Dairies and Other Sources of Nitrate Loading to Groundwater

Task Report 6

Project

"Long Term Risk of Groundwater and Drinking Water Degradation from Dairies and Other Nonpoint Sources in the San Joaquin Valley"

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Abstract

Nitrate loading to groundwater in the Tulare Lake Basin and San Joaquin Valley is widespread and chronic, and is overwhelmingly the result of crop and animal agricultural activities. Urban wastewater, septic systems, and other sources may have significant localized impact. Due to long transit times, the impact on groundwater resources is a legacy for years and decades to come.

The application of synthetic fertilizer and manure to agricultural crops, primarily under irrigated conditions, has resulted in high crop yields and the large-scale production of affordable food for the world's growing population. It has also promoted California to the top of global crop production. The Tulare Lake Basin and San Joaquin Valley have also benefited from animal agriculture, where dairy commodities are the top economic producer. These agricultural operations, however, have not been without costs to the environment. A significant fraction of nitrogen applied in food production worldwide is in excess of crop needs, resulting in nitrate leaching to groundwater, eutrophication of aquatic ecosystems via surface run off, and air pollution from toxic emissions of ammonia and ozone-depleting greenhouse gases. Each of these negative environmental outcomes has the potential to impart significant impact on biogeochemical processes, ecosystem services, and human health. Current human activities cannot be sustained without commensurate and perhaps permanent degradation of vital natural resources, most specifically drinking water from groundwater aquifers. There are cumulative and long-term societal, environmental, and economic costs to our excess utilization of industrially-fixed nitrogen now used in cropland agriculture. Understanding these consequences requires a better scientific understanding of nitrate sources.

Using a mass balance approach, this task report documents the extent and magnitude of nitrogen loading from anthropogenic and natural sources to groundwater in the Tulare Lake Basin with a focus on dairies, the main form of animal farming in the Central Valley. Our approach considers crop demand, fertilization, harvest, and volatilization in cropland agriculture, in addition to accounting for animal agriculture and localized sources, for the period of study (~1940–present). Cropland agriculture is the primary vehicle for nitrate loading to groundwater. Already widespread when agrichemicals first arrived in large quantities (ca. 1940), cropland areas further expanded into the late 1960s and crops diversified greatly over the past 60 years, with specialty crops that have higher nitrogen demands becoming of increasing importance. Animal agriculture, and particularly dairy production, is a dominant and widespread source of nitrogen in the environment. With a sustained, exponential increase in nitrogen output over the past sixty years, dairies currently supply about one-third of all nitrogen applied to cropland. Today's nitrogen loading will not materialize as contaminated groundwater for years to decades to come, and the current average loading rate is three to five times greater than the recognized maximum contaminant levels for drinking water in California. As the sources and fates of nitrogen are transient over space and time, it will require concerted action across many agroeconomic sectors to minimize the long-term degradation of groundwater aquifers.

While cropland and animal agriculture are the principal sources of nitrogen loading in the study area, other sources also require attention. Foremost is the role that wastewater treatment plants and food processing facilities play in distributing excess solids and effluent. We have shown that their contributions on a localized basis can be quite considerable. Therefore, any reduction measures for this source will likely be directed towards protecting local drinking water supplies rather than regional loading reduction. Further, we have documented that there are important seasonal differences in discharge and land application management. This variation also exists in agricultural settings, with dominant phases of application and irrigation. Thus, it is important to recognize that localized drinking water supplies may be affected on a seasonal basis.

We have documented that on a regional scale, groundwater nitrogen loading from sewers is negligible in comparison to loading from fertilizers. However, at the local level, sewer leakage can be a significant source of nitrate contamination. Localized sources of raw sewage near domestic or public wells have the potential to detrimentally affect public health. This localized threat exists regardless of the negligible regional contribution of sewers to groundwater nitrogen. Similarly, we have investigated the local influence of septic systems on groundwater nitrogen and have found that contamination of domestic, unregulated drinking water wells may be a significant problem in peri-urban areas surrounding cities, or in areas of relatively high rural household density. While septic system contributions to regional nitrogen loading are minimal, it is still of local importance as a driver of nitrate contamination in drinking water. Other locally problematic sources of nitrogen include urban sources such as overfertilization of lawns and other ornamental landscapes.

Most nitrate is transported from sources to groundwater via soil percolation and recharge. But dry wells, abandonded 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. We therefore consider these here as separate sources. Locally, significant nitrate contamination may result from these conduits.

Our mass balance approach to understanding the spatial and temporal dimensions of nitrogen loading is informed by observation and based on physical principles. However, it is made with inherent uncertainty. There are considerable information and data gaps in all phases of our analyses. There are few empirical studies specific to conditions found in the study area, especially with respect to agronomic practice, that document the source, transition, and fate of nitrogen in agroecosystems. Further, there are few if any data that provide for long-term composition in a manner that can explicitly quantify what was occurring where, and when. While a synoptic assessment such as ours is difficult, and is made with varying degrees of uncertainty, it does not invalidate our results. Rather, it emphasizes that despite limited information for given aspects of our study, our results, made with conservative assumptions, indicate that the magnitude of the problem far exceeds those degrees of uncertainty. Improvements to subsequent studies should focus on expanding the breadth and resolution of information necessary to reduce uncertainties, rather than in the methods themselves. These findings also suggest the need to develop and implement a programmatic monitoring and evaluation mechanism to capture, collect, and

analyze information critical to understanding the source, extent, and magnitude of nitrate loading in California. California's long term prospects for social, environmental, and economic sustainability may depend upon it.

Further information (publications, related reports, multi-media materials) is available at http://groundwater.ucdavis.edu.

1. Nitrogen Loading from Dairies, Feedlots, and other Animal Farming Operations

1.1 Introduction to N Loading from Dairies

The Tulare Lake Basin (TLB) portion of our study area is home to over half of California's dairy herd, housed predominantly in family-owned and operated confined animal farming operations. The TLB also houses one large beef cattle facility (Harris Ranch). This section focuses on dairy operations as the major source of animal manure nitrogen in the project area. Beef lots are also considered. Poultry and swine manure production is discussed in Section 1.9.

Table 1. Historic number of milk cows, not including dry cows (*from:* National Agricultural Statistics Service). The number of adult dairy cows (lactating and dry) is approximately 20% larger than the number of milk cows.

	1950	1992	2002	2007
Fresno Co.	34,695	72,350	90,550	114,768
Kings Co.	24,012	86,235	138,292	163,600
Tulare Co.	38,981	215,480	412,462	474,497
Kern Co.	9,962	34,566	74,708	124,756
TLB	**107,650**	**408,631**	**716,012**	**877,621**
Monterey Co. (SV)	**9,953**	**4,323**	**1,606**	**2,143**

The TLB is home to approximately 640 dairies with 1 million milking cows (lactating and dry) and over one million support cattle (calves, heifers). Over 10% of the national milk production occurs in the study area. In 2007, the Central Valley (Region 5) Regional Water Quality Control Board (RB5) adopted the Waste Discharge Requirements General Order No. R5-2007-0035[1] ("Dairy General Order") (Central Valley Regional Water Quality Control Board 2007), which regulates waste discharges from dairy operations. The Dairy General Order requires annual reporting as part of each operation's waste and nutrient management planning. For 2007, dairy operators reported 1,020,000 mature dairy cows in the four TLB counties. For the same four counties, the National Agricultural Statistics Service (NASS) reported 877,621 milk cows (about 1, 050,000 adult cows, assuming a ten month lactation period and a two month dry period) in its 2007 census and 716,612 milk cows in its 2002 census. The number of milk cows in 2007 was more than twice the herd size of 408,631 milk cows reported in the 1990 agricultural census (NASS, 1990). It is an eight-fold increase in herd-size since 1950, at which time the agricultural census reported 107,650 milk cows for the four TLB counties.

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[1] http://www.swrcb.ca.gov/rwqcb5/board_decisions/adopted_orders/general_orders/r5-2007-0035.pdf

In contrast, Monterey County (of which the Salinas Valley is a part), housed as many as 23,000 dairy cows in 1945 according to ACR data, but as few as 6,000 adult dairy cows in 1992 and less than 1,500 adult dairy cows in 2007. NASS reports 9,953 milk cows in 1950, 2,143 milk cows in 2007, and 24,686 beef cows in 2007. Today, the Salinas Valley itself houses only one significant cattle facility at the valley margin near Gonzales (Gallo Cattle Farm). The remainder of this chapter will therefore focus on the Tulare Lake Basin.

A typical dairy in the Central Valley consists of many different operational units, all of which can potentially become sources of groundwater nitrate:

- owner and worker housing,
- septic leach field(s),
- shops and equipment storage area,
- animal housing and exercise areas (freestalls, corrals) with
  - a central milking barn,
  - heifer corrals,
  - calf housing area,
  - feed storage area,
- solids manure storage areas,
- one or several liquid manure storage lagoon and settling basins,
- forage and other crop fields.

By far the largest land area of Central Valley dairies are their irrigated crop fields (mostly forage crops), which typically receive liquid manure and solid manure applications from the dairy as part of their nutrient management program. Dairy General Order reports provided by dairy owners to RB5 in 2007 totaled 130,000 ha (315,000 acres) of land application area (based on Existing Conditions Reports for 2007). We also mapped assessor's parcel numbers provided under the Dairy Order to RB5 (Fresno Office). Spatial analysis of these maps yield similar, albeit slightly smaller total areas. More importantly, they provide an impressive comparison of the size of cropland receiving manure applications versus the total acreage of the facilities themselves: dairies reported parcels with 109,500 ha (270,000 acres) of cropland and 11,900 ha (29,500 acres) of facility areas (corrals, milking barns, storage areas, and lagoons).

In the TLB, dairies operate either as a freestall operation, as a drylot operation, or as a combination of both. In a freestall dairy operation, adult animals are housed in covered freestalls that have access to exercise yards, which are here referred to as corrals. Freestalls are long rows of individual stalls bordered on the front side by a feed bunk and on the back side by a concrete-paved flush- and travel-lane used for both, manure collection and as access pathway for the animals to their stalls. The stalls themselves are unpaved and generally bedded with dry manure solids or other dry materials (e.g.,

almond hulls) that are refreshed frequently to keep the freestalls clean and comfortable for the animals. Feed rations are distributed into feed bunks along the front of the freestalls. Two or three times daily, milking cows walk to a centrally located milking barn. The entire complex of freestall, flush-lane, and feed bunk is roof-covered to protect from sun and rain.

Animal manure (from liquid and solid excretions) accumulates primarily in the flush-lane that passes behind an individual animal's bedded stall. Flush-lanes are flushed two- to five times daily with recycled water from the liquid manure storage lagoon. Flush lanes are also used to traffic animals to and from the milking barn. Flush water is collected, passes through a mechanical solid separation system, and the liquid portion (with suspended solids) is stored in a manure storage lagoon. A number of different collection and solid separation systems are available and in use. Systems differ in their effectiveness of separating coarse solids and fine solids from the liquid fraction. Separated solids are generally stored in stockpiles or windrows for drying and storage. Dried, separated solids are reused for bedding in freestalls and corrals, as soil amendment in crop fields, or hauled off-property as soil amendment. Liquid manure is stored in manure storage lagoons ("lagoons") and recycled for flushing. All liquid manure is ultimately blended with irrigation water and used as fertilizer in crop fields associated with the dairy.

Drylots are earthen-surface exercise yards without flooring or plant cover, and usually without any roofing. So-called drylot dairies mostly lack flushlanes for the collection of manure, except in the milking barn area and its associated travel lanes. Animal excrements collect in the corral area, which is regularly scraped. Scraped solids are dried, sometimes (partially) composted and then either reused as bedding in the freestalls and corrals, used as soil amendment in fields, or sold off-dairy as soil amendment. The total roofed area (which may affect the amount of runoff diverted to a lagoon) in a drylot dairy tends to be less than in a freestall dairy.

Dairies also collect surface runoff from animal housing areas. Stormwater runoff from roof tops is often collected separately and diverted to stormwater drains. Any runoff that has come in contact with animal waste must be collected in the liquid manure storage lagoon.

Of the various management units within a dairy, the three major areas for potential groundwater nitrate loading are the corrals (uncovered animal holding areas), the liquid manure storage lagoons ("lagoons"), and the crop fields receiving either liquid or solid manure applications or both (manured cropland). Septic leach fields as a source of groundwater nitrate are reviewed in Section 6.4. Beef cattle feedlots, as a source of groundwater nitrate, are considered here to function similarly to dairy corrals, although the animal stocking rate may be significantly higher.

The following sections first provide a review of literature and field data of nitrate loading to groundwater, then describe the specific methods applied in this report to estimate groundwater nitrate loading from animal farming operations in the TLB. Data are provided and results presented and discussed. Separate methods were applied for corrals, lagoons, and manure irrigated croplands, as described below. Briefly, groundwater nitrate loading from corrals and lagoons is based on recharge rates and nitrate concentrations found in previous field studies, and based on the actual size of a corral

or lagoon. Groundwater nitrate loading on manured cropland, as on other cropland, is estimated by considering all nitrogen fluxes to and from an individual field, which are crop type dependent and include fertilizer and manure nitrogen applications, and harvest removal of nitrogen, among others. Groundwater nitrate loading on cropland is then estimated as the difference between nitrogen inputs to and outputs from an agricultural field (mass balance approach) rather than based on literature values.

A note on measurement units: Unless noted otherwise, this section (and others in this report) reports nitrate concentrations in water in mg nitrate (nitrate) per liter [mg/l], a unit for which the maximum contaminant level (MCL) in drinking water is 45 mg/L. However, in the agricultural context, fertilizer and manure nitrogen is applied in various forms including organic nitrogen (N-org), ammonium nitrogen (NH_4-N), and nitrate nitrogen (nitrate-N). For agronomic calculations (application rates, harvest rates, etc.), nitrogen mass flux of any of these forms is typically reported in mass of nitrogen (N), rather than in the mass of the specific nitrogen-form (organic N, ammonium, or nitrate), to allow for direct comparisons of these fluxes. When convenient, we therefore will sometimes be reporting nitrate concentrations in mg nitrate-N per liter, denoted by (mg N/L). In that case, the MCL in drinking water is 10 mg N/L (i.e. as nitrate-N), which is equivalent to 45 mg/L (as nitrate).

A note on unit conversions: Original measurements and estimates are all made in scientific units using the metric system and at least five significant digits. The scientific units are here reported to one, two, three, or more significant digits depending on the approximate accuracy of the estimate or measurement. Conversions to American units are sometimes made from the original number (with a large number of significant digits) and sometimes reflect a direct conversion of the number reported here (with limited number of significant digits). Regardless, we always report numbers of the American unit system with the same number of significant digits as the numbers reported in the scientific units.

1.2 Review of N Loading Rates from Dairy Corrals

The largest number of animal feedlots and corrals in the Tulare Lake Basin is associated with dairy facilities. In addition, there are several mostly small feedlots throughout the TLB and one large feedlot (Harris Ranch), and only a single cattle farm in the Salinas Valley. We mapped the total area of open dairy corrals in the Tulare Lake Basin in 2010 using a 2007 list of dairy addresses provided by the Regional Water Quality Control Board, Department of Water Resources year 2000, 2003, 1999, and 2006 land use surveys[2] for Fresno, Kings, Tulare, and Kern County, respectively, and 2009 aerial photography provided by the Department of Conservation Farmland Mapping and Monitoring Program[3] (FMMP) as the basis for digitization of the actual open corral area in dairies.

Feedlots and corrals are characteristically an un-vegetated, bare soil area where cattle spend all (dry-lot dairy) or part (freestall dairy) of their time. Animal stocking densities vary. Within the Tulare Lake Basin, our digitized maps of open dairy corrals on approximately 640 dairies show that these

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[2] http://www.water.ca.gov/landwateruse/lusrvymain.cfm
[3] http://www.conservation.ca.gov/dlrp/fmmp/Pages/Index.aspx

corrals encompass 8,316 ha (20,548 acres). Approximately half of the corral acreage in the TLB is concentrated in the Tulare County portion of the study area. The average stocking rate is on the order of 123 adult animals per ha (50 adult animals per acre) (81 m^2 per adult animal). The same space is shared with an additional 1.4 support stock animals (calves and heifers) per adult cow (according to EPA data, see below). In addition, two relatively large beef cattle feedlots stand out, with exceptionally higher than average stocking rates. Harris Ranch, located on the Westside of the TLB, houses approximately 100,000 head of cattle on over 320 ha [800 acres]. The Joseph Gallo Cattle Company Feedlot, located at the edge of Salinas Valley east of Gonzales, houses up to 30,000 head of cattle on approximately 40 ha (100 acres, stocking rate of at least 13 m^2/head or 310 hd/ac). Together, these two feedlots average 300 to 800 head of cattle per hectare (120–320 head of cattle per acre, stocking rate of 12.5–33 m^2/head):

California regulations require that corrals have sufficient slope for rapid drainage during rainstorms. Ponding (storage of water from corrals) beyond 72 hours after the last rainfall is illegal. According to the 2007 Dairy General Order, B.6, p.16:

> "The milk parlor, animal confinement area (including corrals), and manure and feed storage areas shall be designed and maintained to convey all water that has contacted animal wastes or feed to the wastewater retention system and to minimize standing water as of 72 hours after the last rainfall and the infiltration of water into the underlying soils."

Typically, the corral surface soil consists of three distinct layers: a manure pack, a compacted black interface layer, and the underlying original soil (Mielke et al., 1974, Miller et al., 2008). The manure pack predominantly consists of fresh and aged manure, sometimes mixed with bedding material (in many cases dried, aged manure reapplied to the corral surface). The hoof action and weight of the animals lead to mixing of manure with the underlying original soil, and to the subsequent compaction of this mixing layer. The black compaction layer is typically from 5 to 15 cm thick (2-6 in). The hydraulic conductivity of this layer is much lower than that of the natural, underlying soil. This is due to:

1. compaction and mixture of manure with native soil materials; and
2. high microbial content of this interface layer, which forms biofilms that further impede water flow (Mielke et al., 1974).

For example, Miller et al. (2008) found in a study conducted in southern Alberta, Canada, that the hydraulic conductivity of corral floors is similar for medium-fine textured soils (33%–39% clay content) and for medium-coarse textured soils (12% clay content). This comes despite the fact that these are two hydraulically very different soil parent materials. Saturated hydraulic conductivities, measured in field infiltrometer experiments, ranged from 4 to 93 x 10^{-7} m/s (0.1 – 2.6 ft/d) (ibid.). Analysis of the chloride profile below three feedlot pen surfaces (aged 4, 5, and 53 years) revealed elevated chloride (4,000 ppm) only to 0.7 m (2.3 ft) depth (200 ppm below that depth). Average annual rainfall at this study site is 378 mm (15 in). A similar study at four older beef feedlots in central and northeastern Kansas (21 to 50 years of continuous operation) also used chloride to determine the leaching depth below the corral surfaces (Vaillant et al., 2009). Long-term average annual rainfall at these sites ranges from 630 mm to

880 mm (25 – 35 in), three times higher than in the Tulare Lake Basin (about 250 mm or 10 in). Underlying soil textures range from silty clay loam to loamy fine sand. Cattle stocking densities varied from 17 to 29 m^2/head (140-240 heads/ac). Nitrogen deposition rates in the pen surfaces were estimated to range from 23,000 to 42,000 kg N/ha/year (21,000 – 37,000 lbs/ac/yr). The annual water equivalent in urine and manure at these sites was estimated to range from 1,100 mm to 1,460 mm (43-57 in). Following the results of Kissinger et al. (2007), 13% of this nitrogen was estimated to be available for leaching. However, the total amount of nitrogen found in the soil profile was only one-fifth of the estimated leachable nitrogen during the quarter to half century of feedlot operation (1,000 kg N/ha/yr [900 lbs/ac/yr] or about 3% of the excreted N). Ammonium and chloride concentrations, while highly elevated near the surface, reached background levels at depths of 1 m to 2 m (3–7 ft) below the corral surface. Nitrate concentrations in the soil profiles were also below background levels at depths of 2 m (7 ft) and lower with indication of anoxic conditions at some sites. The results suggested no significant leaching of nitrate to below 3 m [10 ft] from these four sites. Other researchers come to varied conclusions on the leaching potential of feedlot pens and corrals – some studies indicate leaching while others indicate no leaching (reviewed in Miller et al. 2008, Vaillant et al., 2009).

Harter et al. (2002) reported data from a monitoring well network across five dairies in the dairy region west of Modesto and Turlock (Stanislaus and Merced County), where groundwater is shallow (depth to water table less than 4.5 m (15 ft)) and where soils are well-drained and relatively coarse-textured. In that study, nitrate concentrations in monitoring wells downgradient of corrals averaged 293 mg/L (as nitrate) with a coefficient of variation of 0.45. While the nitrate concentration downgradient of corrals was often similar to those upgradient of the corrals, a significant increase in the groundwater salinity between upgradient and downgradient corral monitoring wells indicated that the downgradient nitrate originated from the corral area/production facility. In a few of the cases in the Merced/Stanislaus county study, upgradient nitrate concentrations were significantly less than downgradient of the corrals.

We would expect similar groundwater concentrations in dairies in the Tulare Lake Basin, where soils are similarly well-drained and where the water table is less than 15 m (50 ft). Few other studies have focused on leaching from corral areas in dairies. In a study of three Georgia dairies, impacted groundwater nitrate ranged from 212 to 608 mg/L (Drommerhausen et al. 1995).

In a mass balance and groundwater modeling study of a dairy landscape, VanderSchans et al. (2009) found that groundwater models are insensitive to leaching from corrals, but estimated that urine and manure adds approximately 500 mm/yr (20 in/yr) of equivalent water to the corral surface, much of which evaporates. Total leaching rates (from manure equivalent water and precipitation) were estimated to vary from 290 mm/yr (11 in/yr) to 580 mm/yr (23 in/yr) for a sloped and unsloped corral, respectively. Annual nitrogen loading to groundwater from corrals was estimated to be 872 kg N/ha (778 lbs/acre), obtained by calibrating the loading rate against measured monitoring well observation data. This value is consistent with the annual accumulation rate of 1,000 kg N/ha/yr (900 lbs N/ac/yr) found in the soil profile by Vaillant et al. (2009, see above).

Corrals as a source of groundwater nitrate were also reviewed in a report to the Central Valley Regional Water Quality Control Board (Brown et al., 2003). Facility-average nitrate concentrations in monitoring wells downgradient from corrals were reported to be ranging from 1 mg/L to as high as 110 mg/L (as nitrate). The total average across ten facilities was 58 mg/L. Five of those facilities with corral monitoring wells are located in the Tulare Lake Basin (Tulare/Kings/Fresno Counties). Average reported nitrate concentrations at each of these dairies were 1, 18, 46, 95, and 110 mg/L. These concentrations are significantly lower than those found by Harter et al. (2002) in the Modesto area.

Harter et al. (unpublished data) recently completed an extensive groundwater sampling program in a monitoring well network spanning five dairies in Tulare and Kings County. The campaign included a total of seven corral monitoring well sites, with water table depths ranging from 15 m to 30 m (50 ft to over 100 ft). Over a 2.5 year period between 2007 and 2009, they measured nitrate at eight sampling events per year. Average nitrate concentration in corral monitoring wells was 55 mg/L (193 samples) with a coefficient of variation of 0.67. The *relative* variability is similar to the earlier study in the northern San Joaquin Valley, but the concentrations are significantly lower and comparable to Brown, Vence & Associates, 2004. Concentrations typically vary from below the MCL to as high as three times the MCL.

In contrast, soil cores taken at the monitoring well sites (Harter et al., unpublished data) during the well construction revealed elevated nitrate concentrations in the upper unsaturated zone, with concentrations typically above 200 mg/kg (dry soil) near the surface and gradually decreasing to 20-50 mg/kg at 10 m to 15 m (35 to 50 ft) depth. Elevated nitrate concentrations were associated with two older dairies that have been in operation for well over 50 years. The thickness of the affected unsaturated zone soil layer is significantly larger than in the Kansas feedlot study (Vaillant et al. 2009). If we interpret the 10 – 15 m (35–50 ft) penetration depth of elevated nitrate (and salinity) in these profiles as an expression of the downward water and solute movement rate underneath corrals, then the effective downward transport velocity in the unsaturated zone is 0.2 – 0.3 m/yr (0.7–1 ft/yr). Given an average moisture content of approximately 20% in deep alluvial vadose zones (Onsoy et al. 2005; Scanlon et al. 2010), the effective recharge rate under these corrals can then be estimated to be in the range of 40–60 mm/yr (about 2 in/yr). Consequently, the nitrogen loading rate, given an approximate average nitrate concentration of at least 90 mg/kg (20 mg N/kg) in the upper unsaturated zone profile, can be readily computed to be 60 – 90 kg N/ha/yr (50 –80 lbs/ha/yr). This is an order of magnitude less nitrogen loading from corrals than estimated by Vaillant et al. (2009) and by VanderSchans et al. (2009). Possible factors for this discrepancy are lower stocking rates, a significantly drier climate (250 mm [10 in] total precipitation) and higher annual ET than in either the northern San Joaquin Valley or in Kansas, and therefore both, lower recharge rates and higher atmospheric losses of nitrogen. Lower recharge rates and these lower nitrate loading rates are consistent with the uppermost groundwater nitrate concentrations found in Harter et al. (unpublished data) and in Brown, Vence & Associates (2004) (see above).

1.3 Groundwater N Loading from Corrals: Methods and Results

County and Study Area Nitrate Loading from Corrals: Review of literature data and field data from Tulare and Kings County provide a wide range of potential nitrogen loading and recharge rates in corral areas (see section 4.3). The only direct measurements of nitrogen in the deeper unsaturated zone below corrals in the Tulare Lake Basin indicate an annual loading rate that is on the order of at least 75 kg N/ha/year (70 lbs N/yr) with recharge rates around 50 mm/yr (2 in/yr) and corresponding soil moisture nitrate concentrations on the order of 675 mg/L (Harter et al., unpublished data, see Section 4.3). These data may provide a lower bound estimate of corral nitrogen leaching. However, these data do not include measurements from the first 2 m (7 ft) below the corral surface, where potentially most of the nitrogen is stored, but not transported to groundwater. Other studies vary in their estimation of recharge in corrals and exercise yards under similar climate conditions from less than 40 mm/yr to 300 mm/yr (2-12 in/yr) (Vaillant et al., 2009, VanderSchans et al., 2009), but at estimated nitrogen loading rates that are approximately one order of magnitude larger. Based on these latter results, an upper limit for the loading rate from corrals in the TLB is 1,000 kg N/ha/year (900 lbs/ac/yr).

Table 2. County by county summary of corral area and of the lower and upper limits of estimated N loading to groundwater. The numbers of dairies reflect 2007-2009 conditions.

