rate is low relative to other crops in the Central Valley. Hence, the absolute (as opposed to relative) amount of N loss in vineyards tends to be relatively lower.

**Table 1. Total synthetic N applied and N harvested within the Central Valley in the 2005 period for crop groups that do not receive manure. The partial nutrient balance calculation indicates the nitrogen use efficiency across the entire crop group. 1 gigagram = 1,000 metric tons = 1,103 short tons.**

| Crop Group | Synthetic N Applied Gg N | N Harvest Gg N | NUE (harvest/ applied) |
|---:|:---:|:---:|:---:|
| Subtropical Tree Fruit | 10 | 5 | 53% |
| Deciduous Tree Fruit | 14 | 3 | 21% |
| Nuts | 70 | 46 | 65% |
| Rice | 32 | 24 | 75% |
| Vegetables and Berries | 53 | 28 | 52% |
| Grapes | 9 | 4 | 47% |

**Reported Fertilizer Sales.** We used California Department of Food and Agriculture reports of fertilizer nitrogen sales for the years 1988-2011, which include figures for individual counties. A significant increase in reported sales occurred in 2002. Reported sales remained relatively high beyond the apparent jump, and this is not mirrored by a jump in harvested nitrogen statewide (Figure 3). The increase in reported sales is concentrated in San Joaquin County (Table 2). Interestingly, while 2002 marks the beginning of the increase in the average tonnage sold statewide, the percentage of statewide sales being recorded in San Joaquin county began its steep ascent beginning in 1998 (Figure 3).

The bulk of the 2002 sales increases are attributable specifically to sales of anhydrous ammonia in San Joaquin County, and to a lesser degree, aqua ammonia sales in Colusa County. In 2002, 97% of the statewide anhydrous ammonia sales were recorded as taking 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 are reported as taking place in San Joaquin County, accounting for over 35% of statewide total N sales (Figure 3).

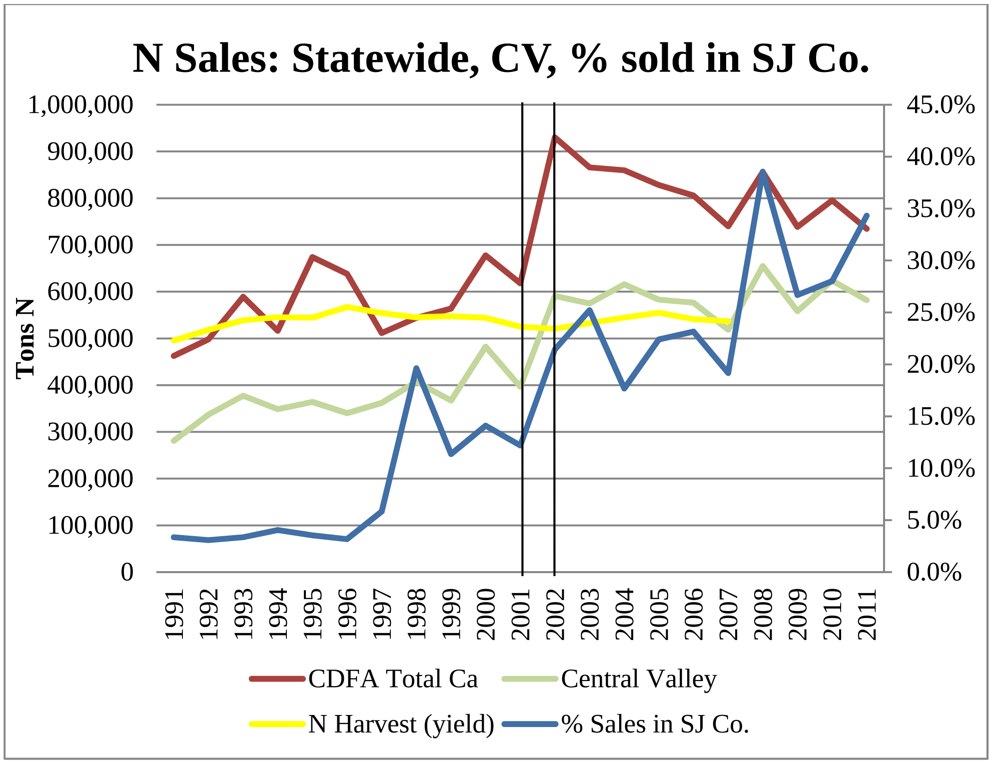


**Figure 2. Statewide and Central Valley N sales as reported in CDFA tonnage reports. Statewide production (N Harvest) does not show a similar increase, highlighting a sales reporting anomaly. The CV accounts for ~65-75% of statewide sales while the sales in San Joaquin County have been increasingly and disproportionately high, accounting for up to 38% of statewide sales.**

While fertilizer sales are required to be reported by the dealer who sells to the end-user only, products may change hands several times before being purchased by the end-user. A possible explanation for over-reporting could occur if a company mistakenly 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 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, it is rare for the relationship between an individual state's N fertilizer sales data and crop acreage figures to differ so dramatically from year to year. While transcription errors and even unit conversion errors may contribute to reported sales anomalies, we conclude that double reporting is the main factor in the inaccurate sales data discussed here.