	Number of Dairies	Corral Area [ha]	Corral Area [acres]	N leached below corral – Lower Limit [Mg/yr] (tons/yr)	N leached below corral – Upper Limit [Mg/yr] (tons/yr)
Fresno Co.	108	1,105	2,731	84 (93)	1,100 (1,200)
Kings Co.	162	1,574	3,889	120 (130)	1,600 (1,700)
Tulare Co.	315	4,168	10,300	320 (350)	4,200 (4,600)
Kern Co.	54	1,468	3,628	110 (120)	1,500 (1,600)
Total TLB	**639**	**8,316**	**20,548**	**630 (700)**	**8,300 (9,200)**

The corral area was obtained by digitizing corrals into a geospatial database using 2009 aerial imagery. The lower limit was obtained by assuming a loading rate of 75 kg N/ha/yr (70 lbs/ac/yr) (Harter et al. unpublished data). The upper limit was obtained by assuming a loading rate of 1,000 kg N/ha/yr (900 lbs N/ac/yr) (Vaillant et al., 2009). The numbers of dairies were provided courtesy of RB5. Numbers in parenthesis represent tons (1 ton = 2,000 lbs).

For the 8,316 ha (20,548 acres) of dairy corrals in the Tulare Lake Basin, potential groundwater nitrogen loading to groundwater is estimated to be in the range of 630 – 8,300 Mg N/yr (700 – 9,200 tons/yr). Approximately half of this load occurs in Tulare County (Table 2). Beef lot corrals may

contribute an additional 5% to 10% of the total shown in Table 2, from 32 to 830 Mg N/yr (35 – 920 ton/yr).

For the TLB, given its relatively low precipitation, the large depth to groundwater underneath many dairies, and given the limited set of field data, the upper bound is likely a conservatively high value and likely to significantly exceed actual loading rates, perhaps by as much as one order of magnitude.

Although unknown sources of nitrogen loading to groundwater in the corral area include leaking underground pipelines for manure recycling within the production facility area, these here are not considered to contribute substantially to the above stated range of total loading rates from corrals.

Current Storage of N in Corrals: A potentially significant but unknown portion of the nitrogen excreted onto corrals is stored in the uppermost unsaturated zone at depths of 0-2 m (0–7 ft), possibly for years or even decades (Miller et al., 2008; Vaillant et al., 2009). Here we provide four independent estimates of the potential magnitude of soil nitrogen storage in the immediate subsurface below the dairy corrals in the Tulare Lake Basin.

The first estimate is based on a single soil core that we obtained from three boreholes drilled in corrals at two Kings County dairy sites with more than 30 m (100 ft) depth to groundwater and a corral age of at least 40 years. The highest measured total nitrogen concentration was 500 mg N/kg (0.05%) in a core extending from 0 – 0.6 m (0 – 2 ft). In cores below 0.6 m, concentrations were generally below the detection limit of 200 mg N/kg (<0.02% total nitrogen). Assuming a total storage of 500 mg N/kg (0.05%) and a bulk density of 1.5 g/cm^3, the total nitrogen storage within the upper 2 m (7 ft) is 15,000 kg N/ha (13,000 lbs/ac). At this level for the entire Tulare Lake Basin, the nitrogen storage would be 125,000 Mg N (138,000 tons) in 8,316 ha corrals.

A second estimate can be made based on the nitrogen excretion rate of dairy cows and the known stocking density. We make the following assumptions:

- the annual excretion rate is 198 kg N (437 lbs) per adult dairy cow, including the excretion from an additional 1.4 support stock per adult cow (see Section 4.7.1);

- the annual stocking rate is 81 m^2/adult cow (50 adult cows/acre)

- half of the annual excretion occurs onto corrals rather than into flush-lanes;

- 3% of the N excreted in corral areas remains within the soil profile (Vaillant et al., 2009; see above);

- The relative total excretion rate, compared to 2005 levels, is 6.0% in 1945, 12.5% in 1960, 25.5% in 1975, and 44.6% in 1990 (see Section 4.8.2); this accounts for historic changes in both, the number of adult cows in TLB and the excretion rate per cow;

The resulting total nitrogen accumulation within Tulare Lake Basin corrals is 3,000 Mg N/yr (3,400 tons) for 2005 or 62,000 Mg N (68,000 tons) since 1945. This is equivalent to 200 mg total N/kg (0.02%)

in the upper 2.0 m (6.7 ft) soil profile across all corrals and consistent with the above field measurements.

A third estimate can be obtained using the carbon storage measured in feedlot soils of southern Alberta (Miller et al., 2008): about 300 g C/kg in the upper 4 cm (1.7 in) of corral soil (manure layer), about 100 g C/kg of carbon in the next 10 cm of soil (black layer), and as much as 30 g C/kg in the immediate subsoil. If we assume a carbon (C) to nitrogen (N) ratio of 14 (Vaillant et al., 2009), and further assume that nitrogen concentrations from 60 cm (2 ft) to 2.0 m (6.7 ft) are 500 mg/kg (see above), the total nitrogen storage in the upper soil profile amounts to 24,000 kg N/ha (22,000 lbs/ac) or 202,000 Mg N (222,000 tons) for the Tulare Lake Basin.

A fourth estimate to consider is the average soil nitrogen storage of 37,000 kg N/ha (33,000 lbs/ac) measured in 20 – 50 year old feedlot corrals in Kansas (Vaillant et al., 2009, see above). This represents the upper 2.0 m (6.7 ft) immediately below the corral. For the Tulare Lake Basin, the equivalent total corral soil nitrogen storage would be 304,000 Mg N (336,000 tons).

Applied to the corral areas of the Tulare Lake Basin, these estimates would suggest a range of less than 62,000 Mg N (68,000 tons) to as much as 304,000 Mg N (336,000 tons). This range represents less than 1.5% to 7.5% of the total amount of N excreted by dairy cattle in the Tulare Lake Basin between 1945 and 2005. For several reasons, feed lot soil nitrogen storage reported for Kansas and Southern Alberta sites are thought to be higher than in the TLB: the climate is wetter (higher precipitation) at significantly lower temperatures; in addition, feed lots are generally managed to keep the lot moist and minimize dust, while dairy corrals in the TLB are managed to stay dry. Higher temperatures and lower moisture could result in more rapid mineralization of nitrogen. Also, feed lots typically remove solids once per year or less, while many dairies in the TLB remove solids twice per year and more. Overall, a reasonable estimate of the total nitrogen storage in TLB corrals is from less than 1.5% to as much as 3% of the total amount of N excreted by dairy cattle.

Importantly, as Vaillant et al. (2009) pointed out, the conversion of corral areas to cropland has a high potential of mineralizing and mobilizing this locally very large amount of nitrogen that is currently immobilized in the immediate subsurface of corrals. Such conversion and subsequent groundwater contamination can be avoided by removing the top layer of corral areas scheduled for conversion and by distributing the soil removed as a soil amendment on cropland, within the framework of a nutrient management plan.

Spatially Distributed Nitrogen Loading Model for Groundwater Model Input: For groundwater modeling (Technical Report 4, Dylan et al., 2012), two input datasets are needed: the recharge rate and the associated nitrate concentration. We use the recharge rate estimated by VanderSchans et al. (2009) for modeling nitrate loading from corrals, and one-fifth of the recharge concentration that was estimated in that study to account for the approximately 5 times lower average nitrate found in Tulare Lake Basin corral monitoring wells, when compared to the dairies studied by VanderSchans et al. (2009): recharge = 305 mm/yr (12 in/yr), recharge nitrate concentration = 270 mg/L. This estimate equals a

nitrogen loading rate of 183 kg N/ha/year (163 lbs/ac/yr) and produces shallow groundwater ,concentrations consistent with those reported by Brown, Vence & Associates (2004) and to those that we have found in groundwater separated from corrals by thick unsaturated zones. Using this approach, the total current corral N loading to groundwater in the TLB is 1,500 Mg/year (1,700 tons/yr), near the lower end of the range indicated in **Error! Reference source not found.**. Groundwater nitrate loading rates are assigned directly to individually mapped corrals.

For the simulation of historic nitrate loading from corrals, we used a simplified conceptual scenario of the historic development of corral loading: nitrate loading in corrals is assumed to have been constant since 1975. Prior to 1960, contributions from (much smaller) corral areas are assumed to have been negligibly small with the dairy herd mostly on pasture. Between 1960 and 1975, we assumed a linear increase in corral nitrate loading from zero to 1975 rates.

1.4 Review of N Loading Rates from Dairy Lagoons

Like corrals, most liquid manure lagoons in the Tulare Lake Basin are associated with dairy facilities. In the Salinas Valley, the Gallo feedlot near Gonzales is the only major confined animal facility and it maintains storage lagoons to collect corral runoff. The total area of dairy lagoons in the Tulare Lake Basin was mapped in the same manner as the open corral area: using a 2007 database of dairy addresses provided by the Regional Water Quality Control Board the latest Department of Water Resources land use surveys for Fresno, Kings, Tulare, and Kern County to locate all dairies, and 2009 aerial photos provided by the Department of Conservation Farmland Mapping and Monitoring Program (FMMP) as the basis for digitization of the lagoons (see previous section).

Based on the digitized map, we find that, within the Tulare Lake Basin, there are nearly 2,300 dairy lagoons that encompass 1,265 ha (3,126 acres). Nearly all or all of these lagoons were built prior to the issuance of the Dairy General Order in 2007. Prior to 2007, regulatory requirements for the construction of liquid manure lagoons were governed under California Water Code Title 27, which required that lagoons are lined with soil containing at least 10% clay (for a review of the guidelines, see Brown et al., 2003). The soil liners typically develop a thin, but highly effective sludge layer that controls the seepage rate from the lagoon (Ham, 2002).

Liquid manure stored in lagoons varies widely in composition and contains nitrogen in the form of dissolved organic nitrogen, dissolved ammonium, organic nitrogen bound to suspended solids, and ammonium nitrogen bound to suspended solids. Pettygrove et al. (2010) report two studies showing the range of total nitrogen in liquid manure to vary from less than 50 mg N/L to over 2,000 mg N/L (typically as ammonium nitrogen and organic nitrogen) depending on the various sources contributing to lagoon manure including the amount of rainfall collected and irrigation water added to the lagoon. One study of nine dairy lagoons over two years reported median lagoon nitrogen concentrations ranging from 164 mg N/L to 645 mg N/L, averaging 360 mg N/L (ibid., see their Table 5), another reported average TKN (total Kjeldahl nitrogen, a measure of the sum of organic and ammonium nitrogen) in eight dairy lagoons over two years ranging from 410 to 1,010 mg/L, an average of 670 mg N/L (ibid., see their Table 4).

Manure lagoons in Kansas are constructed similarly to those in California, and have been extensively tested for percolation rates. In the Kansas study, Ham (2002) used a highly sensitive water balance approach to estimate net (average) water lost from manure lagoons to groundwater. Twenty lagoons were tested (14 swine sites, 5 cattle feedlots, and 1 dairy). Seepage rates varied within a relatively narrow range, given the wide variety of underlying soils, from 0.07 to 0.88 m/yr (0.23 – 2.9 ft/yr), and averaged 0.4 m/yr (1.3 ft/yr). The effective hydraulic conductivity of the sealing layer that develops at the bottom of lagoons was estimated to be 1.8×10^{-7} cm/s (2.2 in/yr). Total estimated nitrogen loading rates to the unsaturated zone varied from site to site, ranging from 400 kg/ha/yr to 5,000 kg/ha/yr (360 to 4,500 lbs/ac/yr).

Harter et al. (2002) provided an extensive review of existing literature on lagoon leaching and presented field data from five dairies in Stanislaus and Merced County. Their data were also applied in a groundwater modeling study that suggests a recharge rate of at least 0.8 m/yr (2.7 ft/yr) with nitrate concentrations on the order of 450 mg/L and a loading rate of 807 kg/ha/yr (720 lbs/ac/yr) (VanderSchans et al., 2009)—values that are confirmed by similar findings in Ham's Kansas study (see above). In the Merced/Stanislaus County study (Harter et al., 2002), groundwater conditions are considered highly vulnerable and lagoons are vertically separated from groundwater by less than 3 m (10 ft) and often less than 1 m (3 ft). Groundwater immediately downgradient of lagoons was frequently found to contain more ammonium than nitrate. Average total nitrogen concentrations in lagoon monitoring wells (including nitrate as nitrogen) were similar to those found for corrals: 55 mg N/L (equivalent to 248 mg nitrate/L). Concentration varied significantly, ranging from less than 10 mg N/L to over 100 mg N/L (45 mg/L–450 mg/L nitrate equivalent), with a coefficient of variation of 0.44. Dissolved ammonium-N will typically be converted to nitrate-N (at a one-to-one ratio in terms of nitrogen mass) as ammonium-laden groundwater moves into more oxic zones. These levels are several times higher than the regulatory limit for drinking water.

In a more recent study of five Tulare Lake Basin dairies, where depth to groundwater is more than 15 m (50 ft) and in most cases exceeded 25 m (80 ft), we found significantly lower total nitrogen concentrations in monitoring wells specifically drilled to monitor first encountered groundwater downgradient of lagoons: average nitrate concentrations were 42 mg/L with a standard deviation of 49 mg/L (162 samples from seven well sites next to six lagoons). At individual sites, average nitrate concentrations over the 2.5 year monitoring period varied from less than 5 mg/L to 122 mg/L. Four of the seven sites averaged nitrate concentrations below the MCL of 45 mg/L. Two lagoon monitoring wells on new dairy sites, built less than 10 years ago, had average nitrate concentrations of 35 mg/L and 22 mg/L. Two monitoring wells next to a lagoon constructed over 40 years ago averaged 4 mg/L and 8 mg/L (as nitrate). No significant ammonium was detected, except during well construction at one site with an old lagoon, in a thin, perched groundwater layer approximately 7 m (20 ft) below ground surface. Subsequent sampling from this perched layer did not yield sufficient water for sample analysis.

Brown, Vence & Associates (2004) summarized information from ten dairies equipped with monitoring wells as part of a regulatory enforcement action. Six dairies with lagoon monitoring wells are

located in the Tulare Lake Basin. Their average nitrate concentrations were 15, 22, 22, <40, 87, and 205 mg/L, a range similar to that observed in our Tulare Lake Basin groundwater monitoring study.

Much of the nitrogen leached from the lagoon is – at least temporarily – stored in the unsaturated zone. Ham (2002) showed that significant amounts of nitrogen are stored in the vadose zone within 1 to 2 m (3–7 ft) below the bottom of the lagoon at sites that have operated for approximately one decade. Typical ammonium-nitrogen concentrations in this upper layer were found to be on the order of 500 mg/kg. In the Tulare and Kings County dairy study (Harter et al., unpublished data), we found similarly high concentrations of ammonium-nitrogen, but also of nitrate-nitrogen (in the 200–500 mg/kg range) in the near-surface soil immediately adjacent to lagoons and to depths of 10 m (35 ft). With further depth, nitrate-nitrogen concentrations decreased to levels ranging from 20-50 mg/kg and ammonium-nitrogen concentrations decreased to below 1 mg/kg.

1.5 Groundwater N Loading from Liquid Manure Storage Lagoons: Methods and Results

Based on the work by VanderSchans et al. (2009), nitrate loading to groundwater under generally vulnerable conditions (shallow water table, sandy aquifer) is estimated to be on the order of 800 kg N/ha/yr (720 lbs/ac/yr). Applying this leaching rate to all current dairy storage lagoons in the Tulare Lake Basin, which occupy a total of 1,265 ha, the total contribution of nitrogen to groundwater would be on the order of 1,000 Mg N/yr (1,100 tons/yr) (Table 3).

The upper limit was obtained by assuming a recharge rate of 365 mm/year (1.2 acre-feet/acre/year) and a combined ammonium-N and nitrate-N concentration of 500 mg N/L (1,825 kg N/ha/yr = 1,628 lbs/ac/yr). An alternative upper limit is obtained by assuming a loading rate of 800 kg N/ha/yr (714 lb/ac/yr), obtained for an older lagoon overlying an aquifer less than 3 m below ground surface and considered highly vulnerable (VanderSchans et al., 2009).

Table 3. County by county summary of lagoon area and estimated largest possible N loading to groundwater from storage lagoons based on leaching rates and lagoon N concentration as well as an alternative largest possible N loading to groundwater based on a loading rate of 800 kg N/ha/yr (714 lb/ac/yr).

	Number of Dairies	Lagoon Area [ha]	Lagoon Area [acres]	N leached below lagoon – Upper Limit [Mg/yr] (tons/yr)	N leached below lagoon – Alternative Upper Limit [Mg/yr] (tons/yr)
Fresno Co.	108	131	325	480 (530)	110 (120)
Kings Co.	162	221	547	810 (890)	180 (200)
Tulare Co.	315	704	1,740	2600 (2,800)	560 (620)
Kern Co.	54	208	514	760 (840)	170 (180)
Total TLB	**639**	**1,265**	**3,126**	**4,600 (5,100)**	**1,000 (1,100)**

On the other hand, Ham's (2002) work suggests that leaching rates from manure lagoons can be as high as 0.88 m/yr (3 ft/yr). Pettygrove et al. (2010) reported typical California liquid manure nitrogen concentrations as high as 1,000 mg N/L. These worst-case numbers would yield an upper limit for N loading on the order of 8,800 kg N/ha/year (7,900 lbs/ac/yr) – an order of magnitude higher than the estimate by VanderSchans et al. (2009). Such high leaching rates are likely to be sporadic only and are not considered to occur at every facility in the Tulare Lake Basin. For a reasonably conservative (high) upper limit of lagoon loading, we assume a leaching rate of 0.73 m/yr (2.4 AF/ac/yr), twice the average leaching rate of 0.37 m/yr (1.2 ft/yr) from Ham (2002) and similar to the leaching rate of VanderSchans et al. (2009), and a lagoon nitrogen concentration of 500 mg N/L, corresponding to an intermediate value of the two studies reported in Pettygrove et al. (2010). These numbers would suggest an upper limit for the lagoon loading rate of 3,650 kg N/ha/yr (3,260 lbs/ac/yr) or 4,600 Mg N/yr (5,100 tons/yr) across all lagoons in the Tulare Lake Basin (Table 3).

The low nitrate (and ammonium) concentrations found in monitoring wells recently constructed in the TLB adjacent to relatively old manure storage lagoons (Harter et al. unpublished data) suggests that, under conditions of deep water table (> 20 m below ground surface), either significant denitrification occurs or lateral movement across perching layers distributes the nitrogen across a larger recharge area.

Overall, an estimated range of 200 – 2,000 Mg N/year (220 – 2,200 tons/yr) total groundwater loading from lagoons appears most reasonable under current conditions.

Current Storage of N in Lagoons: Lagoons, like corrals, may store significant amounts of nitrogen either in a sludge layer at the bottom of the lagoon or in the subsurface below the lagoon. The organic nitrogen stored in the sludge layer or the lagoon is potentially stored there for long periods of time (years to decades) while the lagoon is operating. The magnitude of total amount of nitrogen stored in and below lagoons for the long-term can be estimated from measured sludge concentrations and from measured total nitrogen concentrations immediately below lagoons (see above). We offer the following estimate. We assume the following values to obtain an approximate upper limit of N stored in the sludge layer: average sludge layer thickness of 1 m (3.3 ft) across 1,265 ha (3,126 ac) of lagoons, a sludge dry matter solids content of 10%, a solids density of 2 g/cm^3, a nitrogen concentration of 1,500 mg/kg (0.15%) sorbed to solids, and 500 mg/L dissolved in the liquid. This totals 8,000 Mg N (8,800 tons) that is semi-permanently in storage at the bottom of lagoons. For the immobile organic nitrogen storage immediately below the lagoon, we assume that most of that nitrogen is found in the first 2.0 m (6.7 ft) at concentrations of 500 mg/kg (0.05%, see above) with a soil density of 1.5 g/cm^3. The nitrogen storage below the lagoon then amounts to 15,000 kg N/ha (13,400 lbs/ac). The total nitrogen stored below the subsurface in TLB dairy lagoons amounts to 19,000 Mg N (21,000 tons). In total, we estimate that the semi-permanent storage of organic nitrogen below and within the bottom of dairy lagoons is on the order of 27,000 Mg N (30,000 tons), about 3/4 of one percent of the total estimated N excreted by dairy cattle since the late 1960s, when lagoons began to be constructed.

For the overall mass balance analysis of nitrogen fluxes in TLB dairies, removal of nitrogen into semi-permanent storage within or below lagoons is therefore considered negligible. However, as for corrals, the conversion of lagoons to irrigated land (agriculture or urban) bears the risk of mineralization and subsequent mobilization of this locally very intensive nitrogen pool, leading to subsequent groundwater contamination. Removal of the nitrogen-rich sludge and subsoil layers prior to land conversion is an important preventive step.

Spatially Distributed Nitrogen Loading Model for Groundwater Model Input: To simulate nitrogen loading to groundwater, we assume an average recharge rate of 365 mm/year and an average nitrate concentration of 225 mg/L (182.5 kg N/ha/year). The loading rate is identical to that used for corrals and it is at the lower end of the suggested range for lagoons above. The total N loading from lagoons, using these values, is 230 Mg N/y (250 tons/yr).

For computer simulations of historic loading to groundwater and subsequent fate of groundwater nitrate, we assume that lagoon loading to groundwater was constant in time since 1970, despite the increasing cattle numbers. Prior to 1970, we assume that no lagoons existed in the Tulare Lake Basin. Prior to 1970 and the passing of the Porter-Cologne Act in 1968, few lagoons existed, and many of the animals grazed on pasture for significant portions of the year.

1.6 Review of Nitrate Loading Rates from Irrigated Crop Fields with Manure Applications

Dairies in the Tulare Lake Basin, whether they are drylot or freestall operations, no longer maintain significant acreages of irrigated pasture land for cattle grazing (a practice common prior to the 1970s). Instead, animals are confined to corrals and freestalls, while agricultural land surrounding the animal production facility is used for the production of forage crops other than pasture. The most common forages in the Tulare Lake Basin are alfalfa (*Medicago sativa*), corn (*Zea mays*), sudan grass (*Sorghum bicolor* subsp. *drummondii*), and winter grains including triticale (*Triticale hexaploide*), oats (*Avena sativa*), wheat (*Triticum aetivum*), and barley (*Hordeum vulgare*). Dairies also manage vineyards, cotton, and other crops, which may be used for some (limited) manure application.

Harter et al. (2002, their Table 1) provided a review of existing data on nitrate leaching from manure cropland application areas. Nitrate concentration in leachate below the root zone and in domestic wells nearby such land application areas varied widely, from below detection limits to as much as five to eight times above the drinking water limit. In the same publication, data from monitoring wells on five dairy facilities, specifically downgradient of manure-treated forage fields were reported. The facilities were all located in the north-central San Joaquin Valley (Merced and Stanislaus Counties), on coarse-textured soils (sandy loams) with a shallow groundwater table (less than 5 m below ground surface). The average monitoring well nitrate concentration was six times above the drinking water limit (279 mg/L), with individual measurements varying widely (coefficient of variation of over 50%). Based on these concentrations and estimated recharge rates, nitrogen losses from manured fields to groundwater were estimated to be on the order of 280 kg N/ha/yr. VanderSchans et al. (2009), using a modeling

approach that linked field recharge nitrogen fluxes to measured groundwater nitrate monitoring data on two of these dairies, estimated that nitrogen losses from manured fields ranged from 211 kg N/ha/yr (188 lbs/ac/yr) to over 700 kg N/ha/yr (630 lbs/ac/yr) with an average of 486 kg N/ha/yr (434 lbs/ac/yr). Values near the lower end of the above range were generally achieved under relatively strict nutrient management practices (see Technical Report 3, Dzurella et al. 2012) whereas the average and higher values for nitrate-nitrogen losses to groundwater represent traditional manure management practices.

Significantly lower nitrate concentrations were measured in an ongoing research project (Harter et al. unpublished data) in the Tulare Lake Basin: monitoring wells were installed to measure groundwater quality in the first encountered groundwater (not including aquitards) on five dairies in Kings and Tulare County, with water table depths of approximately 15 m (50 ft) at one dairy, and approximately 30 m (100 ft) at the other four dairies. Nitrate concentrations were measured eight times per year over a 2.5 year period in eight monitoring wells located downgradient of long-term manured cropland typically planted with corn and winter grain (often in a multi-year rotation with alfalfa), a similar land use to those dairies investigated by Harter et al. (2002). Average nitrate concentration was approximately 130 mg/L, three times the level of the MCL, and approximately half of the average nitrate concentration reported for the northern San Joaquin Valley dairy study by Harter et al. (2002). Between monitoring wells, long-term average well nitrate concentrations typically ranged from 70 mg/L to 170 mg/L. One well, not included in the above average, consistently showed nitrate levels exceeding 300 mg/L, but the source of that water was not clear (ibid.).

Measured concentrations reported by Harter et al. (2002) and those modeled by VanderSchans et al. (2009) were found to be consistent with field mass balance estimates of nitrate leaching below the root zone. Groundwater nitrate leaching rates estimated from groundwater models that were calibrated to measured monitoring well nitrate concentrations compared favorably to nitrate leaching estimates obtained by closure of the field scale mass balance. In other words, the groundwater nitrate-nitrogen loading estimated from monitoring wells and groundwater flow dynamics was consistent with groundwater nitrate-nitrogen loading rates estimated from the difference between annual nitrogen application rates (inorganic fertilizer, manure nitrogen, atmospheric deposition, irrigation water) and the sum of crop nitrogen removal and atmospheric losses (Harter et al., 2002; VanderSchans et al., 2009).

This previous work showed that such a mass balance approach, while not exact, provides a valuable approximation of groundwater nitrate losses from manure applications. Over the past decade, this has led to the introduction of manure management practices that directly account for the nitrogen-fertilizer value of manure by measuring the amount and nitrogen-content of manure applied to fields, by timing the manure applications, and by including manure into the overall field fertilization schedule. The 2007 Dairy General Order issued by the Central Valley Regional Water Quality Control Board requires dairies to fully account for the nitrogen content of land applied manure and other nitrogen sources, while meeting a nitrogen application ratio (ratio of total nitrogen applied to total nitrogen removed in the harvest) of 140%–165%.

Historically—prior to the 2007 Dairy General Order—manure (liquid or solid) was typically applied during the spring and during the fall fallow seasons between harvest of summer/winter crops and planting of winter/summer crops on fields with corn and winter grains. Alfalfa, a leguminous crop capable of fixing nitrogen directly from atmospheric sources, may receive some solid manure prior to planting or after the last cutting in the fall, but generally receives little or no manure water application and only small amounts of fertilizer application. It is an important forage and widely grown on dairy farms. Farms also apply manure (mostly manure solids, but also manure liquids) to cotton fields, orchards, and vineyards, albeit in relatively moderate amounts.

1.7 Dairy Manure N Applications to Cropland

1.7.1 Total Amount of N Excreted at Each Dairy

We had two data sources available to estimate the total amount of N excreted, some of which is then land applied. We initially used a table obtained from the U.S. EPA Region 9 ("Central Valley Dairies.dbf," courtesy of Don Hodge, U.S. EPA Region 9),[4] which contains data reported by dairy owners and collected by RB5 during 2005. This database is referred to here as the "EPA 2005 dairy database." The EPA 2005 dairy database lists 621 individual dairies in Fresno, Kings, Tulare, and Kern County and – according to Central Valley RWQCB staff – represents 2004-2006 conditions. For each dairy, the list also provides the number of milking cows, the number of dry cows, and an estimated number of support cattle. The number of support cattle was set equal to 117% of the number of adult cows. We later obtained a similar table from RB5, which listed 639 dairies in the study area with 2007, 2008, and 2009 animal numbers and 2007 cropland acreage for each dairy. We refer to this table as the "RB5 2010 dairy database." Ultimately, we chose the latter database to estimate nitrogen excretion in manure on individual dairies, within each county, and study area wide.

The total amount of N excreted from cattle on each dairy identified in the RB5 2010 dairy database (Table 5) was estimated by assuming that the daily N excretion from lactating cows and dry cows is 462 g N d^{-1} and 195 g N d^{-1}, respectively (UC Committee of Consultants – Harter, 2007). This amounts to 153 kg N/yr (336 lbs/yr) excreted per adult cow, consistent with Pettygrove et al. (2010). To estimate the N excretion from support stock, we used the ratios in Table 1 of Pettygrove et al. (2010), which suggest that 25 kg N/yr (56 lbs/yr) are excreted by support stock for every adult cow, which – according to their Table 1 – excretes 148 kg N/yr (326 lbs/yr). Their computation was based on the assumption that, on average, each dairy has 0.17 calves (0-6 months) and 0.5 heifers (6 months to 24 months) per adult cow. We adopted the EPA estimate of 1.4 support stock per milk cow (lactating cows[5]) or 1.17 support stock per adult dairy cow, and scaled the Pettygrove et al. (2010) support stock excretion rate to 45 kg N/yr (101 lbs/yr) for the 1.17 support stock per adult dairy cow. Per adult cow, and including support stock, the total excretion rate is therefore 198 kg N/yr (437 lbs/yr).

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[4] http://www.epa.gov/region9/ag/dairy/locations.html
[5] In the EPA database, lactating cows are referred to as "milking cows" to which "dry cows" are added to obtain the total number of "adult cows"

In total, 202 Gg N/yr (223,000 tons/yr) are excreted by dairy cattle in the TLB (Table 5). More than half of the excreted manure is generated in Tulare County. The fate of this nitrogen, and how we estimate the breakdown between the three pathways (i.e., atmospheric losses, exported (sold) manure, and land application of manure within a dairy), is explained further below.

Table 4. Number of milking cows, dry cows, and support stock (calves, heifers, etc.) in the Tulare Lake Basin study area, and the cropland acreage associated with dairies, total and by county (based on data obtained from RB5, representing the most recent number of mature cows reported between 2007-2009, and in the text referred to as "RB5 2010 dairy database").

	Lactating Cows	Dry Cows	Support Stock	Cropland Acreage 2007 [ha (acres)]
Fresno County	110,793	21,795	155,110	25,067 (61,943)
Kings County	148,486	29,210	207,880	22,621 (55,897)
Tulare County	455,987	89,702	638,381	60,760 (150,140)
Kern County	137,147	26,980	192,006	19,059 (47,097)
Tulare Lake Basin	**852,412**	**167,688**	**1,193,377**	**127,507 (315,077)**

Table 5. Total amount of manure nitrogen excreted by dairy cattle in each TLB county, atmospheric nitrogen losses from manure, manure nitrogen sold off dairy, and manure nitrogen land applied within dairies. The average dairy manure N loading rate is the arithmetic average across individual dairy's ratio of direct applied manure N [kg/yr] to cropland area [ha]. The countywide dairy manure loading rate is the county total direct applied manure N [kg/yr] divided by the county total dairy cropland [ha]. See text for further explanation.

	Manure N Excreted [Mg/yr]	Atmospheric Losses of N [Mg/yr]	Maximum Limit, Manure N Export [Mg/yr]	Minimum Limit, Direct Applied Manure N within Dairies [Mg/yr]	Minimum Limit, Average Dairy Manure N Loading Rate [kg/ha/yr]	Minimum Limit, Countywide Dairy Manure N Loading Rate [kg/ha/yr]
Fresno Co.	26,303	9,995	12,707	3,601	371	144
Kings Co.	35,252	13,396	12,913	8,943	521	395
Tulare Co.	108,256	41,137	41,960	25,159	546	414
Kern Co.	32,560	12,373	9,867	10,321	944	541
Tulare L.B.	**202,371**	**76,901**	**77,446**	**48,024**	**596**	**377**

1.7.2 Historic Dairy Cattle N Excretion Rates

Historically, the total nitrogen excretion in the TLB has been much less than the 2005 levels of N excretion. The total number of dairy cows has steadily increased over the past 60 years from nearly 110,000 milk cows in 1950 to nearly 880,000 milk cows in 2007. Also, the amount of milk produced per milk cow has tripled over the past 60 years, from a state-average of 7,150 lbs/yr in 1945[6] to 22,440 lbs/yr in 2007.[7] Over the same time period, the relative nitrogen content of milk, compared to the cow's feed intake has risen from approximately 21% in 1945 to 25% in 2005. Thus, the manure output per milk cow has increased somewhat less than three times between 1945 and 2005.

For purposes of estimating historic dairy N excretion rates and the amount of manure nitrogen used for cropland application, we estimate excretion rates from USDA agricultural census data for California. The ratios of historic excretion rates to the 2005 excretion rate estimated from these census data is then used to scale the excretion rate developed in Section 4.8.1 back to 1945, 1960, 1975, and 1990 (Table 6).

Table 6. Estimate of historical manure nitrogen excretion rates in the Tulare Lake Basin based on USDA NASS California census data on milk production per head of cattle (hd) and total number of milk cows in the five study area counties.

Year	Milk Production [kg/hd/yr] (lbs/hd/yr)	Milk Nitrogen [kg N/hd/yr] (lbs/hd/yr)	Milk : Feed Intake Nitrogen Ratio	Excretion Rate [g N/milk cow/d] (lbs/milk cow/day)	Number of Adult Dairy Cows in the TLB + SV	Total Excretion Ratio, relative to 2005	Total N Excretion in the TLB & SV [Gg N/yr] (tons N/yr)
1945	3,243 (7,150)	17 (37)	21%	173 (0.38)	141,124	0.060	12 (13,000)
1960	4,432 (9,770)	23 (51)	22%	223 (0.49)	225,510	0.124	24 (26,000)
1975	6,154 (13,566)	32 (70)	23%	292 (0.64)	352,089	0.255	49 (54,000)
1990	8,372 (18,456)	43 (95)	24%	376 (0.83)	478,668	0.446	86 (95,000)
2005	9,709 (21,404)	50 (111)	25%	413 (0.91)	977,887	1	194 (214,000)
2020	11,263 (24,831)	58 (128)	26%	432 (0.95)	977,887	1.129	219 (241,000)
2035	13,431 (29,612)	69 (153)	27%	489 (1.08)	977,887	1.280	248 (273,000)
2050	14,986 (33,039)	78 (171)	28%	520 (1.15)	977,887	1.360	264 (291,000)

Notes: The increase in milk N to feed N intake ratios is estimated to fit 1973 Committee of Consultant N excretion rate for California and approximate historic conditions. The number of cows in 1945 was assumed to be identical to the 1950 census

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[6] http://usda01.library.cornell.edu/usda/nass/MilkProdDa//1940s/1946/MilkProdDa-02-15-1946.pdf
[7] http://usda01.library.cornell.edu/usda/nass/SB988/sb1022.pdf

data. The number of cows in 1960, 1975, and 1990 were estimated by linear interpolation of the 1950 and 1992 national agricultural census data. Similarly, the 2005 number of cows was estimated by linear interpolation of the 2002 and 2007 national agricultural census data. The historical total excretion rates for the TLB are based on the 2005 estimated N excretion and the N excretion ratio.

Since 1945, the total nitrogen excretion from dairy animals in the Tulare Lake Basin (with a very small fraction in the Salinas Valley, see Table 5), has risen exponentially, doubling every 15 years. Until the 1960s, much of the nitrogen excretion in the study area is assumed to have occurred on irrigated pasture where plant uptake rates were absorbed most of the manure nitrogen entering the root zone. However, since the early 1970s, liquid and solid manure is collected and land applied on crops. Since then, the amount of nitrogen that needs to be land applied – in direct proportion to the amount of nitrogen excreted - has increased five-fold.

1.7.3 Atmospheric nitrogen losses from manure prior to land application

Atmospheric losses of nitrogen from the total mass of nitrogen excreted are assumed to be 38%, which is based on a 2003 EPA draft report on ammonia emissions from manure (EPA, 2003). This estimate is near the upper end of the range of atmospheric losses provided by the University of California Committee of Consultants (Harter, 2007), which suggested that these losses may range from 20% to 40% of excreted N. We use the higher number to account for the fact that a significant number of dairies in the Tulare Lake Basin are drylot dairies, where atmospheric N losses tend to be higher than on freestall dairies.

Across the study area, 77 Gg N/year (85,000 short-tons/year) are lost to the atmosphere. The 38% loss rate is assumed constant across all dairies. Hence, more than half of all atmospheric losses occur in Tulare County, which houses over half the dairy animals in the TLB (Table 5).

1.7.4 Distribution of cropland applied manure nitrogen

For the years prior to the 2007 Dairy General Order, little is known about the actual distribution of cropland applied manure nitrogen including:

- The distribution across crops (crop categories)
- The distribution between on-dairy cropland and off-dairy cropland
- The distribution within county of origin and outside of the county of origin
- The distribution of synthetic fertilizer and manure nitrogen to meet applied fertilizer needs (discussed in Section 3 of this Technical Report)

Most manure is land applied to field crops, particularly corn, which – on dairies - is often double-cropped with winter grain. Manure is also likely being applied to grain and hay crops. Dried or composted manure solids may be applied as soil amendment to other crops including perennial crops. Limited amounts of manure are applied to alfalfa, typically before seeding, and occasionally at the end of the season.

Farmer's in the SV apply approximately 10 Mg/ha (~4 tons/acre) of compost (not necessarily dairy manure) once every other year. At 60% dry matter content and 2% nitrogen content, this is equivalent to approximately 60 kg N/ha/yr (50 lbs/ac/year). Furthermore, a composter in the TLB shared that he typically delivers compost over distances of a few to several tens of kilometers (few to tens of miles).

The overall exportation of manure from dairies to cropland outside dairy operated cropland can be a significant proportion of the nitrogen generated on the dairy, but typically is much smaller than the amount of manure nitrogen retained on dairies. Most of the manure exported, due to transportation cost, does not leave the county of origin and even less manure nitrogen leaves the study area.

Until recently (including the 2005 period), manure has been applied effectively as a soil amendment, in addition to synthetic fertilizer. Under the 2007 Dairy General Order, dairies are required to account for both synthetic and manure nitrogen as well as other sources of nitrogen (e.g., irrigation water) in their nutrient management planning.

While future research of the dairy nutrient management data collected by RB5 will likely provide more detail on the distribution of manure, at least within dairy cropland, here we employed simplified manure distribution scenarios. These scenarios are designed to reflect the overall, very qualitative nature of what is known about the distribution of manure. The objective in designing these scenarios is to provide several scenarios for the likely quantitative distribution of manure in cropland application that can illustrate the potential range in groundwater nitrate loading and that can be used as more quantitative information on the distribution of manure becomes available.

Scenario for Crop-Group and County Analysis: For the mass balance analysis of crop- and county level groundwater nitrate loading based on land areas reported by the county agricultural commissioners (see Section 1 of this Technical Report), we make no distinction between manure land applied on dairies and manure land applied outside of dairies. We assume that all manure generated within a county is land applied within the county. Two-thirds of dairy manure is assumed to be applied to field crops and one-third of dairy manure is applied to grain and hay crops. In corn and other field crops (CAML classes 600, 602 to 612, but not including 601-cotton), 50% of crop nitrogen requirements are assumed to be met with synthetic fertilizer, in small grain and hay crops 90% of their crop nitrogen requirements are assumed to be met by synthetic fertilizer. For the mass balance analysis and to derive groundwater nitrate loading, the manure nitrogen available for cropland application is added to these synthetic fertilizer nitrogen applications for these two crop groups only.

CAML-based Analysis with the Groundwater Nitrate Loading Model (GNLM) – Scenarios A-D: For the CAML-based analysis, where the mass balance is computed on a field-by-field basis according to the CAML landuse maps (see Sections 1, 2, and 3 of this Technical Report), the amount of manure exported from dairies must be specified, and the specific crops receiving land applied manure must be specified as input to GNLM.

Within dairies, GNLM operationally assumes that manure nitrogen is applied, primarily as liquid manure, to the following CAML land use categories: field crops (600), cotton (601), sugar beets (605),

corn (606), grain sorghum (607), sudan (9608), sunflowers (612), grain and hay (700), barley (701), wheat (702), oats (703), pasture (1600), and mixed pasture (1603). The numbers in parentheses refer to the CAML land use categories (see Section 3 of Viers et al., 2012).

Outside of dairies, and on dairy cropland other than the previously listed crop categories, exported manure (assumed to be dry manure or composted manure only) is distributed across all crop categories identified in CAML. For the amount of manure that is distributed off-dairies, we developed six hypothetical scenarios with the objectives
1. to broadly bracket the potential export (past, current, and future) of manure nitrogen from dairies (scenario D versus other scenarios) and
2. to broadly bracket the potential distribution of exported manure nitrogen between counties, study area, and areas outside of the study area (scenarios A-C).

The scenarios are:

- "Scenario A": Manure exported by dairies does not affect the typical N fertilization rates (Figure 4) on non-dairy cropland within the study area, after accounting for the combined synthetic and organic sources of nitrogen fertilizer applied to non-dairy cropland. This is a hypothetical (future) scenario representing the possibility that manure exported from dairies

    o   is applied to non-dairy cropland as part of the typical N fertilization rates,

    o   is transported to areas completely outside the study area, possibly after some processing,

    o   is intentionally processed and lost to the atmosphere,

    o   or any combination thereof.

- "Scenario B (by county)": Half of the manure exported by dairies is applied as soil amendment on non-dairy cropland within the county of origin. The other half of the exported manure has the same fate as listed under "Scenario A". The manure exported by dairies for soil amendment within each county is distributed in direct proportion and in addition to the typical N fertilization needs of crops within that county (manure applied as soil amendment does not leave the county). This scenario represents the mid-point between "Scenario A" and "Scenario C (by county)".

- "Scenario B (study area)": Half of the manure exported by dairies is applied as soil amendment on non-dairy cropland within the study area (not restricted to the county of origin). The other half of the exported manure has the same fate as listed under "Scenario A". The manure exported by dairies for soil amendment in the study area is distributed across all non-dairy cropland in the study area in direct proportion and in addition to their typical N application needs. This scenario represents the mid-point between "Scenario A" and "Scenario C (by study area)".

- "Scenario C (by county)": All manure exported by dairies is applied as soil amendment on non-dairy cropland within the same county. The total manure exported by dairies within each county is distributed in direct proportion and in addition to the typical N application rates of crops within that county (manure does not leave the county).

- "Scenario C (study area)": All manure exported by dairies is applied as soil amendment within the study area (not restricted to the county of origin), and the total manure exported by all dairies in the study area is distributed across all non-dairy cropland in the study area in direct proportion and in addition to their typical N fertilization rates.

- "Scenario D": No manure is exported by dairies. All manure is land applied on applicable forage crops within the dairy. Note that, groundwater nitrate loading on non-dairy cropland is therefore identical to that simulated in Scenario A. Groundwater nitrate loading on dairy cropland receiving manure is significantly higher under this Scenario than under the export scenarios.

Historically, for simulation purposes, manure N exports are assumed to be negligible (under all scenarios) prior to 1980, increase linearly from 0% to 38% between 1980 and 2005, and stay constant at 38% after 2005 (scenarios "A", "B", and "C").

In the current version of GNLM (Section 2.6), the fraction of manure nitrogen exported is an arbitrary percentage set to 38% basin-wide, but varying from county to county in proportion to the ACR category "manure sold". While Scenario D brackets manure export at the lowest end (zero), a 38% export ratio brackets actual export ratios at the very high end (although a few individual dairies may export more). County- and study area specific ratios of hypothetical fractions of exported N are shown in Table 7.

Table 7. Operational model on the fate of excreted nitrogen, by county.

Region	% N Excreted	% Atmospheric Losses before Land Application	% N Land Applied on Dairy Cropland	% N Land Applied Offsite
Fresno Co.	100	38.0	13.7	48.3
Kings Co.	100	38.0	25.4	36.6
Tulare Co.	100	38.0	23.2	38.8
Kern Co.	100	38.0	31.7	30.3
TLB	100	38.0	24.0	38.0

With 202 Gg N/yr (223,000 tons/yr) excreted, atmospheric losses prior to land application amount to 77 Gg N/yr (85,000 tons/yr). With this amount of atmospheric N losses, the N exports in 2005 are no more than 77 Gg N/yr (85,000 tons/yr) and the amount of manure nitrogen applied to cropland within dairies is at least 48 Gg N/yr (53,000 tons/yr, Scenarios "A"-"C"), but not exceeding 125 Gg N/yr (138,000 tons/yr, Scenario "D") (see Table 5).

In GNLM, all manure applications, within and outside of dairies, are distributed proportional to the nitrogen application needs of the particular crop grown on a specific field (see Section 2 of this Technical Report). Briefly, for the distribution of manure N within a dairy on the specific crops listed above (field crops, corn, etc.), we use the RB5 2010 dairy database to estimate the amount of manure N excreted on an individual dairy, and compute the scenario-specific amount of manure N applied to cropland within that individual dairy. The cropland associated with an individual dairy is obtained from the reported assessor parcel numbers and the CAML landuse map (see next section). At least 50%, but no more than 100% of the applied nitrogen need is met by synthetic fertilizer N, regardless of crop type. The remaining applied nitrogen needs are assumed to come from manure N. On many dairies, the total amount of manure N applied exceeds 50% of the applied nitrogen needs and is therefore in excess of the applied nitrogen need.

The above estimation of the amount of manure N available for a) land application within the dairy, b) for application on cropland across the study area, and c) volatilized to the atmosphere is associated with significant uncertainties. Estimates of manure exports from dairies could be further improved by compiling the dairy data collected by RB5 under the 2007 Dairy General Order. Atmospheric N losses, assumed to be 38%, also are a significant source of uncertainty in estimating the amount of manure N land applied on dairies or exported.

Historic Simulation of Manure Nitrogen Application to Cropland: For the historic simulations of spatially distributed nitrogen applications to cropland, we assume that until the late 1960s, manure nitrogen is not land applied but excreted on irrigated pasture. Hence, for modeling purposes, dairy manure from any dairy application source or location (cropland, lagoon, or corral) is assumed to not contribute to groundwater nitrate loading prior to the 1970s. In the 1970s, land application of manure is assumed to be limited to cropland belonging to a dairy. No manure is exported from dairy-owned land prior to 1980. After 1980, exports of manure (Scenarios A-C) are assumed to gradually increase. GNML assumes that the full amount of export in Scenarios A-C is only reached in 2005. Between 1980 and 2005, the fraction of manure exported from dairies increases linearly from zero to the amount specified for 2005. In Scenario D, manure never leaves the dairy. All Scenarios are simulated through 2050.

1.7.5 Manure N cropland application on dairies: Identifying dairy cropland

For the CAML-based field-by-field analysis in GNML, a link between individual dairies and their associated fields must be created in a database to approximate the manure distribution within a dairy facility according to the number of cows in the dairy. One possible approach, taken previously by a pilot study for CV-SALTS, is to use a geographic information system (GIS) analysis that distributes manure

nitrogen to cropland at agronomic rates, and selects a sufficiently large area of cropland. This approach assumes *a priori* that manure is distributed at agronomic rates. Another approach for identifying fields receiving manure is to consider the total acreage of dairy land identified, by dairy, in the RB5 2010 dairy database and identify the equivalent amount of cropland in the land use database described in Section 3. A minor shortcoming of this method is that the cropland areas identified in this way may include areas that are in fact facility and other non-crop acreage.

Here, we choose a third approach, based on the assessor parcel numbers (APNs) identified by dairies in their facility assessment of 2007. As part of the RB5 Dairy General Order, each dairy operator was required to submit a list of APNs that were either part of the facility or cropland potentially receiving manure. From RB5, we obtained a database that listed dairy name, and – for each dairy – the APNs of all parcels considered to be "facility" and of all parcels considered to be "cropland". We refer to this database, henceforth, as the "RB5 APN database". The RB5 APN database did not list address, or any other georeferences associated with the dairy name, only the county location. The dairy names in the RB5 APN database did not all match the dairy names in the RB5 2010 dairy database: Matches were found for 495 of 639 dairies. Within each county, all parcels in the RB5 APN database with unmatched dairy names were combined into a single large virtual dairy, which was associated with the combined number of animals (and their manure) of those dairies in the RB5 2010 dairy database that were not matched with the RB5 APN database. Thus, we account for the total number of animals in the RB5 dairy database as well as the total dairy land area identified by APN numbers in the RB5 APN database.

In total, approximately one in eight cows (13%) is assigned to facilities for which APN parcels are unknown and approximately 5% of the APN parcels area are assigned to a dairy for which the animal numbers are unknown. For simulation purposes, this means that manure N application on the unassigned land areas is 2.5 times higher than the average on land with assigned animals (Table 8).

Table 8. Matching of RB5 2010 Dairy database adult dairy animal numbers for 2007-2009 with the RB5 APN database of 2007 reported land area of dairy facilities and cropland for land application via dairy name. The table provides the number of adult cows and the total associated acreage of the match.

	Number of cows with assigned APN land	Number of cows with unassigned APN land	APN land area with cows assigned [ha (acres)]		APN land area with no cows assigned [ha (acres)]	
Fresno	118,964	13,624	19,808	(48,946)	398	(984)
Kings	150,452	27,244	17,304	(42,759)	821	(2,030)
Tulare	482,289	63,400	61,095	(150,967)	3,944	(9,745)
Kern	137,834	26,293	19,736	(48,768)	1,456	(3,598)
Total TLB	889,539	130,561	117,943	(291,439)	6,620	(16,357)

Table 8 compares the total county-wide land area identified by the APN database and compares it against the total county wide land area reported in the RB5 dairy database (which does not identify, whether the reported land area is facility or cropland acreage). For the entire Tulare Lake Basin, the dairy land area identified by the RB5 APN database is 98% of the total land area listed (as total acreage per dairy) in the RB5 2010 dairy database.

We use the RB5 APN database to identify dairy land parcels on a digital map using the counties' APN GIS data layers. We thus create a digital map corresponding to the RB5 APN database (dairy APN GIS layer). Using GIS-based spatial analysis, we can overlay the dairy APN GIS layer with the CAML land use GIS layer described in Section 3. The spatial analysis within GIS allows us to identify the crop mix within the land area identified by dairy APNs; and it allows us to simulate the proper crops to which to apply manure within the area identified by a dairy as potentially receiving manure applications.

Table 9. Cropland and facilities acreage of assessor parcel numbers (APNs) reported by dairies to the RB5 (data provided courtesy of RB5, 2011). Also shown are the acreages reported in the RB5 2010 dairy database as 2007 conditions, for comparison. The last column is the ratio of the land area reported in the RB5 APN database and the land area reported in the RB 2010 dairy database.

	APN cropland (acres)	APN facilities (acres)	APN facilities/ cropland (acres)	APN total (acres)	RB5 2010 dairy database (acres)	APN total/ RB5 dairy (%)
Fresno County	36,771	13,159	-	49,930	61,943	81%
Kings County	41,329	3,460	-	44,789	55,897	80%
Tulare County	151,113	9,599	-	160,712	150,140	107%
Kern County	41,256	3,229	7,881	52,366	47,097	111%
Tulare Lake Basin	**270,469**	**29,447**	**7,881**	**307,796**	**315,077**	**98%**

For each county we summed the CAML land use areas within the areas identified as dairy APNs and computed the distribution of crops and other land uses within dairies: Approximately one-quarter (26%) of the acreage identified with the APNs is in alfalfa land use in CAML, another 57% of the APNs identified correspond to field crops, grain and corn crops, or pasture crops. Alfalfa is generally rotated with field crops, grain crops, and corn. The ratio of alfalfa acreage to field, corn, and grain crop acreage is not unreasonable. Manure is typically not applied to fields while they grow alfalfa except an unknown amount of solids sometimes applied prior to planting or after the last cutting in the fall. Two land uses that are unlikely to receive significant amounts of manure include farm structures (6%) and vineyards (3%), which make up most of the remaining land use identified by the APNs (Table 10).

For the field-by-field nitrogen mass balance computations in GNLM, we assume that non-exported manure is applied only to land within dairies ("direct manure applications"), as identified by the RB5 APN database, and within that area only to the following CAML land use categories: field crops (600), cotton (601), sugar beets (605), corn (606), grain sorghum (607), sudan (9608), sunflowers (612), grain and hay (700), barley (701), wheat (702), oats (703), pasture (1600), and mixed pasture (1603). The numbers in parentheses refer to the CAML land use categories (see Section 3).

The simulation process described here spatially allocates cropland specifically used for manure applications and associates that land with a dairy that has a known number of animals (see above). For the historic simulation of nitrogen budgets, we lack a similar knowledge base, but would like to use the same simulation approach. For simplicity, we assume that the land identified as currently belonging to a dairy, using the RB5 APN database, remained unchanged since 1975 (the first period for which land application of manure was considered to be significant).

To be consistent with the overall historic nitrogen fluxes, the number of animals associated with each facility was scaled according to the total number of animal excretion reported for the TLB historically (Table 1). Hence, in 1950, each facility is assumed to have less than one-tenth of the number of animal excretion than it has today (Table 1). The land use and crop mix within each dairy (within its associated parcels) change over time according to the historic land use simulations described in Section 3. The list of specific crops, to which on-dairy, direct manure applications were assigned, remains constant in time. But the simulated (back-casted) land use will vary over time (Section 3). In any given period, the actual parcels receiving manure directly on the dairy are reassigned according to that period's landuse distribution among the APN parcels of a specific dairy.