Sales and synthetic N application are thus not comparable for the 2005 period. The 1990 period shows lower harvests, and accordingly, lower application estimates and sales records (Figure 1). Estimating more realistic sales figures for the 2005 period based on the relationship between application and harvest estimates in the 1990 period, is not possible with any reasonable certainty. While both the estimated application and N harvest increased by 20% from 1990 to 2005, reported sales are 10% less than estimated N application rates in the 1990 period. To attempt to adjust 2005 sales figures on this relationship (i.e. lower sales than estimated application rates) would not be reasonable.

Attempting to distinguish between importing and exporting counties, which may have improved adjustments to 2005 sales data, is also difficult to perform with any certainty. When looking at the county by county difference between sales and estimated synthetic application rates for both periods, the interpretation becomes more complicated. While in both periods Madera, Merced, Kern and Tulare counties reported less N sales than what we estimated for total synthetic N application, the majority of the remaining counties do not share a relationship between the two periods. Cross-county N sales accounting 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. Thus, while we able to provide a relatively thorough explanation for reported nitrogen sales anomalies, no attempt was made to adjust sales figures.

**Table 2. Central Valley county N 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. (Note: 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* | 18,207 | **removed 1995 outlier of 43,000 tons* |
| **Colusa** | **22,932** | **38,549*** | **large increase in aqua ammonia* |
| Contra Costa | 2,262 | 2,443 | |
| Fresno | 64,784 | 67,342 | |
| Glenn | 13,545 | 15,019 | |
| Kern | 44,304 | 50,509 | |
| Kings | 28,091 | 33,168* | **spike in 2006* |
| Madera | 10,148 | 9,413 | |
| Merced | 17,130 | 23,217 | |
| Placer | 850 | 1,363 | |
| Sacramento | 13,525 | 18,529 | |
| **San Joaquin** | **44,265** | **208,549*** | **large increase in anhydrous ammonia* |
| Shasta | 1,566 | 4,254* | **removed 2002 outlier of 15,000 tons* |
| Solano | 9,142 | 9,633 | |
| **Stanislaus** | **18,867*** | **28,687** | **removed 1995 outlier of 66,000 tons* |
| Sutter | 17,482 | 14,397 | |
| Tehama | 1,345 | 2,113 | |
| Tulare | 24,589 | 26,808 | |
| Yolo | 16,472 | 14,729 | |
| Yuba | 3,262 | 2,781 | |
| **CV Co. Total** | **369,333** | **587,802** | *Above outliers excluded* |
| **California Total** | **572,042** | **815,416** | *Outliers and county 'unknown' included* |

## LITERATURE CITED

Harter, T., Lund, J.R., Darby, J., Fogg, G.E., Howitt, R., Jessoe, K., Pettygrove, G.S., Quinn, J.F., Viers, J.H., Boyle, D.B., Canada, H.E., DeLaMora, N., Dzurella, K.N., Fryjoff-Hung, A., Hollander, A.D., Honeycutt, K.L., Jenkins, M.W., Jensen, V.B., King, A.M., Kourakos, G., Liptzin, D., Lopez, E.M., Mayzelle, M.M., McNally, A., Medellin-Azuara, J. & Rosenstock, T.S. (2012) Addressing Nitrate in California's Drinking Water with a Focus on Tulare Lake Basin and Salinas Valley Groundwater. Center for Watershed Sciences, University of California, Davis, http://groundwaternitrate.ucdavis.edu.

Kourakos, G., Klein, F., Cortis, A. & Harter, T. (2012) A groundwater nonpoint source pollution modeling framework to evaluate long-term dynamics of pollutant exceedance probabilities in wells and other discharge locations. Water Resources Research, 48.

Rosenstock, T.S., Liptzin, D., Six, J. & Tomich, T.P. (2013) Nitrogen fertilizer use in California: Assessing the data, trends and a way forward. California Agriculture, 67, 68–79.

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.