Table 10. Total land area of cropland and other land uses within land parcels managed by a dairy. The land area was computed by an overlay of the land area self-identified by dairies as APNs of land receiving manure, and reported to RB5, with GIS processed data on the crop type and landuse distribution in CAML (see Section 3). Results are obtained from a GIS spatial analysis of an overlay of APN identified dairy "cropland" parcels with the CAML land use map (see Section 3).

CAML Land Use within Land Parcels Managed by Dairies	Area Across All Dairy Parcels in the TLB [ha (acres)]	% of Total Dairy Land Area
Alfalfa	27,315 (67,498)	25.6
Farm structures	6,019 (14,873)	5.64
Field crops (including cotton)	16,211 (40,059)	15.19
Grains and corn	43,740 (108,085)	41
Idle cropland	292 (722)	0.27
Natural vegetation	4,035 (9,970)	3.78
Other crops	31 (77)	0.03
Pasture	626 (1,547)	0.59
Tree crops	3,624 (8,954)	3.4
Urban	1,047 (2,587)	0.98
Vegetable crops	817 (2,044)	0.78
Vineyards	2,927 (7,234)	2.74
TOTAL	**106,684 (263,650)**	**100**
Field + grain + pasture (typical crops used for manure applications)	**60,577 (149,691)**	**57**

A final note of caution: The data used as input for this land allocation simulation, on a field by field basis, are subject to potential errors. For example, it is likely that both, those parcels receiving manure and the APN identification of these parcels, were occasionally misidentified or that data were reported incorrectly. Parcels receiving manure may also change from year to year. It is unclear, whether the data provided by an individual dairy facility represent the acreage used in 2007 only or the complete acreage of all crops typically used for manure applications, even if only on a rotating basis. Furthermore, the CAML land use cover described in Section 3 and used for the spatially distributed, field-by-field nitrogen loading mass balance analysis, represents only a snapshot of cropping conditions that are often transient from year to year and may not be the actual cropping conditions of 2007.

Hence, the simulation process described in this section can only be a much simplified conceptual approximation of complex processes in space and time involving people and land. The complexity of these processes is difficult to capture for current conditions, let alone under historic conditions, for

which data cannot be collected retroactively. We emphasize that our approach is not designed to predict historic and current loading rates with high accuracy for each field or even for each individual dairy. Instead, our approach is designed to recreate the approximate conditions across all dairies in the study area, while preserving the variety of crops grown, and the variability in management practices between dairies, as expressed by animal numbers and land base. The simulation algorithm provides overall consistency in the conceptual approach, given the lack of historic landuse and land ownership data for more detailed modeling input.

1.8 Review of N Loading from Non-Dairy Animal Farming Operations

Besides dairies and beef lots, the study area is or has been used to raise poultry (i.e., chickens, turkeys) and swine. We estimated the amount of manure nitrogen used for land application based on number of animals reported in the same four national agricultural census reports from NASS from which the number of milk cows were tabulated in Table 1. We also included the 1945 agricultural census data. The NASS reports identify, by county, chickens, broilers, turkeys, and total hogs and pigs. We used the following annual total nitrogen excretion rates for these animals (D. Liptzin, personal communication, 2011; U.S. EPA, 2004): chicken (layers, inventory) - 0.55 kg N/yr/head, chicken (broiler sales) – 0.07 kg N/head, turkeys (sales) – 0.4 kg N/head, and hogs (inventory) – 5.9 kg N/yr/head. Atmospheric losses due to ammonia volatilization were estimated based on a 51% atmospheric loss rate for poultry and a 63% loss rate for swine (U.S. EPA, 2004, their Table E-2). Manure nitrogen not lost to the atmosphere is assumed to be applied to cropland across the study area as soil amendment, in addition to typical fertilization rates (see Section 3).

The agricultural census years do not all coincide with the five historic and current periods used in this study and centered on 1945, 1960, 1975, 1990, and 2005. For 1960 and 1975, land applied manure N was estimated by linear interpolation of the 1950 and 1992 data. For 1990, we assumed the same values as in the 1992 census. Linear interpolation of the 2002 and 2007 census data provided an estimate of 2005 land applied manure N from poultry and hogs. The data presented in Table 11 summarizes the total land applied swine and poultry manure nitrogen across all five counties. For 2005, the total in TLB and SV is somewhat lower than in 1990, when production peaked at 1 Gg N/year (less than 1% of the estimated 2005 dairy manure N land applied).

Table 11. Manure nitrogen from swine and poultry used for land application on cropland within the study area.

	Hogs and Pigs [Mg N/yr]	Chicken [Mg N/yr]	Turkey [Mg N/yr]	Total [Mg N/yr]
1945	170	53	0	223
1960	16	155	141	313
1975	19	308	311	638
1990	22	482	503	1,007
2005	0	456	406	862

1.9 Summary: Animal Farming as a Source of Groundwater Nitrate

Dairies represent the major animal farming industry in the Tulare Lake Basin with one million adult milking cows. Other animal farming operations (AFOs) within the study area include beef cattle feedlots (one in the Salinas Valley and one of significant size in the Tulare Lake Basin), and a small number of poultry operations and hog farms with approximately 10,000 hogs, 14 million broilers, and 2 million turkeys. Given the dominant size of the dairy herd in the study area, compared to other confined animal facilities, this chapter focuses on N loading to groundwater from dairies and feedlots.

Animal farming is a significant source of nitrogen due to the organic and ammonium nitrogen contained in the manure excreted by animals. In dairies, manure is collected in dry and liquid forms, recycled within the animal housing area for bedding (dry manure) and as flushwater (freestall dairies), stored in lagoons (liquid manure), and ultimately applied to the land. Manure is land applied in solid or liquid form, typically on forage crops (e.g., summer corn, winter grain) that are managed by the dairy farm or it is exported to nearby farms (mostly as manure solids) and used as a soil amendment. Nitrogen contained in manure applied to cropland or leached from corrals or lagoons can be a significant source of nitrate leaching to groundwater.

We consider three separate sources of nitrate within a dairy farm: open corrals and feedlots, manure storage lagoons, and manured cropland. Each of these sources contributes to groundwater nitrate via distinctly different mechanisms. Groundwater nitrate loading is estimated by different methods for each of these land use categories. Groundwater nitrate loading from corrals and lagoons is based on recharge rates and nitrate concentrations found in previous field studies, and based on the actual size of a corral or lagoon. Groundwater nitrate loading on manured cropland, as on other cropland, is estimated by considering all nitrogen fluxes to and from an individual field, which are crop type dependent and include fertilizer and manure nitrogen applications, and harvest removal of nitrogen, among others. At the county and study area level, land applied manure is added to the study area and county cropland mass balance. For the CAML-based spatially distributed simulation of groundwater nitrate loading, individual dairies and the cropland under their managemend is considered. For this simulation, we also consider six different hypothetical scenarios that bracket actual conditions for the land application of manure to on-dairycropland versus off-dairy cropland. Groundwater nitrate loading on cropland is estimated as the difference between nitrogen inputs to and outputs from an agricultural field (mass balance approach) rather than based on literature values (see Sections 1 and 2).

Using recently published studies on dairy cow excretion and on atmospheric nitrogen losses in dairy facilities, along with county data on manure sales, and applying recent data collected by the Central Valley Regional Water Board, we estimate the nitrogen produced by the dairy herd, of which 38% is lost to the atmosphere as ammonia before land application of the manure. The amount of land-applied dairy manure nitrogen in the area is about 127 Gg N/yr [140,000 t N/yr] applied either directly to portions of 130,000 ha (320,000 ac) of dairy cropland or exported to nearby cropland. Due to

transportation costs, manure nitrogen exports are limited to cropland within the study area, often nearby dairies. Land applied manure nitrogen becomes part of the cropland nitrogen mass balance, which includes other input terms. Groundwater leaching is determined based on the overall cropland mass balance.

Direct leaching of manure N to groundwater from animal corrals and manure lagoons is about 1.5 Gg N/yr (1,700 t N/yr) and 0.2 Gg N/yr (220 t N/yr), respectively. There is significant uncertainty about the overall magnitude of corrals and lagoons as groundwater nitrate sources. Actual loading may range somewhere between 0.5 to 8 Gg N/yr (about 500 to 9,000 t N/yr) for corrals and between 0.2 – 2 Gg N/yr (about 200 – 2,200 t N/yr) for lagoons. Other CAFOs in the study area generate a total of about 0.9 Gg N/yr (1,000 t N/yr) that is land applied as manure or compost.

Over the past 60 years, dairy manure applied to land has increased exponentially, effectively doubling every 15 years, from 8 Gg N/yr (9,000 t N/yr) in 1945 to 16 Gg N/yr (18,000 t N/yr) in 1960, 32 Gg N/yr (35,000 t N/yr) in 1975, 56 Gg N/yr (62,000 t N/yr) in 1990, and 127 Gg N/yr (140,000 t N/yr) in 2005, an overall 16-fold increase in manure nitrogen output. The increase in manure nitrogen is a result of increasing herd size (7-fold between the late 1940s and 2005) and increasing milk production per cow (3-fold), and is slowed only by the increased nitrogen-use efficiency of milk production.

Until the 1960s, most dairy animals in the region were only partly confined, often grazing on irrigated pasture with limited feed imports. Manure from dairy livestock generally matched the nitrogen needs of dairy pastures. Since the 1970s, dairies in the Tulare Lake Basin have operated mostly as confined animal facilities, growing alfalfa, corn, and other grain feed on-site, importing additional feed, and housing the animals in corrals and freestalls. The growth in the dairy industry has created a nitrogen excess pool that remains unabsorbed by crops. Much of the nitrogen excess is a recent phenomenon. With groundwater quality impacts delayed by decades in many production wells, the recent increase in land applied manure nitrogen is only now beginning to affect water quality in wells of the Tulare Lake Basin, with much of the impact yet to come.

2. Nitrogen Source Loading - Synthesis

2.1 Overview

Groundwater is a vital natural resource extracted from subterranean aquifers for a broad array of purposes including agricultural irrigation, industrial production, and human drinking water supply. In California, access to and utilization of groundwater is indispensable. However, increases in human population density and concomitant urban uses, overdraft from expanding urban and agricultural demand, and worsening contaminant loading threaten the suitability and sustainability of groundwater as a hydrological resource in California. In select regions of California, nitrate leaching to groundwater impairs its beneficial use as drinking water and the source of contamination is poorly quantified.

This section of the Task Reports summarizes the results of our extensive analysis completed with joint funding from two projects (Dairy Project and SBX2 1 Nitrate in Drinking Water Project). We provide a detailed description of the nitrate loading to groundwater from various sources, at the study area level, the county level, the source category level, and at the land parcel level. Methods are explained only briefly and with a focus on the conceptual framework. Supporting methodological details, other than those provided on animal farming in the previous sections, can be found in Viers et al., 2012. While geographically focused on the Tulare Lake Basin and Salinas Valley, much of the methodology and many of the underlying data developed for this report are applicable, with modifications in some cases, to other areas of California or similar semi-arid, irrigated agricultural regions around the world.

This technical report identifies relevant sources and quantifies relative amounts of nitrate loading to groundwater in the Tulare Lake Basin and Salinas Valley. As will be shown in this Technical Report, human-generated nitrate sources to groundwater in the study area include (Figure 1):

- cropland (96% of total), where nitrogen applied to crops, but not removed by harvest, air emissions, or runoff is leached from the root zone to groundwater. Nitrogen intentionally or incidentally applied to cropland includes
  - o synthetic fertilizer (54%),
  - o animal manure (33%),
  - o irrigation source water (8%),
  - o atmospheric deposition (3%), and
  - o municipal effluent and biosolids (2%);
- percolation of wastewater treatment plant (WWTP) and food processing (FP) wastes (1.5% of total);
- recharge from animal corrals and manure storage lagoons (1% of total);
- leachate from septic system drainfields (1% of total);
- urban parks, lawns, golf courses, and leaky sewer systems (less than 1% of total); and

- downward migration of nitrate-contaminated water via wells (less than 1% of total).
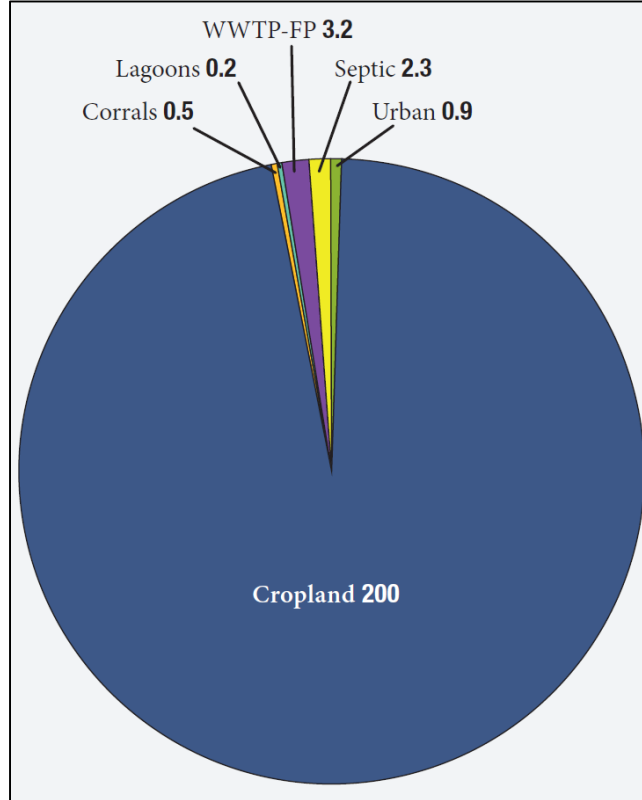
Figure 1. Estimated groundwater nitrate loading from major sources within the Tulare Lake Basin and Salinas Valley, in Gg nitrogen per year (1 Gg = 1,100 t).

Depending on the type of source, two principal methods are employed to assess nitrate loading:

- a mass balance approach was used to estimate nitrate loading from all categories of cropland except alfalfa;

- alfalfa cropland and nitrate sources other than cropland were assessed by reviewing permit records, literature sources, and by conducting surveys to estimate groundwater nitrate loading.

2.2 Nitrogen Cycle: Basic Concepts

Nitrogen is an essential element for all living organisms. Nitrogen cycles through the atmosphere, hydrosphere, and biosphere. The dominant gas (78%) in the atmosphere is highly stable (inert) N_2 gas. Biological nitrogen fixation transforms N_2 gas into ammonia (NH_3), which is rapidly converted to the forms of nitrogen needed for plant growth. Nitrogen fixation is performed only by specialized soil and aquatic microbes. Other living organisms cannot use inert atmospheric N_2 directly, but rely on accumulated soil organic matter, plants, animals, and microbial communities for nitrogen.

Soil nitrogen is most abundant in the organic form (N_{org}). Mineralization is a suite of processes performed by soil microbes that converts organic nitrogen to inorganic forms of nitrogen. The rates of mineralization depend on the environmental conditions such as temperature, moisture, pH, and oxygen content, as well as the type of organic matter available. The first product of mineralization is ammonium (NH_4^+), but under aerobic conditions, microbes can convert ammonium (NH_4^+) first to nitrite (NO_2^-) and then to nitrate (NO_3^-). Most plants use nitrate or ammonium as their preferred source of nitrogen (White 2006). Immobilization is the reverse of mineralization in that soil ammonium and nitrate are taken up by soil organisms and plants and converted into N_{org}.

The ultimate fate of "reactive" nitrogen (organic nitrogen, ammonium, nitrate, ammonia, nitrous oxide, etc.) is to return back to the atmosphere as N_2. For nitrate, this is a microbially mediated process ("denitrification") that requires an anoxic (i.e., oxygen-free) environment (see Section 2 for an expanded discussion).

Groundwater is becoming a growing component of the global nitrogen cycle because of the increased nitrogen inflows and because of long groundwater residence times. Nitrate does not significantly adhere to or react with sediments or other geologic materials, and it moves with groundwater flow. Other forms of reactive nitrogen in groundwater are less significant and much less mobile: ammonia occurs under some groundwater conditions, but it is subject to sorption and rapidly converts to nitrate under oxidizing conditions. Dissolved organic nitrogen concentrations are generally much less than those of nitrate, except near wastewater sources, due to the high adsorption of dissolved organic nitrogen to aquifer materials.

Groundwater nitrate inputs may come from natural, urban, industrial, and agricultural sources. Groundwater nitrate outputs occur through wells or via discharge to springs, streams, and wetlands. Discharge to surface water sometimes involves denitrification or reduction of nitrate to ammonium when oxygen-depleted conditions exist beneath wetlands and in the soils immediately below streams.

2.3 Nitrate Discharge to Groundwater

Nitrogen enters groundwater at varying concentrations and in varying forms (organic nitrogen, ammonium, nitrate) with practically all sources of recharge: diffuse recharge from precipitation and irrigation; focused recharge from streams, rivers, and lakes; focused recharge from recharge basins and storage lagoons; and focused recharge from septic system drainfields. Across major groundwater basins in California, diffuse recharge from irrigation, stream recharge, and intentional recharge are the major contributors to groundwater. Since groundwater is an important reservoir for long-term water storage, recharge is extremely important and desirable in many areas. Controlling nitrate in recharge and managing recharge is therefore a primary key to nitrate source control.

Current groundwater nitrate, its spatial distribution, and its changes through time result from recent, as well as historical, nitrate loading. To understand current and future groundwater conditions requires knowledge of historical, current, and anticipated changes in land use patterns, recharge rates,

and nitrate loading rates. Providing a comprehensive review of land use and nitrate loading rate information for the study area is a key objective of this technical report. Groundwater recharge is reviewed in Boyle et al. (2012).

2.4 Natural Nitrate Sources

Nitrate occurs naturally in many groundwater basins but at levels far below the regulatory maximum contaminant level (MCL) for drinking water (Mueller and Helsel, 1996). The main potential sources of naturally occurring nitrate are bedrock nitrogen and nitrogen leached from natural soils. Surface water nitrate concentrations can be elevated in areas with significant bedrock nitrogen (Holloway et al., 1998), but they are not high enough to be a drinking water concern. During the early twentieth century, conversion of the study area's semiarid and arid natural landscape to irrigated agriculture may have mobilized two additional, naturally occurring sources of nitrate. First, nitrate was released from drained wetlands at the time of land conversion due to increased microbial activity in agricultural soils; that is, stable organic forms of nitrogen that had accumulated in soils over millennia were converted to mobile nitrate. Second, nitrate salts that had accumulated over thousands of years in the unsaturated zone below the grassland and desert soil root zone due to lack of significant natural recharge were mobilized by irrigation (Dyer, 1965; Stadler et al., 2008; Walvoord et al., 2003). However, the magnitude of these sources (Scanlon, 2010) is considered to have negligible effects on regional groundwater nitrate given the magnitude of human sources.

2.5 Human Nitrate Sources

Human Nitrate Sources. Anthropogenic groundwater nitrate sources in the study area include agricultural cropland, animal corrals, animal manure storage lagoons, wastewater percolation basins at municipal wastewater treatment plants (WWTPs) and food processors (FPs), septic system drainfields (onsite sewage systems), leaky urban sewer lines, lawns, parks, golf courses, and dry wells or percolation basins that collect and recharge stormwater runoff. Incidental leakage of nitrate may also occur directly via poorly constructed wells. Croplands receive nitrogen from multiple inputs: synthetic fertilizer, animal manure, WWTP and FP effluent, WWTP biosolids, atmospheric deposition, and nitrate in irrigation water sources.

Categories of Sources and Timeline. We estimated the groundwater nitrate contributions for 58 agricultural cropland categories, for animal corrals, for manure lagoons, for each individual WWTP and FP within the study area, for dairies and other animal farming operations, for septic system drainfields, and for urban sources. Contributions from dry wells and incidental leakage through existing wells were estimated at the basin scale. Groundwater nitrate contributions were estimated for five time periods, each consisting of 5 years: 1943–1947 ("1945"), 1958–1962 ("1960"), 1973–1977 ("1975"), 1988–1992 ("1990"), and 2003–2007 ("2005"); the latter is considered to be current. Future year 2020, 2035, and 2050 loading was estimated based on anticipated land use changes (increased urbanization).

Data on the Spatial Extent (Area) of Cropland. The actual spatial extent or area of cropland acreage cannot be precisely reconstructed. Except for perennial crops, the specific crops grown in a field (if any) change seasonally and yearly. Even perennial cropping patterns change significantly over time. Three major sources of information are available that provide estimates of the spatial area or extent (acreage) of cropland sources (see also Section 3 for expanded discussion):

California Augmented Multisource Landcover (CAML): Aerial photography and detailed field mapping conducted at nearly decadal time intervals by the Department of Water Resources and other agencies leads to a detailed spatial map of crop categories with field-by-field resolution, albeit it can only be a snapshot in time. Maps of crop categories (and the total land area of each category) are available for one year in the late 1990s or early 2000s, and for one year in the early to mid-1990s, depending on county. Older maps are simulated based on county Agricultural Commissioner reports.

Agricultural Commissioner Reports (ACR): County Agricultural Commissioner offices annually survey and report the total amount of land harvested and the total amount of harvest. Data are available for each year over the entire period of interest (1943 – 2007). Data are reported as county totals, by crop category, and are not mapped. Often referred to as Ag Commissioner data or reports herein.

National Agricultural Statistics Survey (NASS) and agricultural census: NASS compiles county agricultural commissioner data and also infrequently conducts an agricultural census of harvested area and crop yields, independent of the county agricultural commissioner. Agricultural census data are available for 1950, 1992, 1997, 2002, and 2007. Data are reported as county totals, by crop category, and are not mapped.

All three sources of information were used separately (and comparatively) to derive estimates of groundwater nitrate loading from cropland: County agricultural commissioner reported crop acreages were averaged over five-year periods representing five historical time periods (1945, 1960, 1975, 1990, and 2005) to derive estimates of nitrate groundwater loading by crop category, by crop group, by county, and for the study area. Data reported in Section 1.6 are based on the cropping area data provided by the ACR. We compare NASS agricultural census data for the year closest to the most recent CAML mapping dates, by county and crop group, against the CAML and against the ACR derived nitrate loading (Section 1.7). The CAML information and the historic land use simulations generated from recent CAML maps were used to derive maps of groundwater nitrate loading with a resolution of 0.25 ha (less than 1 acre) for 1945, 1960, 1975, 1990, 2005, and 2050. Information in these maps was then aggregated to the crop category, crop group, county, and study area level (Section 1.8).

Spatial Granularity of Nitrate Source Loading Estimates. The groundwater nitrate loading estimates are computed and reported at four different levels of granularity or spatial resolution, depending on the source of information used and the amount of processing and aggregation:

- by land use parcel: individual categories of nitrate discharges to groundwater are mapped at a resolution of 0.25 ha (less than 1 ac) for the entire study area, in 15 year intervals between 1945 and 2050 (CAML based estimates);
- by crop categories (e.g., olives, persimmons, lettuce, strawberries) and crop groups (e.g., 'subtropicals', 'vegetables and berries'), averaged or summed over the entire study area, 1945 - 2005; (CAML, Ag Commissioner reports, NASS based estimates)
- by county, totaled across all cropland, all WWTPs and FPs, all dairies, all septic drains, and all municipal areas, 1945 - 2005 (CAML, Ag Commissioner reports, NASS based estimates); and
- summed or averaged for the study area, 1945 - 2005 (CAML, Ag Commissioner based estimates).

The higher levels of aggregation (coarser granularity, lower spatial resolution) provide more accurate estimates of nitrate loading for the spatial unit considered (crop category, crop group, county, study area) but are less descriptive of the actual loading in any given land parcel within each category. Aggregated totals are most useful for policy and planning.

We report nitrate loading to groundwater in two ways:

- Total annual nitrate leached to groundwater, measured in gigagrams of nitrate-nitrogen per year (Gg N/yr).[8] As a practical measure, 1 gigagram is roughly equivalent to $1 million of nitrogen fertilizer at 2011 prices.
- Intensity of the nitrate leaching to groundwater, measured in kilograms of nitrate-nitrogen per hectare of use per year (kg N/ha/yr) [lbs per acre per year, lbs/ac/yr], which represents the intensity of the source at its location (field, pond, corral, census block, city) and its potential for local groundwater pollution.

To provide a broad reference point of what the source loading numbers mean with respect to potential groundwater pollution, it is useful to introduce an operational benchmark that indicates whether nitrate leached in recharge to groundwater exceeds the nitrate drinking water standard. This operational benchmark considers that nearly all relevant anthropogenic nitrate sources provide significant groundwater recharge and therefore remain essentially undiluted when reaching groundwater. Our benchmark for "low" intensity versus "high" intensity of nitrate leaching is 35 kg N/ha/yr (31 lb N/ac/yr).[9] Aggregated across the 1.5 million ha (3.7 million ac) of cropland, the benchmark for total annual nitrate loading in the study area is 50 Gg N/yr (55,000 t N/yr). Total nitrate

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[1]. One gigagram is equal to 1 million kilograms (kg), 1,000 metric tons, 2.2 million pounds (lb), or 1,100 tons (t). In this report, nitrogen application to land refers to total nitrogen (organic nitrogen, ammonium-nitrogen, and nitrate-nitrogen). For consistency and comparison, total nitrate loading and the intensity of nitrate loading from the root zone to groundwater are also provided in units of nitrogen, not as nitrate. However, concentrations of nitrate in groundwater or leachate are always stated as nitrate (MCL: 45 mg/L) unless noted otherwise.

2. A typical groundwater recharge rate in the study area is roughly 300 mm/yr (1 AF/ac/yr). If that recharge contains nitrate at the MCL, the annual nitrate loading rate is 30 kg N/ha/yr (27 lb N/ac/yr). We allow an additional 5 kg N/ha/yr (4.5 lb N/ac/yr) to account for potential denitrification in the deep vadose zone or in shallow groundwater.

loading to groundwater above this benchmark indicates a high potential for regional groundwater degradation.

Estimating nitrate loading by source category. We used two methods to assess nitrate loading:

- a mass balance approach was used to estimate nitrate loading from all categories of cropland except alfalfa;
- alfalfa cropland and nitrate sources other than cropland were assessed by reviewing permit records, literature sources, and by conducting surveys to estimate groundwater nitrate loading (Viers et al. 2012).

2.6 Groundwater Nitrate Loading by Major Source Category

Cropland is by far the largest nitrate source, contributing an estimated 96% of all nitrate leached to groundwater (Table 12). The estimated total nitrate leached to groundwater (200 Gg N/yr [220,000 t N/yr]) ±30% is about three to five times the benchmark amount, which suggests large and widespread degradation of groundwater quality. Wastewater treatment plants and food processor waste percolation basins are also substantial, high-intensity sources.[10] Septic systems, manure storage lagoons, and corrals are relatively small sources basin-wide, but since their discharge intensity significantly exceeds the operational benchmark of 35 kg N/ha/yr (31 lb N/ac/yr), these source categories can be locally important. The magnitude and intensity of urban sources (other than septic systems) does not suggest widespread impact to groundwater (see Sections 5 and 6). The following provides further, more detailed discussion on these sources.

2.6.1 Agricultural Sources

Cropland sources: Overview. The five counties in the study area include 1.5 million ha (3.7 million ac) of cropland, about 40% of California's total irrigated cropland. Agricultural production includes many individual crops and significant year-to-year changes in crops grown and crop yields. The dominant crop groups in the project area include subtropical tree fruits (citrus and olives), deciduous tree fruits and nuts, field crops (including corn and cotton), grain crops, alfalfa, vegetables and strawberries, and grapes (see Figure 2). The study area also supports 1 million dairy cows. These produce one-tenth of the nation's milk supply as well as large amounts of manure.

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[10] The benchmark of 35 kg N/ha (31 lb N/ac) is not adequate for percolation basins, as their recharge rate is much more than 1 AF/ac. Acual average concentration (by county) of nitrogen in FP and WWTP discharges to percolation basins range from 2 to 10 times the MCL and 1 to 2 times the MCL, respectively (see Section 6).
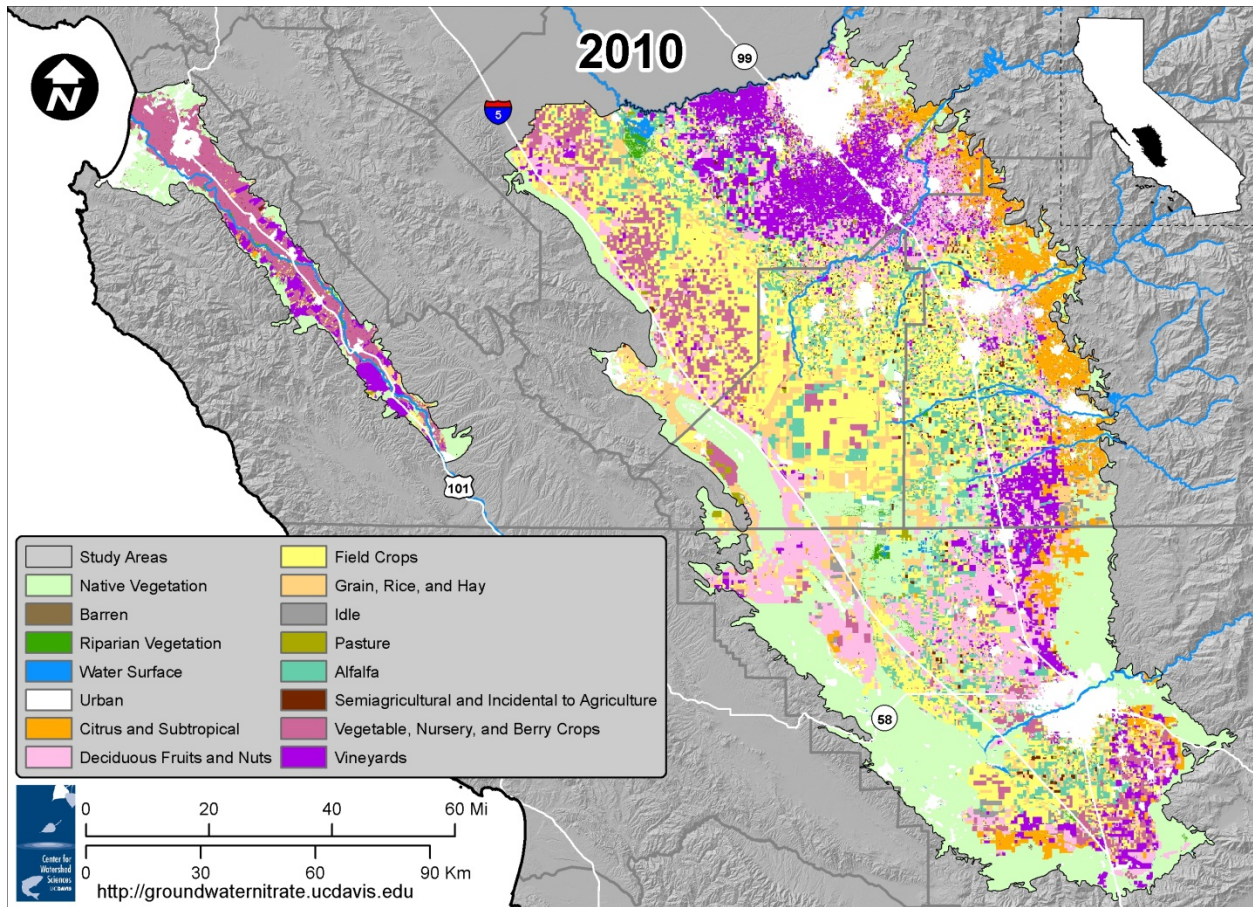
Figure 2. The Tulare Lake Basin (TLB) and Salinas Valley (SV) are the focus of this study. The study area represents 40% of California's diverse irrigated agriculture and more than half of its confined animal farming industry. It is home to 2.6 million people, with a significant rural population in economically disadvantaged communities. Spatial distribution of crop and other land use categories based on CAML data (see Section 3).

Cropland sources: Alfalfa. The mass balance approach is not applied to alfalfa because it does not receive significant amounts of fertilizer, while fixing large amounts of nitrogen from the atmosphere. Little is known about nitrate leaching from alfalfa; we used a reported value of 30 kg N/ha/yr (27 lb N/ac/yr) (Letey et al., 1979; Robbins et al., 1980, Viers et al., 2012). In total, 170,000 ha (420,000 ac) of alfalfa fields are estimated to contribute about 5 Gg N/yr (5,000 t N/yr) in the study area. Alfalfa harvest exceeds 400 kg N/ha/yr (360 lb N/ac/yr), or 74 Gg N/yr (82,000 t N/yr), in the study area.

Cropland sources other than alfalfa. Unlike other groundwater nitrate source categories, cropland has many sources of nitrogen application, all of which can contribute to nitrate leaching. Principally, crops are managed for optimal harvest. Synthetic nitrogen is the fertilizer of choice to achieve this goal, except in alfalfa and a few other leguminous crops (e.g., beans). Other sources of nitrogen are also applied to cropland, providing additional fertilizer, serving as soil amendments, or providing a means of waste disposal. These additional nitrogen sources include animal manure and effluent and biosolids from WWTPs, FPs, and other urban sources. Often do they replace synthetic

fertilizer as the main source of nitrogen for a crop. Atmospheric deposition of nitrogen and nitrate in irrigation water are mostly incidental but ubiquitous.

For the mass balance analysis, external nitrogen inputs to cropland are considered to be balanced over the long run (5 years and more) by nitrogen leaving the field in crop harvest, atmospheric losses (volatilization, denitrification), runoff to streams, or groundwater leaching. Hence, cropland nitrate leaching to groundwater is estimated by summing nitrogen inputs to a field (fertilizer, effluent, biosolids, manure, atmospheric deposition, irrigation water) and then subtracting the three other nitrogen outputs (harvest, atmospheric losses, and runoff).

Table 12. Major sources of groundwater nitrate, their estimated total contribution in the study area, their percent of total contribution, and their estimated average local intensity, which indicates local pollution potential. Actual total nitrate loading from these source categories is very likely within the range provided in parentheses.

	Total Nitrate Loading to Groundwater, Gg N/yr[1] (range) [1,000 t N/yr] (range)	Percent Contribution to Total Nitrate Leaching in the Study Area	Average Intensity of Nitrate Loading to Groundwater kg N/ha/yr [lbs N/ac/yr]
Cropland	195 (135 − 255) 215 (150 − 280)	93.7%	154 137
Alfalfa cropland	5 (<1 −10) 5 (<1--11)	2.4%	30 27
Animal corrals	1.5 (0.5 − 8) 1.7 (0.5 − 9)	0.7%	183 163
Manure storage lagoons	0.23 (0.2 − 2) 0.25 (0.2 − 2)	0.1%	183 163
WWTP and FP[2] percolation basins	3.2 (2 - 4) 3.5 (2 − 4)	1.5%	1,200[3] 1070
Septic systems	2.3 (1 − 4) 2.5 (1 − 4)	1.1%	<10->50 <8.8->45
Urban (leaky sewers, lawns, parks, golf courses)	0.88 (0.1–2) 0.97 (0.1 − 2)	0.5%	10 8.8
Surface leakage to wells	<0.4	—	—[4]

1. At 2011 prices, 1 Gg N (1,000 metric tons N or 1,100 t N) is roughly equivalent to $1 million in fertilizer nitrogen.
2. WWTP = wastewater treatment plant; FP = food processor.
3. The benchmark of 35 kg N/ha/yr does not apply to WWTP and FP percolation basins, which may recharge significantly more water than other sources. The nitrate loading may be high even if concentrations are below the MCL.
4. Surface leakage through improperly constructed wells is based on hypothetical estimates and represents an upper limit.

In total, the 1.27 million ha (3.1 million ac) of cropland, not including 0.17 million ha (0.4 million ac) of alfalfa, receive 380 Gg N/yr (419,000 t N/yr) from all sources. Synthetic fertilizer, at 204 Gg N/yr (225,000 t N/yr), is more than half of these inputs (Figure 3). Manure applied on dairy forages or exported for cropland applications off-dairy (but not leaving the study area) is one-third of all nitrogen inputs. Atmospheric deposition and nitrate-nitrogen in groundwater used as irrigation water are

approximately one-tenth of all nitrogen input. Urban effluent and biosolids application are small portions of the overall nitrogen input in the study area, but they are locally significant.
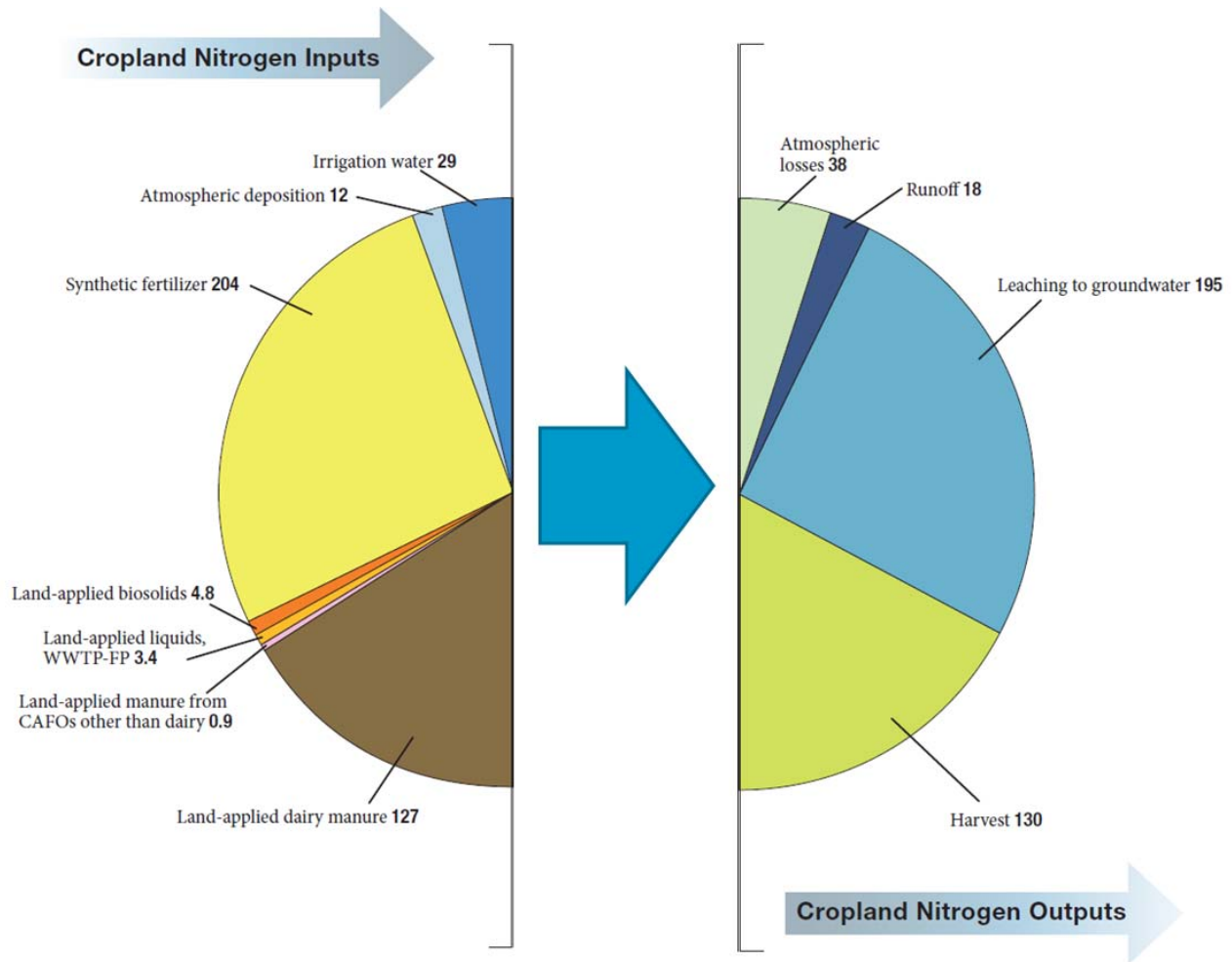
Figure 3. Overview of cropland input and output (Gg N/yr) in the study area (Tulare Lake Basin and Salinas Valley) in 2005. The left half of the pie chart represents total nitrogen inputs to 1.27 million ha (3.12 million ac) of cropland, not including alfalfa. The right half of the pie chart represents total nitrogen outputs with leaching to groundwater estimated by difference between the known inputs and the known outputs. No mass balance was performed on 0.17 million ha (0.4 million ac) of nitrogen-fixing alfalfa, which is estimated to contribute an additional 5 Gg N/yr to groundwater. Groundwater nitrate loading from all non-cropland sources is about 8 Gg N/yr

On the output side, the total nitrate leaching to groundwater from cropland (not including alfalfa) comprises 195 Gg N/yr (215,000 t N/yr) and is by far the largest nitrogen flux from cropland, much larger than the harvested nitrogen at 130 Gg N/yr (143,000 t N/yr). The nitrogen leached to groundwater nearly matches the amount of synthetic fertilizer applied to the same cropland, suggesting large system surpluses of nitrogen use on cropland. Other outputs are small: atmospheric losses are

assumed to be one-tenth of the inputs (see Section 7), and runoff is assumed to be 14 kg N/ha/yr (12.5 lb N/ac/yr) (Beaulac and Reckhow 1982).

Applying the benchmark of 50 Gg N/yr (55,000 t N/yr), groundwater leaching losses would need to be reduced by 150 Gg N/year (165,000 t N/yr) or more area-wide to avoid further large-scale groundwater degradation. Figure 3 suggests three major options to reduce nitrate loading to groundwater from cropland: develop techniques to make manure a useful and widely used fertilizer and reduce synthetic fertilizer application in the study area by as much as 75%; drastically reduce the use of manure in the study area; or significantly increase the agricultural output (harvest) without increasing the nitrogen input. Nitrate source reduction efforts will involve a combination of these options (Dzurella et al., 2012).

The following sections further discuss individual inputs and outputs that control agricultural cropland nitrate leaching.

Cropland inputs: Synthetic fertilizer (204 Gg N/yr [225,000 t N/yr]). Synthetic fertilizer application rates are estimated by first establishing a typical nitrogen application rate for each crop, derived from the literature, United States Department of Agriculture (USDA) Chemical Usage Reports, and UC Davis ARE agricultural cost and return studies for each of 58 crop categories within 10 crop groups (Figure 4). In a second step, we assess whether some of the typical nitrogen application rate is met by other sources such as effluent, biosolids, and manure. The procedure varies with crop type, location, and aggregation level. Fertilizer needs not met by effluent, biosolids, or manure (see below) are assumed to be met by synthetic fertilizer, providing an estimate of synthetic fertilizer use at local (Figure 4), crop (see Figure 6), county (see Table 13), and study area (see Figure 3) levels. The magnitude of total estimated synthetic fertilizer use (204 Gg N/yr [225,000 t N/yr]) in the study area, on about 40% of California's irrigated land, is consistent with statewide average recorded sales of synthetic fertilizer used on cropland of 466 Gg N/yr (514,000 t N/yr) (D. Liptzin, pers. comm., 2012).
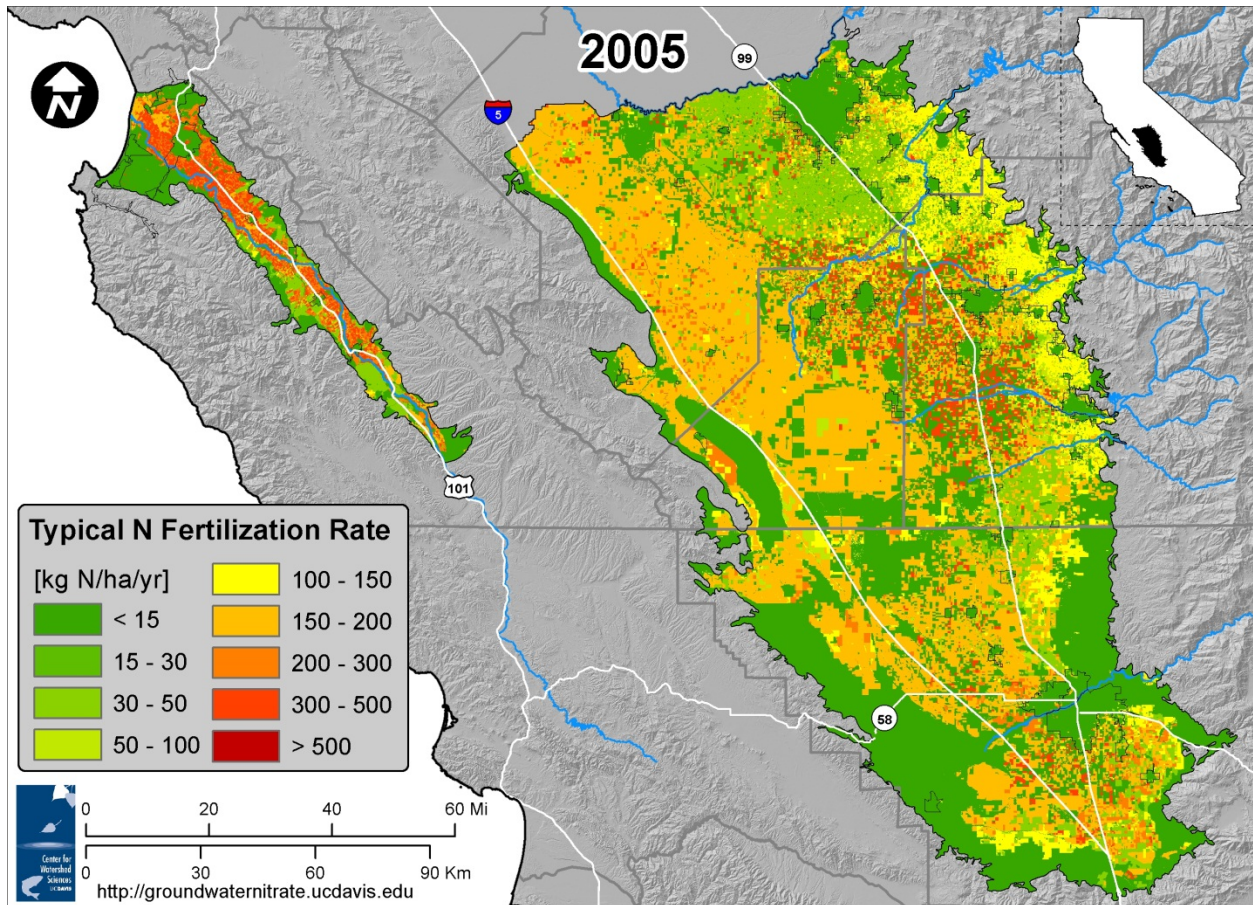
Figure 4. Current typical annual fertilization rates (1 kg/ha/yr = 1.1 lbs/ac/yr) in irrigated agricultural cropland of the study area derived from the literature, United States Department of Agriculture (USDA) Chemical Usage Reports, and agricultural cost and return studies for each of 58 crop categories (does not include manure applications). Rates account for multi-cropping in some vegetable crops and double-cropping of corn and winter grain. Spatial distribution of crop categories based on CAML data (see Section 3).

Cropland inputs: Animal manure (land-applied: 128 Gg N/yr [141,000 t N/yr]; corral and lagoon loading directly to groundwater: 1.7 Gg N/yr [1,900 t N/yr]). The Tulare Lake Basin houses 1 million adult dairy cows and their support stock (more than half of California's dairy herd), 10,000 hogs and pigs, and 15 million poultry animals. Dairy cattle are by far the largest source of land-applied manure nitrogen in the area (127 Gg N/yr [140,000 t N/yr]; see Figure 3). Manure is collected in dry and liquid forms, recycled within the animal housing area for bedding (dry manure) and as flushwater (freestall dairies), and ultimately applied to the land. Manure is applied in solid and liquid forms, typically on forage crops (e.g., summer corn, winter grain) managed by the dairy farm, or is exported to nearby farms (mostly as manure solids) and used as soil amendment. The amount of land-applied manure nitrogen is estimated based on: recently published studies of dairy cow, swine, and poultry excretion rates; animal numbers reported by the Regional Water Board and the USDA Agricultural Census; and an estimated 38% atmospheric nitrogen loss in dairy facilities before land application of the manure. Manure not exported from dairy farms is applied to portions of 130,000 ha (320,000 ac) of dairy cropland. Exported manure

nitrogen is largely applied within the study area, mostly within the county of origin, on cropland nearby dairies.

Direct leaching to groundwater from animal corrals and manure lagoons is about 1.5 Gg N/yr (1,700 t N/yr) and 0.2 Gg N/yr (220 t N/yr), respectively (see Table 12).

Cropland inputs: Irrigation water (29 Gg N/yr (32,000 t N/yr)). Irrigation water is also a source of nitrogen applied to crops. Surface irrigation water is generally very low in nitrate. Nitrate in groundwater used as irrigation water is a significant source of nitrogen but varies widely with location and time. We used average nitrate concentrations measured in wells and basin-wide estimates of agricultural groundwater pumping (Faunt, 2009) to estimate the total nitrogen application to agricultural lands from irrigation water, in the range of 20 Gg N/yr (22,000 t N/yr) to 33.4 Gg N/yr (36,800 t N/yr).
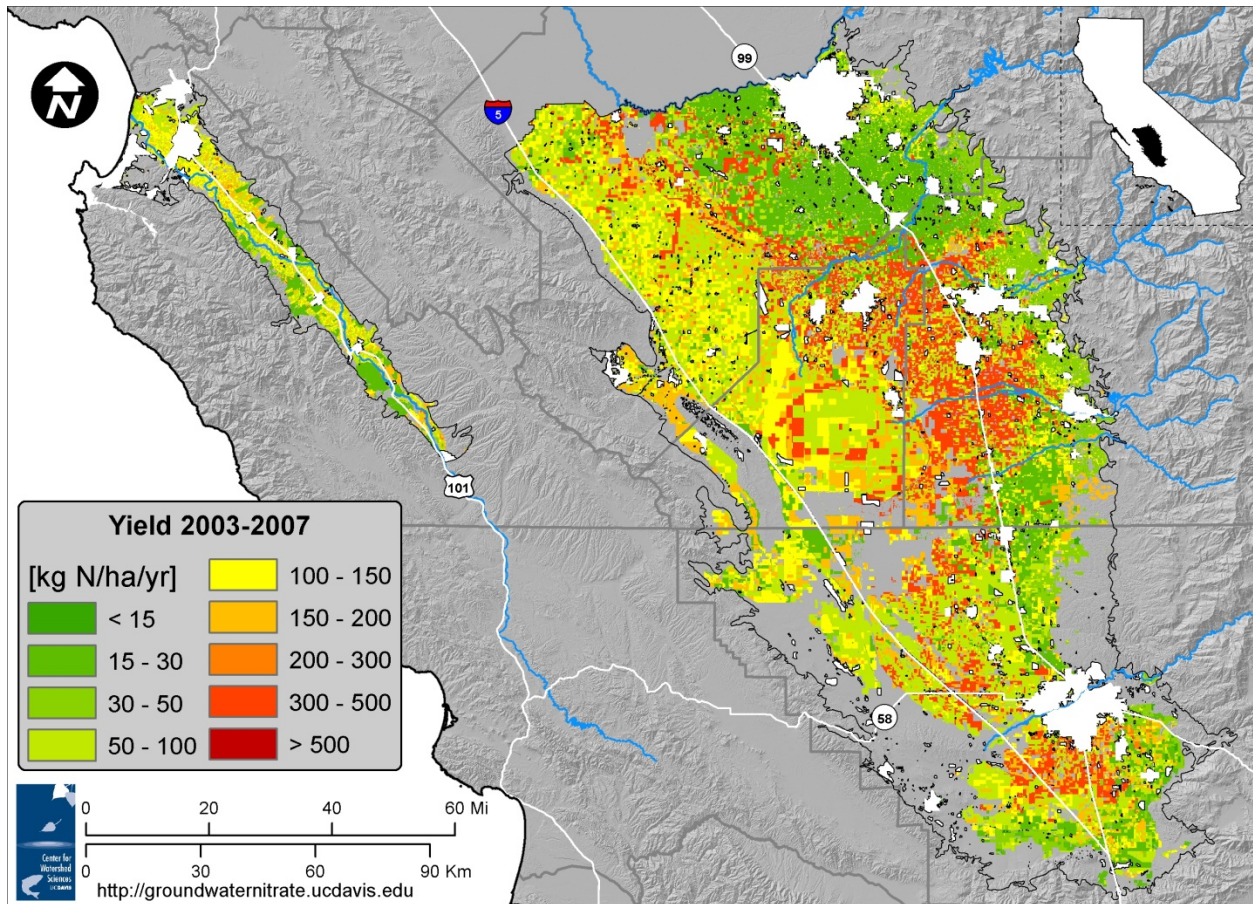
Figure 5. Current annual nitrogen removal rate in harvested materials (1 kg/ha/yr = 1.1 lbs/ac/yr) derived from county reports of harvested area and harvested tonnage for each of 58 crop categories. Rates account for multi-cropping in some vegetable crops and double-cropping of corn and winter grain. Spatial distribution of crop categories based on CAML data (see Section 3).

Cropland and general landscape inputs: Aerial deposition (12 Gg N/yr [13,000 t N/yr]).
Nitrogen emissions to the atmosphere as NOx from fossil fuel combustion and ammonia from manure at confined animal feeding operations undergo transformations in the atmosphere before being redeposited, often far from the source of emissions. Nitrogen deposition estimates at broader spatial scales are typically based on modeled data. Nitrogen deposition in urban and natural areas was assumed to be retained with the ecosystem (Vitousek and Howarth, 1991). In cropland, nitrogen deposition was included in the nitrogen mass balance. For the Salinas Valley, average aerial deposition is 5.6 kg N/ha/yr (0.6 Gg N/yr) (5.0 lb N/ac [660 t N/yr]). The Tulare Lake Basin receives among the highest levels in the state, averaging 9.8 kg N/ha/yr (11.3 Gg N/yr) (8.7 lb N/ac/yr [12,500 t N/yr]).

Cropland output: Harvested nitrogen (130 Gg N/yr [143,000 t N/yr]). The nitrogen harvested is the largest independently estimated nitrogen output flow from cropland. Historical and current annual ACR data provide annual harvested acreage and yields for major crops. From the reported harvest, we estimate the nitrogen removed. For each of 58 crop categories, the study area total harvest nitrogen and total acreage used to estimate the rate of nitrogen harvested (Figure 5). All crops combined (not including alfalfa) contain a total of 130 Gg N/yr (143,000 t N/yr), with cotton (21 Gg N/yr [23,000 t N/yr]), field crops (28 Gg N/yr [31,000 t N/yr]), grain and hay crops (30 Gg N/yr [33,000 t N/yr]), and vegetable crops (30 Gg N/yr [30,000 t N/yr]) making up 85% of harvested nitrogen. Tree fruits, nuts, grapes, and subtropical crops constitute the remainder of the nitrogen export from cropland.

Groundwater loading from irrigated agriculture, by crop group and by county. Significant differences exist in groundwater loading intensity between crop groups.[11] The intensity of groundwater loading is least in vineyards (less than 35 kg N/ha/yr [31 lb N/ac/yr]), followed by rice and subtropical tree crops (about 60 kg N/ha/yr [54 lb N/ac/yr]), tree fruits, nuts, and cotton (90–100 kg N/ha/yr [80–90 lb N/ac/yr]), vegetables and berry crops (over 150 kg N/ha/yr [130 lb N/ac/yr]), which includes some vegetables being cropped twice per year), field crops (about 480 kg N/ha/yr [430 lb N/ac/yr]), and grain and hay crops (about 200 kg N/ha/yr [180 lb N/ac/yr]). Manure applications constitute the source of nearly all of the nitrate leaching from these latter two crop groups. Without manure, field crops leach less than 35 kg N/ha/yr (31 lb N/ac/yr), and grain and hay crops leach 50 kg N/ha/yr (45 lb N/ac/yr). Figure 6 shows the rate of reduction (in kg N/ha/crop) that would be needed, on average across each crop group, to reduce groundwater nitrate leaching to benchmark levels.

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[11] Aggregated estimates were obtained from study area-wide totals for harvested area (by crop group), for typical nitrogen application, and for harvested nitrogen. The following averages were assumed: irrigation water nitrogen (24 kg N/ha/yr (21 lbs N/ac/yr)), atmospheric nitrogen losses (10% of all N inputs), and runoff (14 kg N/ha/yr (12.5 lbs N/ac/yr)). Most manure is likely land applied to field crops, particularly corn, and to grain and hay crops. Little is known about the actual manure distribution prior to 2007 and the amount of synthetic fertilizer applied on fields receiving manure. As an illustrative scenario, we here assume that two-thirds of dairy manure is applied to field crops and one-third of dairy manure is applied to grain and hay crops. In field crops, 50% of crop nitrogen requirements are assumed to be met with synthetic fertilizer, in grain and hay crops 90% of their crop nitrogen requirements are assumed to be met by synthetic fertilizer. These are simplifying assumptions that neglect the non-uniform distribution of manure on field and grain crops between on-dairy, near-dairy, and away-from-dairy regions. However, corn constitutes most (106,000 ha (262,000 ac)) of the 130,000 ha (321,000 ac) in field crops, with at least 40,000 ha (99,000 ac) grown directly on dairies. Grain crops are harvested from 220,000 ha (544,000 ac). (For further detail, see Sections 3 and 4 in Viers et al., 2012).

At the county level, we aggregate cropland area, fertilizer applications (by crop category), manure output from individual dairies, effluent and biosolid land applications from individual facilities, and crop category–specific harvest. Differences in cropping patterns between counties and the absence or presence of dairy facilities within counties are the main reason for county-by-county differences in total groundwater loading and in the average intensity of groundwater loading (Table 13). Fresno County, which has fewer mature dairy cows (133,000) than Kings (180,000), Tulare (546,000), or Kern (164,000) Counties and also has large areas of vineyards (see Figure 2), has the lowest average groundwater loading intensity (103 kg N/ha/yr [103 lb N/ac/yr]). Monterey County is dominated by vegetable and berry crops (high intensity) and grape vineyards (low intensity). The partial nutrient balance (PNB), which is the ratio of harvested N to cropland N inputs, varies from less than 35% in Tulare County to nearly 45% in Fresno County. If manure or other organic materials were applied only to within estimated typical fertilizer application rates, throughout the study area (Figure 4), then the resulting hypothetical partial nutrient balance (PNB_0) would range from nearly 45% in Monterey County to about 55% in Fresno County and Kern County, and to over 70% in Tulare County (Table 13). The difference between PNB and PNB_0 indicates the importance of accounting for all sources of nitrogen to cropland and the importance of properly managing organic nitrogen sources, especially manure.
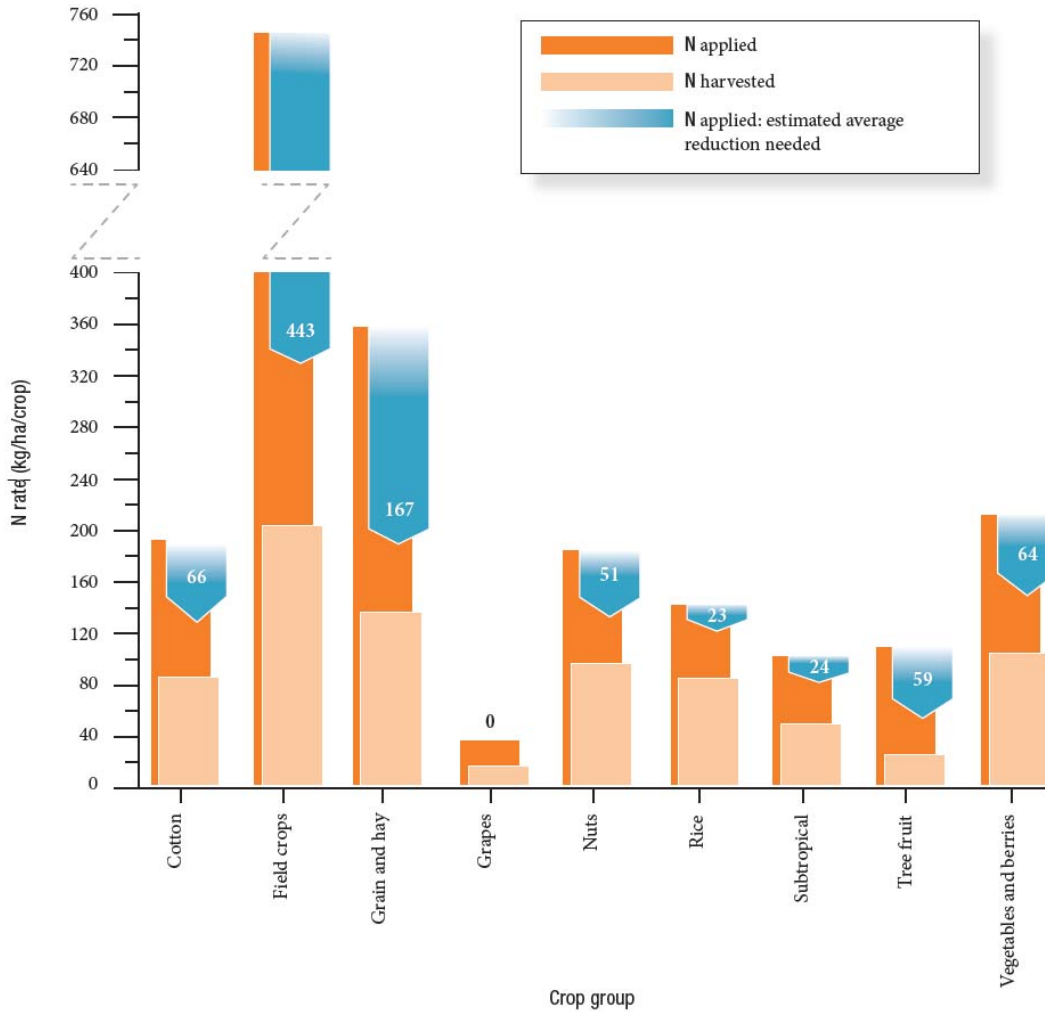
Figure 6. Nitrogen application reduction needed to reduce groundwater nitrate loading to less than 35 kg N/ha/crop, compared with average nitrogen applied (synthetic fertilizer and manure) and nitrogen harvested (all units in kg N/ha/crop). Rates are given per crop, and the required reduction does not account for double-cropping. Some vegetables and some field crops are harvested more than once per year. In that case, additional reductions in fertilizer applications would be necessary to reduce nitrate loading to less than 35 kg N/ha. Large reductions needed in field crops and grain and hay crops are due to the operational assumption that manure generated in the study area is applied to only these crop groups. Typical amounts of synthetic fertilizer applied ("N applied") to these crops, without excess manure, are 220 kg N/ha/crop for field crops and 190 kg N/ha/crop for grain and hay crops. Thus, without excess manure, average field crops and grain and hay crops may require relatively small reductions in nitrogen application.

Table 13. Major nitrogen fluxes to and from cropland in the study area, by county (not including alfalfa).

Table 2(a). Metric units.

	Synthetic Fertilizer Application Gg N/yr	Manure Application Gg N/yr	Land Applied Effluent and Biosolids Gg N/yr	Harvest Gg N/yr	PNB[1] %	PNB$_0$[2] %	Ground-water Loading Gg N/yr	Ground-water Loading Intensity kg N/ha/yr
By County								
Fresno	62.1	16.6	0.8	35.5	44.7	54.4	42.4	103
Kern	50.3	20.4	4.6	29.6	39.3	56.4	42.8	141
Kings	27.5	22.0	1.9	19.6	38.1	62.7	29.2	179
Tulare	36.0	67.3	0.7	32.7	31.4	72.5	65.1	236
Monterey	28.1	1.4	0.1	12.4	41.9	43.5	15.6	138
By Basin								
TLB	176	127	8.1	118	37.8	60.5	179	155
SV	28	1	0.1	12	41.9	43.5	16	138
Overall	**204**	**128**	**8.2**	**130**	**38.2**	**58.3**	**195**	**154**

1. PNB = partial nutrient balance, here defined as Harvest N ÷ (Synthetic + Manure + Effluent +Biosolids Fertilizer N).

2. PNB$_0$ = hypothetical PNB, if no manure/effluent/biosolids overage is applied above typical fertilizer rates.

Note: Manure applications include non-dairy manure nitrogen (0.9 Gg N/yr (990 t N/yr) for the entire study area). Groundwater loading accounts for atmospheric deposition (9.8 and 5.6 kg N/ha/yr (8.7 and 5.0 lbs N/ac/yr) in TLB and SV, respectively), atmospheric losses (10% of all inputs), irrigation water quality (22.8 kg N/ha/yr (20 lbs N/ac/yr)), and runoff (14 kg N/ha/yr (12.5 lbs N/ac/yr)) to and from agricultural cropland, in addition to fertilizer and manure application, and harvested nitrogen. Synthetic fertilizer application on field crops is assumed to meet 50% of typical application rates; on grain and hay crops, 90% of typical applications, with the remainder met by manure.

Table 2(b). US Standard units

	Synthetic Fertilizer Application 1,000 t N/yr	Manure Appli-cation 1,000 t N/yr	Land Applied Effluent and Biosolids 1,000 t N/yr	Harvest 1,000 t N/yr	PNB[1] %	PNB$_0$[2] %	Ground-water Loading 1,000 t N/yr	Ground-water Loading Intensity lb N/ac/yr
By County								
Fresno	68.3	18.3	0.88	39.1	44.7	54.4	46.7	92
Kern	55.4	22.5	5.0	32.6	39.3	56.4	47.2	123
Kings	30.3	24.3	2.1	21.6	38.1	62.7	32.2	160
Tulare	39.7	74.2	0.77	36.0	31.4	72.5	71.8	210
Monterey	30.9	1.54	0.11	13.6	41.9	43.5	17.2	123
By Basin								
TLB	194	140	8.9	130	37.8	60.5	197	138
SV	30.8	1.1	0.11	13	41.9	43.5	18	123
Overall	**225**	**141**	**9**	**143**	**38.2**	**58.3**	**215**	**137**

1 & 2. See notes in metric unit table (2a) above

2.6.2 Historical Development of Fertilizer Use, Manure Production, Harvested Nitrogen, and Estimated Nitrate Leaching to Groundwater.

Current and near-future groundwater nitrate conditions are mostly the result of past agricultural practices. So the historical development of nitrogen fluxes to and from cropland provides significant insight in the relationship between past agricultural practices, their estimated groundwater impacts, and current as well as anticipated groundwater quality. Two major inventions effectively doubled the farmland in production from the 1940s to the 1960s: the introduction of the turbine pump in the 1930s, allowing access to groundwater for irrigation in a region with very limited surface water supplies, and the invention and commercialization of the Haber-Bosch process, which made synthetic fertilizer widely and cheaply available by the 1940s.
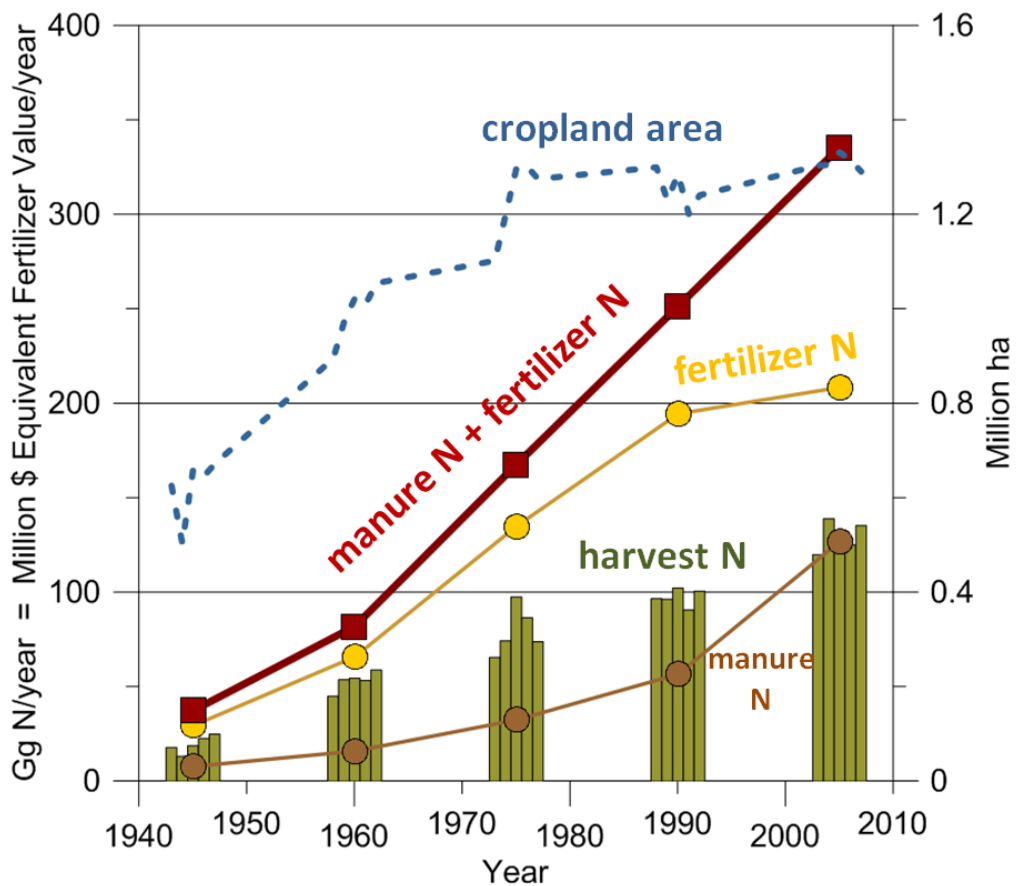

Figure 7. Estimated historical agricultural development in the study area (not including alfalfa): total harvested area, total harvested nitrogen in fertilized crops, fertilizer applied to cropland (5 year average), manure applied

to cropland (5 year average), and sum of manure and fertilizer applied to cropland (5 year average).[12] Note: 0.4 million ha = 1 million ac.

The amount of cropland (not including alfalfa) in the study area nearly doubled in less than 20 years, from 0.6 million ha (1.5 million ac) in the mid-1940s to nearly 1.0 million ha (2.5 million ac) in 1960 (Figure 7). Further increases occurred until the 1970s, to 1.3 million ha (3.2 million ac), but the extent of farmland has been relatively stable for the past 30 years.

In contrast, the harvested nitrogen has consistently increased throughout the past 60 years (Figure 7). From 1945 to 1975, total harvested nitrogen increased twice as fast as farmland expansion, quadrupling from 20 Gg N/ yr (22,000 t N/yr) to 80 Gg N/yr (88,000 t N/yr). Without further increases in farmland, harvests and harvested nitrogen increased by more than 60% in the second 30-year period, from the mid-1970s to the mid-2000s.

Synthetic fertilizer inputs also increased from the 1940s to the 1980s but have since leveled off. Between 1990 and 2005, the gap between synthetic nitrogen fertilizer applied and harvested nitrogen has significantly decreased.[13]

In contrast, dairy manure applied to land has increased exponentially, effectively doubling every 15 years (see Figure 7), from 8 Gg N/yr (9,000 t N/yr) in 1945 to 16 Gg N/yr (18,000 t N/yr) in 1960, 32 Gg N/yr (35,000 t N/yr) in 1975, 56 Gg N/yr (62,000 t N/yr) in 1990, and 127 Gg N/yr (140,000 t N/yr) in 2005, an overall 16-fold increase in manure nitrogen output. The increase in manure nitrogen is a result of increasing herd size (7-fold) and increasing milk production per cow (3-fold) and is slowed only by the increased nitrogen-use efficiency of milk production.

Until the 1960s, most dairy animals in the region were only partly confined, often grazing on irrigated pasture with limited feed imports. Manure from dairy livestock generally matched the nitrogen needs of dairy pastures. Since the 1970s, dairies in the Tulare Lake Basin have operated mostly as confined animal facilities, growing alfalfa, corn, and grain feed on-site, importing additional feed, and housing the animals in corrals and freestalls. The growth in the dairy industry has created a nitrogen excess pool that remains unabsorbed by crops (see Figure 7). Much of the nitrogen excess is a recent phenomenon (see Figure 7). With groundwater quality impacts delayed by decades in many production wells (Boyle et al., 2012), the recent increase in land applied manure nitrogen is only now beginning to affect water quality in wells of the Tulare Lake Basin, with much of the impact yet to come.

2.6.3 Urban and Domestic Sources

Urban and domestic sources: Overview. Urban nitrate loading to groundwater is divided into four categories: nitrate leaching from turf, nitrate from leaky sewer systems, groundwater nitrate contributions from WWTPs and FPs, and groundwater nitrate from septic systems. For all these systems,

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[12] Not shown: In the study area, harvested alfalfa area grew from 0.12 million ha (0.3 million ac) in the 1940s to 0.2 million ha (0.5 million ac) around 1960, then leveled off to current levels of 0.17 million ha (0.42 million ac). Since the 1960s, nitrogen removal in alfalfa harvest has varied from 50 to 80 Gg N/yr.

[13] Fertilizer application rates and statewide fertilizer sales have grown little since the late 1980

groundwater nitrate loading is estimated based on either actual data or reported data of typical nitrate leaching.

   Urban and domestic sources: Wastewater treatment plants and food processors (11.4 Gg N/yr [12,600 t/yr]: 3.2 Gg N/yr [3,500 t/yr] to percolation ponds, 3.4 Gg N/yr [3,800 t/yr] in effluent applications to cropland, and 4.8 Gg N/yr [5,300 t/yr] in WWTP biosolids applications to cropland). The study area has roughly 2 million people on sewer systems that collect and treat raw sewage in WWTPs. In addition, many of the 132 food processors within the study area generate organic waste that is rich in nitrogen (Table 14). Potential sources of groundwater nitrate contamination from these facilities include effluent that is land applied on cropland or recharged directly to groundwater via percolation basins, along with waste solids and biosolids that are land applied. Typically, WWTP influent contains from 20 mg N/L to 100 mg N/L total dissolved nitrogen (organic N, ammonium N, nitrate-N), of which little is removed in standard treatment (some WWTPs add treatment beyond conventional processes to remove nutrients including nitrate and other forms of nitrogen). Across the study area, WWTP effluent nitrogen levels average 16 mg N/L. Within the study area, 40 WWTPs treat 90% of the urban sewage. FP effluent nitrogen levels to percolation basins and irrigated agriculture average 42 mg N/L and 69 mg N/L, respectively.

Table 14. Total nitrogen discharge to land application and average total nitrogen concentration (as nitrate-N, MCL: 10 mg N/L) in discharge to percolation basins from WWTPs and FPs, based on our surveys of WWTPs and the FP survey of Rubin et al. (2007).

Table 3(a). Metric units.

	Biosolids	WWTP Land Application	WWTP Percolation Concentration	FP Land Application	FP Percolation Concentration
By County	Gg N/yr	Gg N/yr	mg N/L	Gg N/yr	mg N/L
Fresno	0.006	0.40	18.5	0.42	56.2
Kern	3.1	0.92	17.7	0.56	43.9
Kings	1.6	0.09	11.2	0.26	2.1
Tulare	0.038	0.50	14.9	0.13	34.2
Monterey	0	0.09	13.9	0.05	22.1
By Basin					
Tulare Lake Basin	4.8	1.9	16.3	1.37	43.3
Salinas Valley Basin	0	0.09	13.9	0.05	22.1
Overall Average	**4.8**	**2.0**	**16**	**1.4**	**42**

Table 3(b). US standard units.

	Biosolids	WWTP Land Application	WWTP Percolation Concentration	FP Land Application	FP Percolation Concentration
By County	1,000 t N/yr	1,000 t N/yr	mg N/L	1,000 t N/yr	mg N/L
Fresno	0.006	0.40	18.5	0.46	56.2
Kern	3.4	0.92	17.7	0.62	43.9
Kings	1.7	0.09	11.2	0.29	2.1
Tulare	0.044	0.50	14.9	0.14	34.2
Monterey	0	0.09	13.9	0.05	22.1
By Basin					
Tulare Lake Basin	5.3	2.1	16.3	1.51	43.3
Salinas Valley Basin	0	0.09	13.9	0.05	22.1
Overall Average	**5.3**	**2.2**	**16**	**1.5**	**42**

Urban and domestic sources: Septic systems (2.3 Gg N/yr [2,500 t N/yr]). Crites and Tchobanoglous (1998) estimated that the daily nitrogen excretion per adult is 13.3 g. Approximately 15% of that nitrogen is assumed to either stay in the septic tank, volatilize from the tank, or volatilize from the septic leachfield (Siegrist et al. 2000). Based on census data, the number of people on septic systems in the study areas is about 509,000 for the Tulare Lake Basin and 48,300 for Salinas Valley. Total nitrate loading from septic leaching is 2.1 Gg N/yr (2,300 t N/yr) in the Tulare Lake Basin and 0.2 Gg N/yr (220 t N/yr) in the Salinas Valley. The distribution of septic systems varies greatly. The highest density of septic systems is in peri-urban (rural sub-urban) areas near cities but outside the service areas of the wastewater systems that serve those cities (Figure 8). In the Tulare Lake Basin and Salinas Valley, 7.9% and 12.6%, respectively, of the land area exceeds the EPA-recommended threshold of 40 septic systems per square mile (0.154 systems per ha). Nearly 1.5% of the study area has a septic system density of over 256 systems per square mile (1 system/ha, or 1 system/2.5 ac). In those areas, groundwater leaching can significantly exceed our operational benchmark rate of 35 kg N/ha/yr (31 lb N/ac/yr).
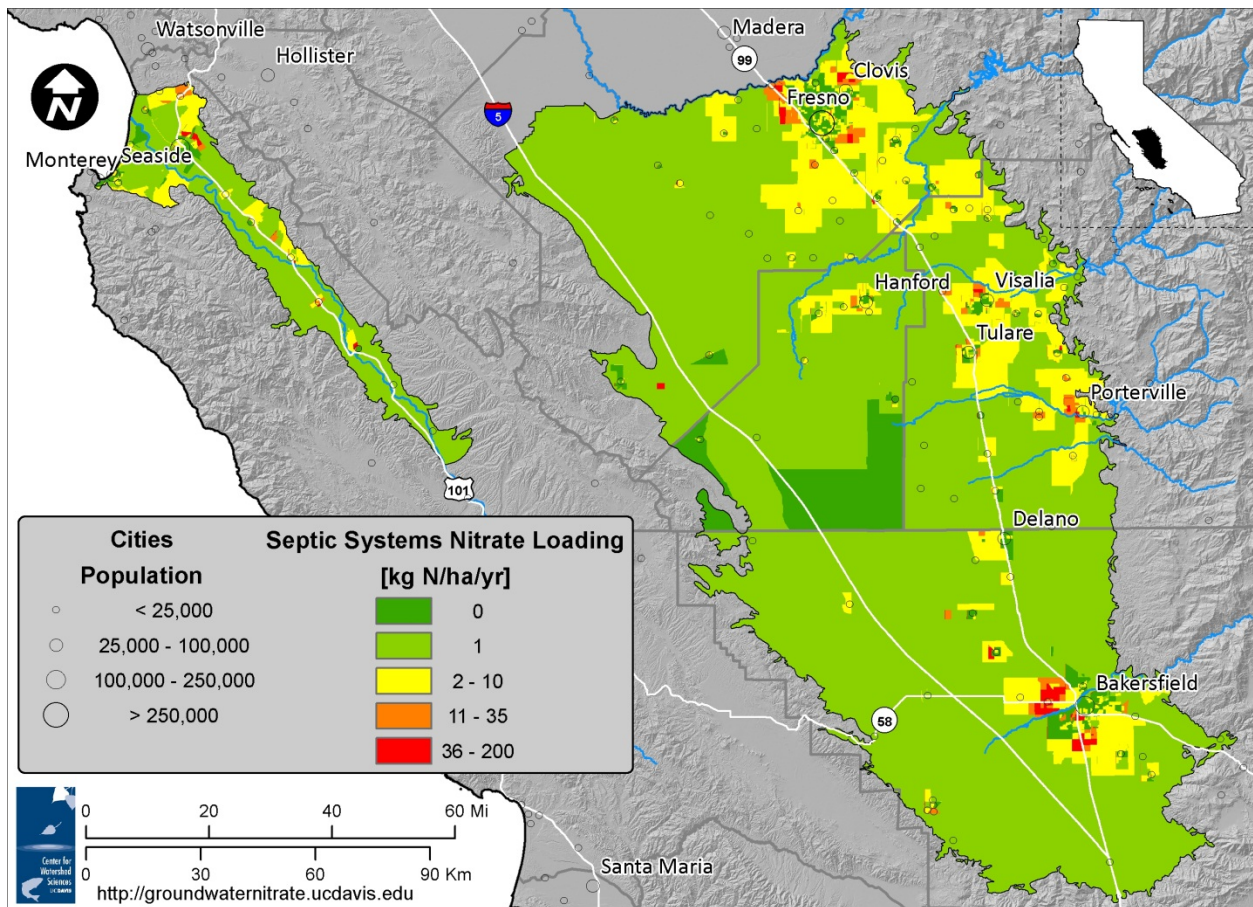
Figure 8. Septic-derived nitrate leaching rates within the study area.

Urban and domestic sources: Fertilizer and leaky sewer lines (0.88 Gg N/yr [970 t N/yr]). Fertilizer is used in urban areas for lawns, parks, and recreational facilities such as sports fields and golf courses. These land uses differ in their recommended fertilizer use, and there is almost no evidence of actual fertilization rates. Based on the most comprehensive survey of turfgrass leaching, only about 2% of applied nitrogen fertilizer was found to leach below the rooting zone (Petrovic, 1990). For our nitrogen flow calculations, we assume a net groundwater loss of 10 kg N/ha/yr (8.9 lb N/ac/yr) from lawns and golf courses in urban areas (0.35 Gg N/yr [380 t N/yr]).

Sewer systems in urban areas can be a locally significant source of nitrogen. We use both reported sewer nitrogen flows and per capita nitrogen excretion rates to obtain total nitrogen losses via leaky sewer lines in urban areas. Nationally, estimated municipal sewer system leakage rates range from 1% to 25% of the total sewage generated. Given that much of the urban area within the study region is relatively young, we consider that the leakage rate is low, roughly 5% or less (0.53 Gg N/yr).

2.6.4 Wells, Dry Wells, and Abandoned Wells as Sources

Wells, dry wells, and abandoned wells (<0.4 Gg N/yr [<440 t N/yr]). Wells contribute to groundwater nitrate pollution through several potential pathways. Lack of or poor construction of the seal between the well casing and the borehole wall can lead to rapid transport of nitrate-laden runoff or irrigation water from the surface into the aquifer. In an inactive or abandoned production well, long well screens (several hundred feet) extending from relatively shallow depth to greater depth, traversing multiple aquifers, may cause water from nitrate-contaminated shallow aquifer layers to pollute deeper aquifer layers, at least in the vicinity of wells. Dry wells, which are large-diameter gravel-filled open wells, were historically designed to capture stormwater runoff or irrigation tailwater for rapid recharge to groundwater. Abandoned wells also allow surface water leakage to groundwater (spills) and cross-aquifer contamination. Lack of backflow prevention devices can lead to direct introduction of fertilizer chemicals into the aquifer via a supply well. Few data are available on these types of nitrate transfer in the Tulare Lake Basin or Salinas Valley. In a worst-case situation, as much as 0.4 Gg N/yr (440 t N/yr) may leak from the surface to groundwater via improperly constructed, abandoned, or dry wells, and as much as 6.7 Gg N/yr (7,400 t N/yr) are transferred within wells from shallow to deeper aquifers. Actual leakage rates are likely much lower than these worst-case estimates.

2.6.5 Groundwater Nitrate Loading: Sources of Uncertainty

The analyses above provide specific numbers for the average amount and intensity of nitrate loading from various categories of sources. However, discharges of nitrate to groundwater may vary widely between individual fields, farms, or facilities of the same category due to differences in operations, management practices, and environmental conditions. Also, average annual nitrate loading estimates for specific categories are based on many assumptions and are based on (limited) data with varying degrees of accuracy; the numbers given represent a best, albeit rough, approximation of the actual nitrate loading from specific sources. These estimates have inherent uncertainty. Very likely, though, the actual groundwater nitrate loading from source categories falls within the ranges shown in Table 12.

The range estimates about the loading rates to groundwater, given in Table 12, are explained in more detail in Section 3 (alfalfa), Section 4 (land applied manure N, animal corrals and manure storage lagoons), Sections 5 and 6 (urban sources including land applied N), and Section 9 (surface leakage to wells). For groundwater nitrate loading from cropland, the range estimate was based on an error analysis of the mass balance shown in Figure 3. The error analysis was performed using Monte Carlo simulation.[14] The analysis indicates that, with a 95% likelihood, groundwater N loading from cropland

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[14] The error analysis of the study area wide mass balance was implemented using Monte Carlo simulation: Ten thousand random trials of the mass balance terms shown in Figure 3 were performed by computer simulation. For each random trial in the simulation, individual mass balance terms, except "leaching to groundwater", were randomly drawn from normal distributions with means equal to the individual N flux rates shown in Figure 3 and listed in the subsections above (Sections 1.6.1 and 1.6.3). The standard deviations of the normal distributions from which these random N flux rates were drawn were set based on an estimated accuracy of the overall study area N fluxes shown in Figure 3: Study area wide estimates for total synthetic fertilizer N application, total manure N land application, and total harvested N are assumed, at the 95% confidence

(not including alfalfa) is in the range of 135 Gg N/yr to 255 Gg N/yr (about three to five times the operational benchmark of 50 Gg N/yr). The uncertainty about total N loading from cropland is dominated by the uncertainty about the largest terms in the mass balance, the total fertilizer N application, the total manure N application, and the total N harvest.

2.6.6 Validation of Groundwater Nitrate Loading Estimates with Field Data

The California Nitrogen Assessment[15] performed an analysis of field research on nitrate leaching to groundwater from various crops (see Section 3 for a summary). From a review of numerous field studies, a median groundwater nitrate loading rate was obtained. Multiplying the statewide acreage of cropland with the average field experiment-derived loading rates, the estimated statewide groundwater nitrate leaching from cropland is estimated to be 333 Gg N/yr or about 40% of all nitrogen inputs to cropland (Liptzin, personal communication, 2012). It is likely, that field experiments do not include a significant number of experiments with crops fertilized with large amounts of manure. In the study area, at least until the late 2000s, extremely high manure application rates occurred on less than 10% of the study area (the area under management by dairy facilities). The CNA estimate of 333 Gg N/yr groundwater leaching would not account for additional losses due to application of excess manure nitrogen. If we assume that statewide land application of manure amounts to be at least 200 Gg N/yr, and if we further assume that half of that N is applied in excess of typical fertilizer rates and therefore leached to groundwater, statewide groundwater nitrate leaching from cropland is on the order of 430 Gg N/yr. The study area represents over 40% of the statewide irrigated cropland area and more than 50% of its dairy herd, hence the study area fraction of the 430 Gg N/yr leaching loss would be over 180 Gg N/yr. This estimate is, roughly, based on leaching study estimates using the stated assumptions about manure N losses to groundwater. This value is within 10% of the total groundwater nitrate loading estimated from the mass balance analysis, and well within the confidence interval of the mass balance derived groundwater loading estimate for the study area, derived in the previous section.

2.7 Comparative Analysis of Cropland Loading

In this section, we compare the land areas designated for cropland and estimated from three different data sources. The data are not directly comparable as there is neither one particular year nor one specific area for which these data could be compared. Hence, the comparison is not of the highest

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level, to be within ±20% of the true value (standard deviation: 10%). Study area wide total WWTP/FP nitrogen land application, total atmospheric N deposition, total irrigation water N, total runoff N, and total atmospheric N losses are assumed, at the 95% confidence level, to be within ±40% of the true value (standard deviation: 20%). The individual mass balance terms were assumed to be independent from each other. For each random trial, groundwater nitrate loading ("leaching to groundwater" in Figure 3) was obtained from mass balance, that is, as the difference between total inputs (each drawn randomly) and the (randomly drawn) outputs to atmospheric losses, runoff, and harvest. Thus, we obtained 10,000 randomized estimates of study area wide groundwater nitrate loading, reflecting the uncertainty in the various N flux terms of the mass balance. The groundwater nitrate loading values are normally distributed with a mean of 195 Gg N/yr and a standard deviation of 30 Gg N/yr. The 95% confidence interval for groundwater nitrate loading, which is the reported range, is determined by subtracting twice the standard deviations from the mean value to obtain the lower bound and by adding twice the standard deviation to the mean to obtain the upper bound).

[15] http://nitrogen.ucdavis.edu

quantitative accuracy. Spatially, the ACR data and the NASS Agricultural Census represent the entire counties, while the CAML data represent only the study area portion of these five counties. While almost all cropland of these five counties is in the study area, Kern County data reported by NASS and the ACR include significant crop acreage outside of the study area (in the high desert region of Kern County). Furthermore, the ACR data and the NASS Agricultural Census data represent the harvested land area, not the land area on the ground. "Harvested land area" represents the product of land area and the number of times that land area was harvested. The harvested land area on a triple cropped field is three times the size of the field itself. Multi-cropping is dominant almost exclusively among some vegetable crops and, to a lesser degree, on corn crops rotated with winter grains (i.e., double-cropping).

We selected datsets from the nearest years for comparison (Table 15). The most recent DWR landuse survey year set the year of interest. The closest NASS agricultural census year to that DWR survey and the digitized ACR year closest to the NASS Agricultural Census year were chosen for comparison to the CAML data. Up to seven year time difference occurred between the datasets chosen for comparison, which explains some, but not all of the discrepancies in the cropped land area.

Table 15. Reporting years, by county, used to compare harvested land area in each county by three different data sources. The CAML year is the year during which the Department of Water Resources last recorded and mapped land use distribution. The NASS Agricultural Census data were taken from the year closest to the CAML reference year. The ACR data were taken from the year closest to the CAML reference year (we only digitized and processed selected ACR data for this study, including 2003-2007 and 1987-1992).

County	ACR (Agricultural Commissioner Reports)	NASS Agricultural Census	CAML
Fresno	2003	2002	2000
Kern	2007	2007	2006
Kings	2003	2002	2003
Monterey	1992	1997	1997
Tulare	1992	1997	1999

Generally, the CAML data are in very good agreement with the ACR data – slightly lower than those reported in Fresno and Tulare County and about 5% larger in Kern County, despite the fact that Kern County has some land area outside of the study area. In Kings County, CAML maps report a significantly larger land area in crop production than the ACR data. In Monterey County, CAML shows only about three-quarters of the cropland production that the ACR data show. In Monterey County, where lettuce and other vegetables are frequently double-cropped, the large discrepancy reflects the difference between "harvested cropland" and actual "on-the-ground" cropland area (Table 16).

Table 16. Comparison of harvested land area in each county, as reported by three different data sources. Data are aggregated from crop-category specific data, by county. The county data used are from the calendar years indicated for the corresponding county – data source in Table 4.
Table 5(a). Metric units.

County	ACR (Agricultural Commissioner Reports) [ha]	NASS Agricultural Census [ha]	CAML [ha]
Fresno	479,021	417,437	470,250
Kern	377,980	231,511	397,480
Kings	207,750	152,569	244,243
Monterey	121,476	143,493	93,899
Tulare	313,382	216,840	309,096
TOTAL	**1,499,610**	**1,161,851**	**1,514,968**

Table 5(b). US standard units.

County	ACR (Agricultural Commissioner Reports) [ac]	NASS Agricultural Census [ac]	CAML [ac]
Fresno	1,183,687	1,031,509	1,162,013
Kern	934,009	572,076	982,194
Kings	513,361	377,006	603,538
Monterey	300,174	354,579	232,029
Tulare	774,384	535,823	763,793
TOTAL	**3,705,617**	**2,870,996**	**3,743,567**

The NASS Agricultural Census data indicate a significantly lower amount of land in production, when compared to the other two sources: only 1.2 million ha as opposed to 1.5 million ha reported by the other two sources. It is unclear, why there is such a significant discrepancy in total harvested area between the ACR and CAML data on one hand and the NASS data on the other hand.

Table 17 . Comparison of harvested land area for each major crop group, as reported by three different data sources. The data were aggregated from crop category-specific data in each county, with county data taken from the year indicated by the corresponding county – data source in Table 4. Since crop-groups are integrated across counties, these land areas do not represent a specific year and are computed here for a "best-possible" comparison between the three data sources only.

Table 17(a). Metric units.

Crop Group	ACR (Agricultural Commissioner Reports) [ha]	NASS Agricultural Census [ha]	CAML [ha]
Subtropical	88,696	78,917	101,697
Treefruit	70,979	55,212	88,102
Nuts	126,879	132,119	186,088
Cotton	259,284	222,140	244,624
Field Crops	144,078	29,042	200,913
Haylage	237,429	133,127	156,031
Alfalfa	145,869	124,197	149,076
Rice	2,098	2,449	5
Vegetables	262,596	210,359	178,583
Grapes	161,701	174,287	209,849
TOTAL	**1,499,610**	**1,161,851**	**1,514,968**

Table 17(b). US standard units.

Crop Group	ACR (Agricultural Commissioner Reports) [ac]	NASS Agricultural Census [ac]	CAML [ac]
Subtropical	219,173	195,008	251,299
Treefruit	175,393	136,432	217,705
Nuts	313,525	326,473	459,833
Cotton	640,705	548,920	604,479
Field Crops	356,024	71,764	496,467
Haylage	586,700	328,964	385,561
Alfalfa	360,450	306,897	368,375
Rice	5,184	6,052	12
Vegetables	648,889	519,808	441,288
Grapes	399,572	430,673	518,548
TOTAL	**3,705,617**	**2,870,996**	**3,743,567**

When we compare the land area (acreage) that is in production by crop group rather than county (Table 17), additional discrepancies between the three data sources become more apparent. In this report, we did not attempt to reconcile these data. Rather, we compute nitrate loading to

groundwater using both the CAML data and the ACR data as the basis for the extent of cropland in the study area. Results are reported separately: Section 1.6 above summarizes the N loading derived based on land area reported by county ACRs, historically and currently. In Section 1.8 below, we provide the N loading estimates based on CAML land area maps.

2.8 Simulation of Groundwater Nitrate Sources and Loading

The previous analysis does not provide a farm scale or field scale differentiation of nitrate source loading. In this section we provide a spatially more detailed analysis of groundwater nitrate loading that takes into account the specific N applications to cropland from individual WWTPs and FPs, and that takes into consideration the amount of manure generated on each of over 600 dairies and the availability of cropland on each of these dairies for land application of manure. We also take advantage of having available detailed maps of septic systems N loading to groundwater, maps of urban areas, golf courses, individual dairy corrals and of individual dairy lagoons, which provide a more detailed spatial context for groundwater nitrate loading.

A spatially detailed and historically dynamic set of nitrate loading maps is also needed to properly assess current and future groundwater nitrate contamination with groundwater models (see Technical Report 4, Dylan et al., 2012). In this section, we describe the results of our CAML-derived spatio-temporal simulation of groundwater nitrate sources and loading, which is more detailed than the crop and county-based analysis presented in Section 1.6.

The various source of groundwater nitrate are spatially distributed across the study area. The CAML maps distinguish individual fields at very high resolution. We also discretized some local sources, such as dairy lagoons and dairy corrals at a high resolution. To model groundwater nitrate loading across the study area, we divide the study area into 0.25 ha (0.6 ac) pixels, each of which has at least one assigned land use. The pixel size is sufficiently small to map individual fields, ponds, lagoons, and other sources with sufficient accuracy. We developed the so-called Groundwater Nitrate Loading Model (GNLM) to simulate direct nitrate loading to groundwater from non-cropland sources and from alfalfa and to simulate the various cropland nitrogen fluxes, including the on-farm and off-farm manure nitrogen distribution needed to compute cropland nitrate loading to groundwater by mass balance (see Sections 2 – 8 for details).

The mass balance modeling in GNLM is based on the same crop-category specific rates of typical N applications and N harvest as those used in the analysis in Section 1.6 above. But here, GNLM applies these rates to the actually mapped land area of each crop category provided by CAML (Figure 1), which yields the mapped distribution of typical N application rates (Figure 4) and N harvest (Figure 5).

In the CAML-based analysis with GNLM, we assume that seven vegetable crops are harvested multiple times per year: celery, lettuce, spinach, broccoli, cabbage, cauliflower, and Brussels sprouts. An analysis of NASS Agricultural Census data indicated that approximately 1.6 crops were planted and harvested per year in the 1990 period and 1.7 crops were planted and harvested per year in the 2005

period (see Sections 2 and 3 for details). We also assume that corn is always double-cropped with winter grain. Both assumptions are over-simplifying the variability in the agricultural systems of the TLB and SV, but provide a best average approximation of management practices in the study area. For land areas with multiple crops per year, the typical N application rate and the harvested N rate were adjusted accordingly.

For effluent and biosolids applications, we identified specific cropland areas in the vicinity of individual WWTPs and FPs (Section 6). The GNLM model distributed known total nitrogen loading to these croplands each year. Similarly, about 600 dairies have provided information to the Central Valley Regional Water Quality Control Board (CVRWB) identifying cropland parcels owned and operated by the dairies. We used the parcel numbers to determine their location and then identified the land use by geospatial analysis with CAML. The GNLM uses this information to distribute the manure nitrogen generated on each dairy (Section 4) to those cropland parcels that are under a dairy's operation. Of those parcels, GNML selects on those for manure application where CAML indicates that field crops are grown that typically receive manure (e.g., corn, winter grain, and others, see Section 4).

After 1980, dairies began to export significant amounts of manure N (see Section 4) to neighboring farms, typically as soil amendment. The actual amount of manure N exported is not well known prior to the Central Valley Regional Water Board dairy general order. Since 2007, dairies report the amount of manure N exported, which can be used to constrain the amount of manure N exported in the past. For the spatially distributed modeling analysis, these data were not available, and we therefore developed six hypothetical scenarios with respect to the amount and fate of exported manure N. These scenarios broadly bracket the actual amount of manure exported by dairies. These scenarios also bracket the potential distribution of exported manure within each of the five counties, between the counties in the study area, and the hypothetical export of manure N to outside the study.

In 2005, after accounting for 38% atmospheric losses from excreted manure prior to land application, land application of manure accounts for 127 Gg N/yr. Manure exported by dairies is mostly solid manure or composted manure. Of the 6 hypothetical manure export scenarios (described below in more detail), scenarios A, B, and C assume that 77 Gg N/yr, a total of 38% of dairy manure excreted, nearly two-third of all land-applied manure, is moved off dairy (an additional 1.5 Gg N/yr land applied to cropland originates from other confined animal operations). This number reflects an approximate upper bound for the amount of manure N that can currently or in the near future be exported from dairies. Scenarios A, B, and C assume that 48 Gg N/yr are land applied on cropland within dairies. This reflects the order of magnitude of manure N that dairies can land apply on their own land within the foreseeable future under the CVRWB dairy general order: The order requires that total nitrogen application to cropland cannot exceed 140% - 165% of harvested nitrogen. Dairies in the study area currently manage approximately 120,000 ha (300,000 ac) of cropland. If much of the land under dairy management were converted to grow summer corn and winter grain at high yields, and if the required 140%-165% ratio of total N applied to total N harvested could be achieved while applying manure N at a rate of 400 kg N/yr (approximately two-third of the total N application), the total N applied on dairies, within the constraints of the dairy general order, would be about 48 Gg N/yr.

On cropland not managed by a dairy ("non-dairy cropland"), exported manure N is assumed to be applied in addition to synthetic fertilizer that meets 100% of the typical N application needs. The total N application on non-dairy cropland[16] is therefore always more than 100% of the typical N application needs (see Sections 2.6.2 and 4.8.4 for details). On the other hand, Scenario D represents the (hypothetical) case that all manure is land applied on corn, grain, and other field crops on land that is under the direct management of dairies. In Scenario D, no manure is exported:

- "Scenario A": Manure exported by dairies does not affect the typical N fertilization rates (Figure 4) on non-dairy cropland within the study area, after accounting for the combined synthetic and organic sources of nitrogen fertilizer applied to non-dairy cropland. This is a hypothetical (future) scenario representing the possibility that manure exported from dairies

  - o is applied to non-dairy cropland as part of the typical N fertilization rates,
  - o is transported to areas completely outside the study area, possibly after some processing,
  - o is intentionally processed and lost to the atmosphere,
  - o or any combination thereof.

- "Scenario B (by county)": Half of the manure exported by dairies is applied as soil amendment on non-dairy cropland within the county of origin. The other half of the exported manure has the same fate as listed under "Scenario A". The manure exported by dairies for soil amendment within each county is distributed in direct proportion and in addition to the typical N fertilization needs of crops within that county (manure applied as soil amendment does not leave the county). This scenario represents the mid-point between "Scenario A" and "Scenario C (by county)".

- "Scenario B (study area)": Half of the manure exported by dairies is applied as soil amendment on non-dairy cropland within the study area (not restricted to the county of origin). The other half of the exported manure has the same fate as listed under "Scenario A". The manure exported by dairies for soil amendment in the study area is distributed across all non-dairy cropland in the study area in direct proportion and in addition to their typical N application needs. This scenario represents the mid-point between "Scenario A" and "Scenario C (by study area)".

- "Scenario C (by county)": All manure exported by dairies is applied as soil amendment on non-dairy cropland within the same county. The total manure exported by dairies within each county is distributed in direct proportion and in addition to the typical N application rates of crops within that county (manure does not leave the county).

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[16] For purposes of simulating "exported manure N" to cropland other than dairy cropland that typically receives significant amounts of manure N (corn, grains, other field crops), the category "non-dairy cropland" is assumed to include vineyards, nut and tree crops, subtropical fruit, vegetables, and other non-forage crops managed by dairies, since they typically do not receive large amounts of manure application except as amendment.

- "Scenario C (study area)": All manure exported by dairies is applied as soil amendment within the study area (not restricted to the county of origin), and the total manure exported by all dairies in the study area is distributed across all non-dairy cropland in the study area in direct proportion and in addition to their typical N fertilization rates.

- "Scenario D": No manure is exported by dairies. All manure is land applied on applicable forage crops within the dairy. Note that, groundwater nitrate loading on non-dairy cropland is therefore identical to that simulated in Scenario A. Groundwater nitrate loading on dairy cropland receiving manure is significantly higher under this Scenario than under the export scenarios.

The six manure export scenarios are coded into GNLM. Historically, for simulation purposes, manure N exports are assumed to be negligible (under all scenarios) prior to 1980, increase linearly from 0% to 38% between 1980 and 2005, and then stay constant at that rate through 2050.

Using the loading methods and mass balance considerations further described in Sections 2.6.2, and in Sections 3 through 8, the GNLM generates maps of spatially distributed groundwater nitrate loading in 1945, 1960, 1975, 1990, 2005, and 2050. These groundwater nitrate loading maps are used as input to the groundwater transport model of the Tulare Lake Basin, which simulates current and future nitrate concentration in wells throughout the Tulare Lake Basin (see Technical Report 4, Boyle et al., 2012).

Table 18 shows the study area totals of various nitrogen fluxes and of the groundwater nitrate loading derived from the CAML-based simulation with GNLM. Comparing the 2005 data from the CAML-based GNLM simulations with the estimates of cropland nitrogen fluxes and groundwater nitrate loading derived based on land areas reported by county ACRs, the magnitude of the nitrogen fluxes is similar and for some sources identical due to fixed source size (compare 2005 results in Table 18 with Figure 3).

The CAML-based GNLM results illustrate the spatial and temporal (historic) distribution of nitrogen fluxes and groundwater nitrate loading across the study area. Fertilizer applications are highest in vegetables in Monterey County and on double-cropped corn (and winter grain) land use areas in the central-eastern Tulare Lake Basin (Figure 9). Vineyards, located mostly around central Fresno County and southern Tulare County have among the lowest synthetic fertilizer application rates.

Manure, effluent, and biosolids applications under Scenario D (no manure exports from dairy) are focused on land areas designated for effluent and biosolids application and on field, grain, and hay crops within land parcels owned or operated by dairies (Figure 10). Application rates typically far exceed 500 kg N/ha/yr. Most of these occur in western Tulare County and northeast Kings County, but also along the central axis of the valley in Fresno County and Kern County.

Significantly lower rates of manure are applied to dairy cropland under Scenario A-C (an average of 38% of excreted manure nitrogen is exported from dairy facilities). Yet, on many dairy fields, the application rates still exceed 500 kg N/ha/yr (the largest category shown on the map). Biosolids and effluent applications are unaffected by the Scenario simulations (Figure 11). In Scenario C, the exported

manure is distributed proportionally to the typical crop nitrogen needs, either within the county of origin (Figure 12), or within the study area (Figure 13). When manure is assumed to remain within the county of origin, the entire cropped area within Tulare County is subject to large amounts of manure nitrogen being applied, not only on dairies (Figure 10), but also on all non-dairy cropland (Figure 12). The spatial distribution of manure nitrogen applied outside of dairies is due to the fact that exported manure is always applied proportional to the applied nitrogen needs of a crop (and it is in addition to "typical" fertilizer needs already being met by application of synthetic fertilizer). Vegetable crops are therefore receiving higher amounts of manure than, e.g., vineyards. When manure is simulated as being distributed across the study area, Monterey County receives large amounts of manure compost or amendment – in some cases in excess of 100 kg N/ha/yr, due to the high fertilization rates in vegetables. While, in reality, some compost is applied to vegetable crops in Monterey County, simulated rates for "Scenarios B and C (study area)" likely overestimate the amount of soil amendment applied in the Salinas Valley. Under these simulations, large amounts of manure are also applied to double-cropped corn – winter grain fields in Tulare County (high fertilization rats), which partially reflects current practices of applying manure primarily to these crops (Figure 13).

Harvested nitrogen is largest in the vegetable crops of the Salinas Valley, in double-cropped corn and grain fields in the central portion of the Tulare Lake Basin, and in alfalfa fields (Figure 14). Intermediate harvest rates are achieved in many other field crops and in nut crops. Largest nitrogen removal rates from fields therefore occur in the Salinas Valley, and on the Westside and in the central portion of the Tulare Lake Basin.

Simulated current (2005) groundwater nitrate loading, including direct percolation from urban areas, septic systems, percolation basin etc., as well as from cropland, is shown in Figures 15 – 20 for the six different manure export scenarios. Highest localized groundwater loading occurs on dairies in Scenario D, where all land applied manure N is applied on land within dairies. Groundwater nitrate loading on dairy cropland is significantly reduced by the hypothetical export of about two-third of the land applied manure nitrogen (Scenarios A-C). This represents, in very approximate terms, the minimum amount of manure that needs to be exported from dairies in the coming years under the 2007 CVRWB general order, such that dairy cropland can meet the required rate of total nitrogen application (140% to 165% of N harvested).

But manure export poses threats to groundwater quality impacts from cropland outside dairies (Scenarios B and C, Figures 16-19), unless manure is applied as part and within the constraints of a typical fertilization regime (Figure 20). That threat is also a function of how much of the exported nitrogen remains within the county of origin, how much is exported to other counties within the study area, and how much will potentially be exported outside the study area or processed for atmospheric loss (Scenarios A-C). Assuming that exported dairy manure remains within the county of origin and is applied as soil amendment to crops outside dairies, large groundwater nitrate loading would be expected particularly in Tulare County, which has the highest density of dairy animals (Figure 16). Even with approximately two-third of the manure exported off-farm and either managed to meet typical fertilization needs or removed from non-dairy study area cropland (Scenario A, Figure 20), the loading

rates from dairy cropland remain relatively high. In the future, it may be possible to manage nutrients in corn, grain crops and other forage crops such that nitrogen needs are met mostly (rather than only to 50%, as simulated here) with manure nitrogen rather than fertilizer nitrogen, but without exceeding total nitrogen application limits imposed by the CVRWB dairy general order.

Non-cropland sources of groundwater nitrate loading other than septic systems are illustrated in Figure 21. The most intense sources are corrals and lagoons located on dairies and some WWTP/FP percolation basins. Other sources are not generally exceeding the operational benchmark leaching rate of 35 kg N/ha/yr (31 lbs N/ac/yr) (leaky sewer lines, turf areas, golf courses).

Maps of GNLM simulated nitrogen fluxes for 1945 – 2050 (including the 2005 maps shown in Figures 9 – 21),which are summarized in Table 18, are shown in Appendix Figures 3 through 120 of Viers et al., 2012, available as a separate file at http://groundwaternitrate.ucdavis.edu.

The simulated groundwater nitrate loading demonstrates the overall spatial variability encountered across the study area due to the type of source, due to the management specifically of dairy manure, due to differences in nutrient management and harvested nitrogen between 58 different crop categories, due to the spatial distribution of percolation basins and liquid dairy manure storage lagoons, due to the location of urban and peri-urban areas, due to the density of septic systems density, etc. However, the data, particularly the cropland groundwater nitrate loading data, only represent averaged values for each crop category and for each source type. The simulations cannot take into account differences in groundwater nitrate loading due to different management practices by different landowners/source managers, due to differences in the physical characteristics between fields/orchards/vineyards of the same crop category, or differences in the specific design of individual septic systems, sewer systems, etc.

Since our estimates do not account for such differences, we caution that actual local groundwater nitrate loading at any location within the study area is likely to vary from those projected by the simulations shown in Figures 15-20. Nonetheless, the range of potential outcomes, across the landscape, across crop categories and source types, and across the listed range of manure management scenarios provides significant insight into both, the large variability of loading and the overall magnitude of groundwater nitrate loading associated with each source.

Future implementations of GNLM may be used to account for heterogeneous field-to-field or farm-to-farm variability in nitrogen fertilizer management. GNLM can also be modified to account for various future management scenarios for specific nitrate loading sources.

Table 18. Study area summary of simulated CAML-based, spatially distributed nitrogen fluxes that account for mapped areas of cropland 1945 – 2050 (not including alfalfa), spatial distribution of WWTP, FP, and dairy facilities, spatial distribution of urban areas, and spatially variable atmospheric nitrogen deposition. All fluxes shown in Gg N/yr. One Gg N/yr = 1,100 tons N/yr. Data are simulated using GNLM (See Section 2.6)

	1945	*1960*	*1975*	*1990*	*2005*	*2020*	*2035*	*2050*
Typical N application to cropland	40.2	85.2	144.6	220.1	240.5	240.5	240.5	240.5
Typical N application to alfalfa and pasture	5.5	13.3	19.4	3.1	3.5	3.5	3.5	3.5
Actual synthetic fertilizer N applied on cropland, Scenario A-C	39.7	84.2	139.0	209.1	228.4	228.2	228.0	227.9
Actual synthetic fertilizer N applied on cropland, Scenario D	39.7	84.2	139.0	209.1	228.2	228.0	227.9	227.8
Land applied manure (on-dairy), biosolids, effluent N, Scenario A-C	2.0	3.1	34.4	45.1	53.8	62.6	72.9	80.5
Land applied manure N to non-dairy cropland, Scenario A-C	0.0	0.0	0.0	14.0	78.0	88.0	99.8	106.1
Land applied manure (on-dairy), biosolids, and effluent N, Scenario D	2.0	3.1	34.4	58.0	131.7	150.6	172.7	186.5
Harvested N	19.4	54.6	70.7	112.8	141.1	141.1	141.1	141.1
Surface runoff N	9.5	14.4	17.7	17.9	19.2	19.2	19.2	19.2
Atmospheric N deposition on all land	13.4	20.0	24.5	25.5	20.1	17.0	12.2	7.4
GW nitrate loading (N) from cropland, Scenario A	23.0	28.0	88.6	133.1	124.9	130.0	136.8	141.4
GW nitrate loading (N) from cropland, Scenario B	23.0	28.0	88.6	139.2	158.9	168.4	180.3	187.6
GW nitrate loading (N) from cropland, Scenario C	23.0	28.0	88.6	145.3	193.3	207.3	224.5	234.6
GW nitrate loading (N) from cropland, Scenario D	23.0	28.0	88.6	145.7	195.3	209.6	227.1	237.3
Septic systems nitrate loading (N)	0.6	1.0	1.2	1.8	2.3	3.2	4.2	5.4
Total non-cropland nitrate loading (N) (not including alfalfa)	1.2	1.9	5.2	7.0	8.2	9.3	10.5	11.9
Alfalfa nitrate loading (N)	3.7	6.5	4.4	3.8	4.5	4.5	4.5	4.5

Note: "Cropland" in the above table always refers to "cropland, not including alfalfa". Typical nitrogen application represents the amount of N thought to be typically applied to a specific crop category (Figure 4). Where manure is applied on-dairy or where effluent or biosolids are applied, up to 50% of this amount is supplied by manure N (applies only after 1970). All manure N in excess of this 50% typically applied N, and all manure N applied outside of dairy-owned cropland is applied in addition to synthetic fertilizer applications that meet the typical nitrogen application needs. The harvested nitrogen reflects crop category specific harvest rates derived from acreage and yield data provided in county agricultural commissioner reports (Figure 5) and applied to the CAML crop category distribution maps for 2005 (Figure 1) or under historic and future conditions (see Section 3). Scenarios A, B, and C for cropland nitrate loading represent nitrogen mass balance modeling solutions assuming that no (A), half (B), or all exported manure N is applied as soil amendment at rates proportional and in addition to typical crop fertilizer rates (exports occur only after 1980). Scenario D assumes that no manure is exported from dairies, even after 1980. Total non-cropland nitrate loading other than from septic systems includes nitrate loading from urban lawns and leaky sewer systems, golf course, and from WWTP and FP percolation basins. After 1968, total non-cropland nitrate loading also includes loading from dairy corrals and dairy lagoons. For 2005, these N fluxes are similar to those obtained at the county and study area level using non-spatial county ACR data (Figure 3).
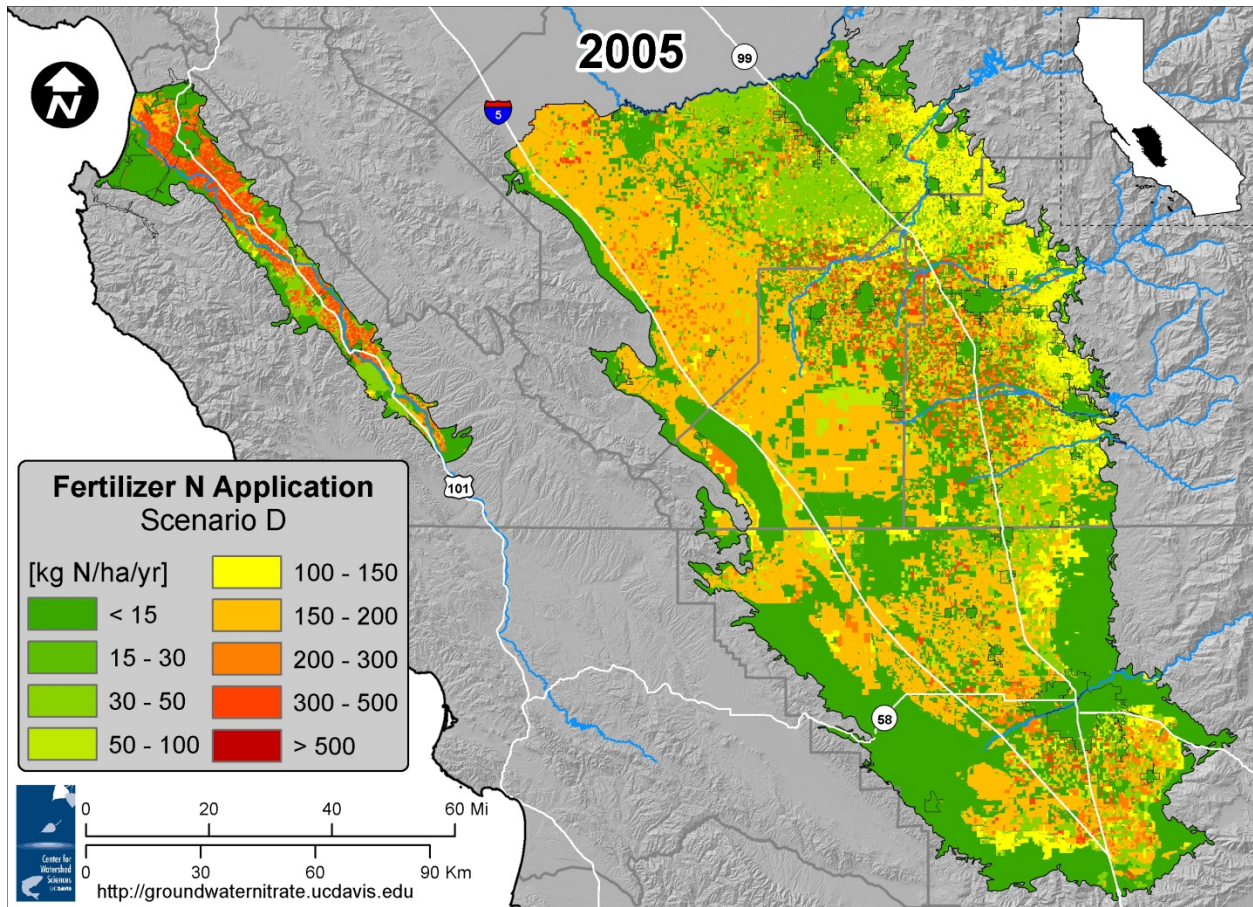
Figure 9. Simulated synthetic fertilizer application on cropland, including alfalfa, after accounting for the application of manure as fertilizer on dairy cropland (manure may make up to 50% of the applied nitrogen need). This map represents results for "Scenario D" (no manure exports from dairies). Differences to Scenarios A-C are very small (see Table 7). Simulated synthetic fertilizer applications account for 1.7x cropping in seven vegetable crops (broccoli, Brussels sprouts, cabbage, cauliflower, celery, lettuce, spinach) and double-cropping of all corn with winter grain.
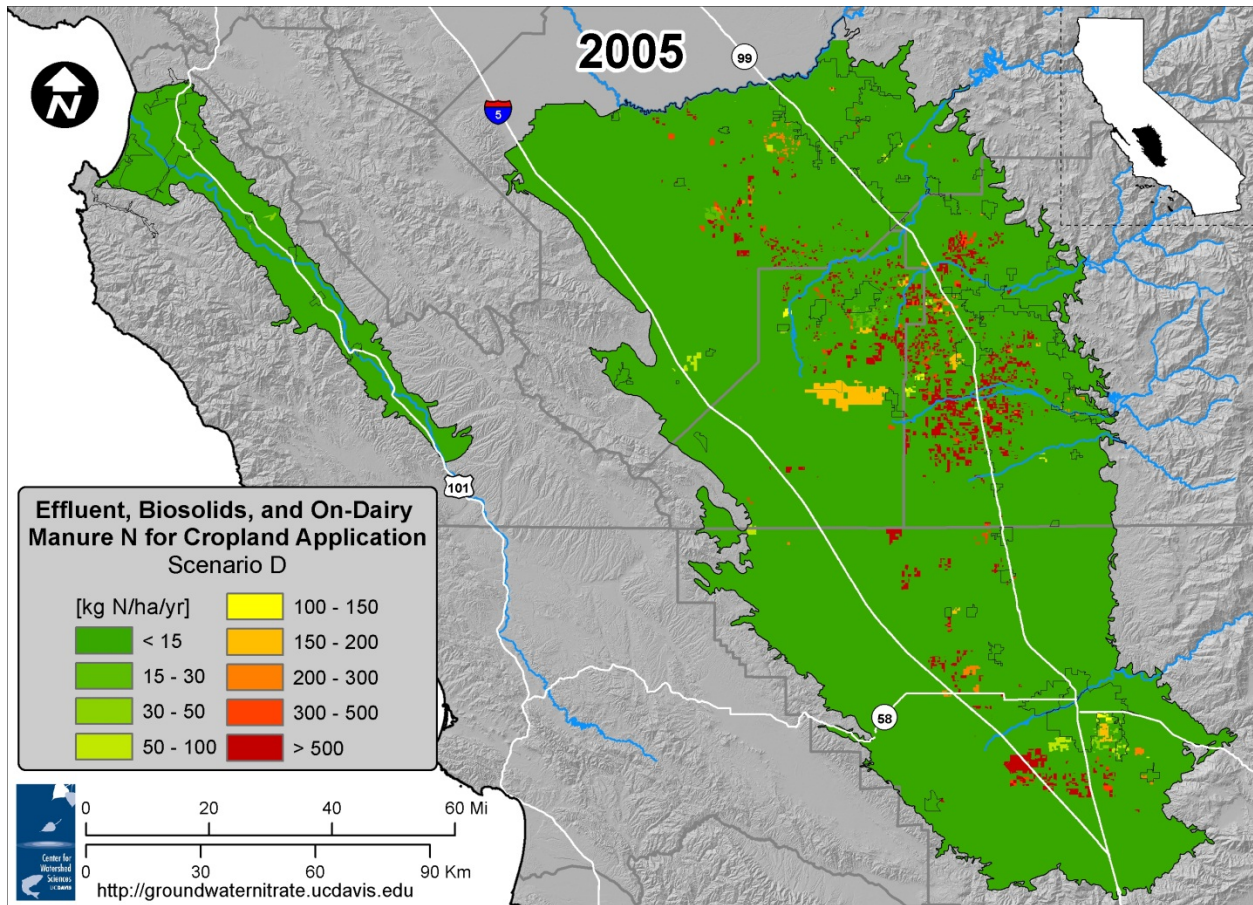
Figure 10. Simulated land applied N from dairy manure (land applied on dairy cropland), and from WWTP/FP effluent and biosolids. This map represents results for the hypothetical "Scenario D" (all manure is land applied on dairies, representing 62% of animal N excretion, no manure is exported from dairies).
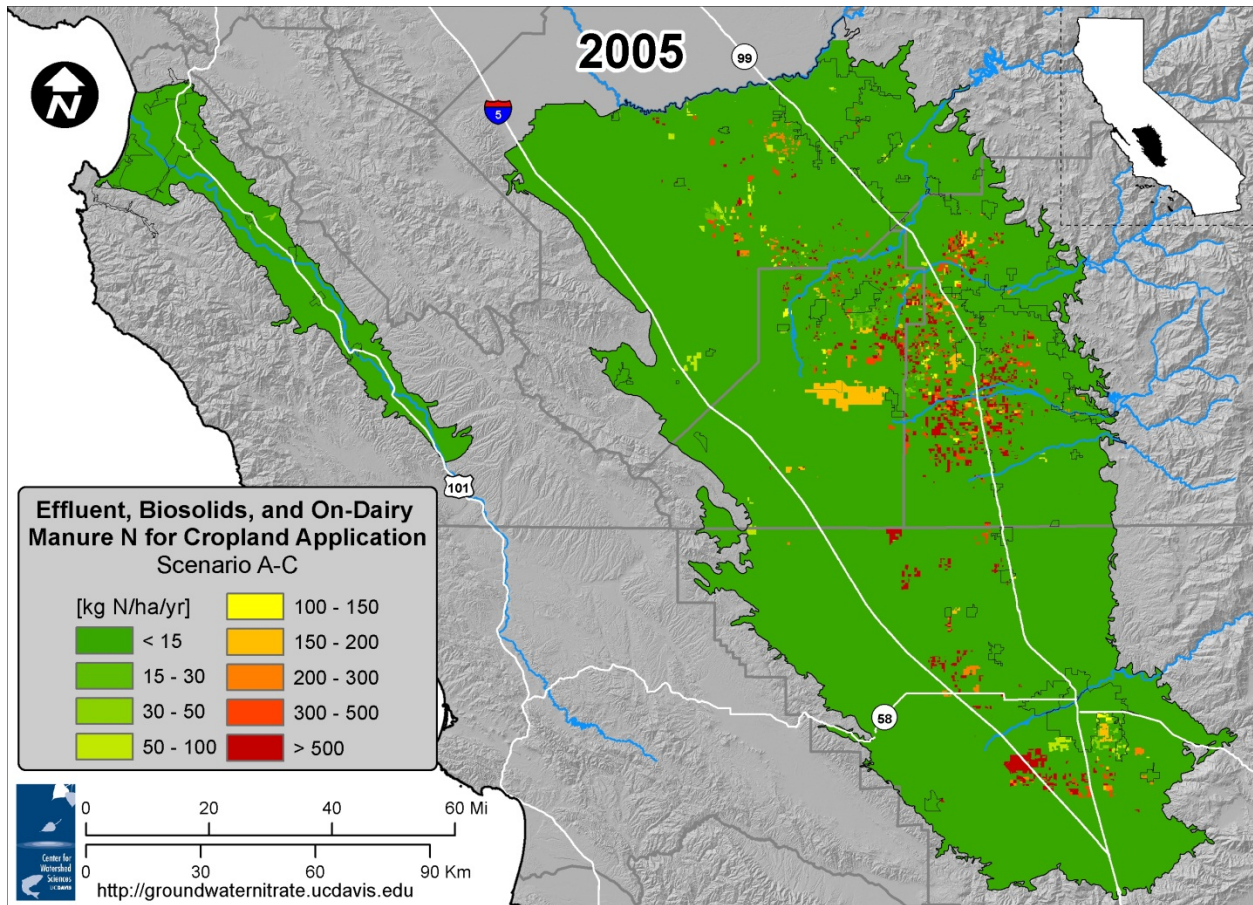
Figure 11. Simulated land applied N from dairy manure (showing only land applied N on dairy cropland, but not exported dairy manure N applications), and from WWTP/FP effluent and biosolids. This map represents results for Scenario A-C (a total of 24% of animal N excreted is land applied on dairies).
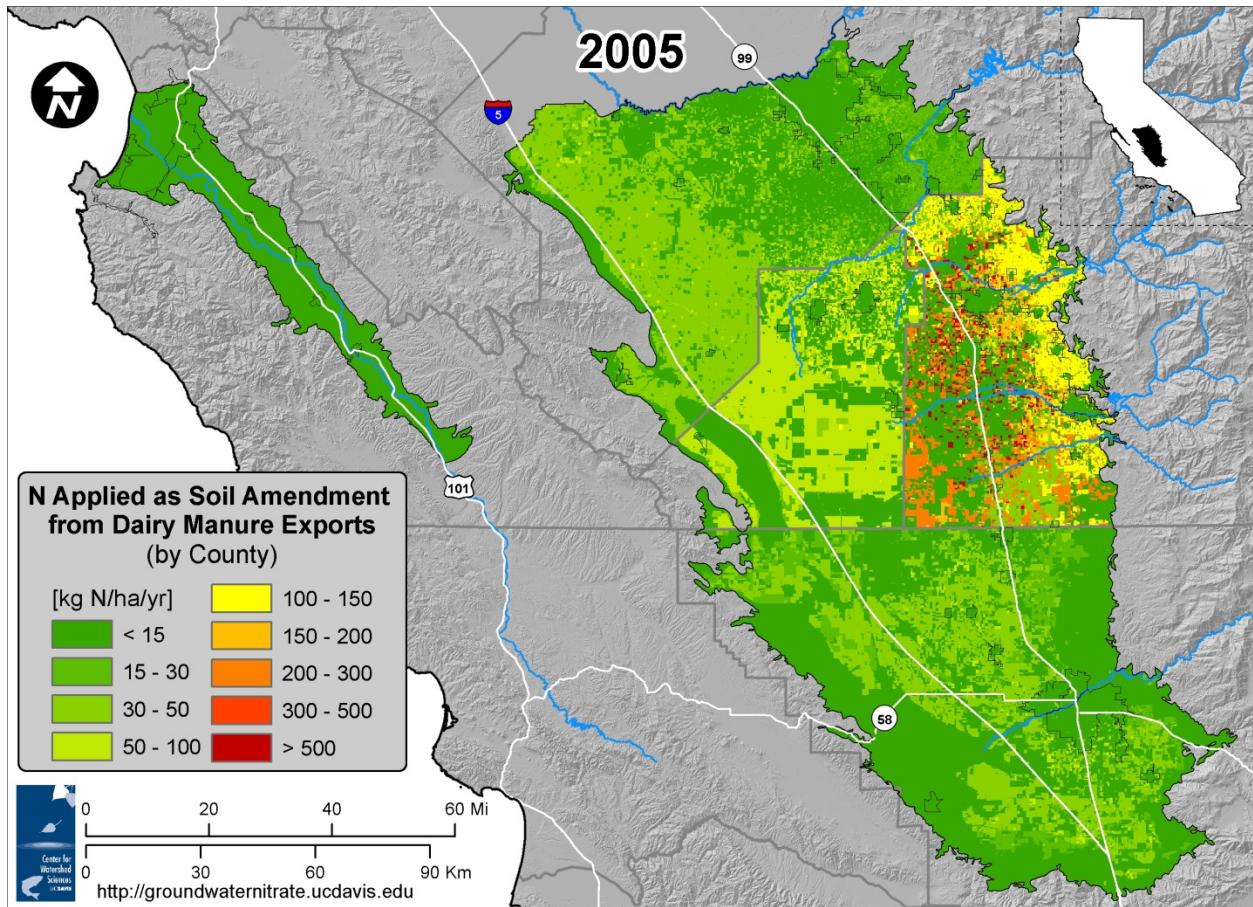
Figure 12. Simulated land application of dairy manure N exported from dairies and land applied within the county of origin at rates proportional and in addition to typical N fertilizer needs in each crop (see Figure 4). Total manure exports represent 38% of animal N excreted ("Scenario C (by County)").
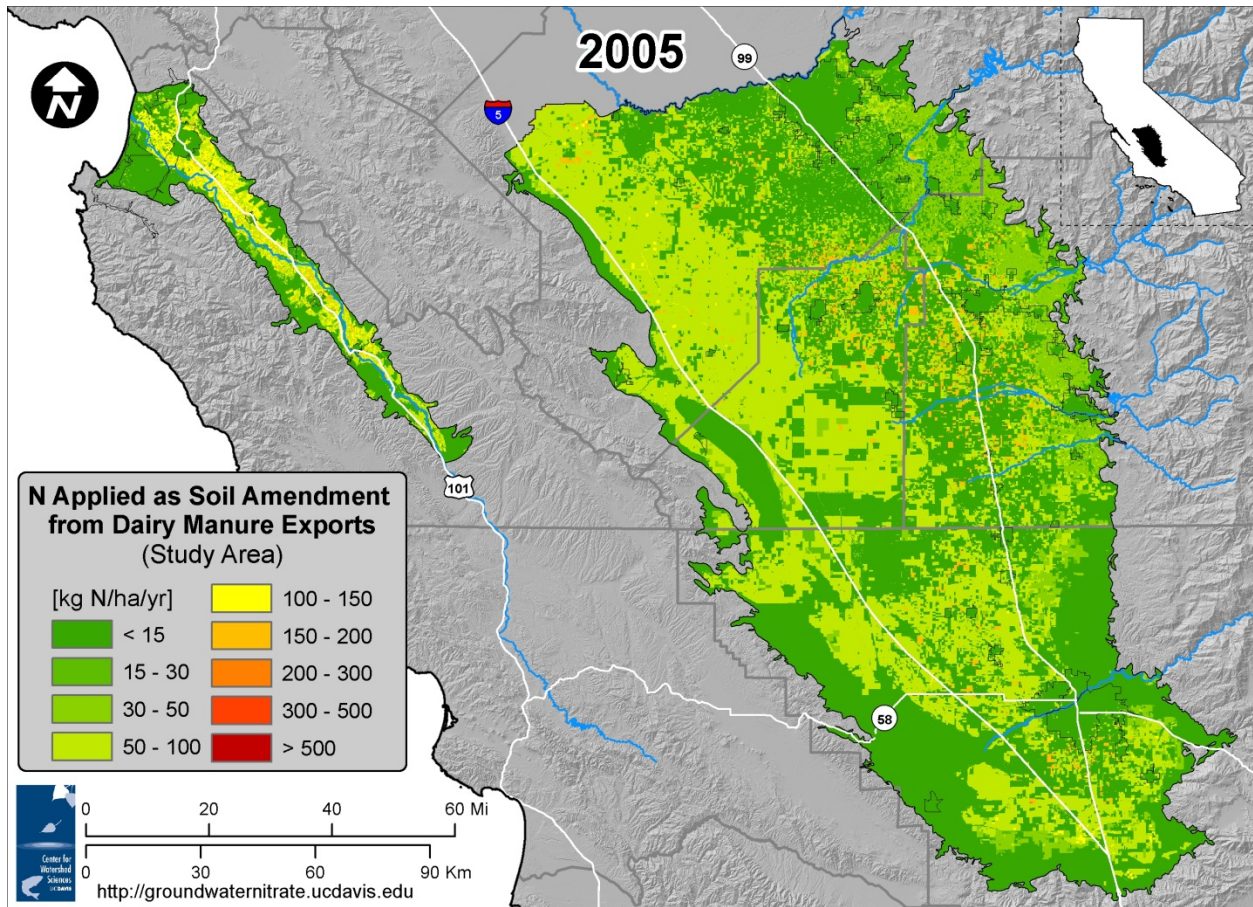
Figure 13. Simulated land application of dairy manure N exported from dairies and land applied across the study area (not restricted to the county of origin) at rates proportional and in addition to typical N fertilizer needs in each crop (see Figure 4). Total manure exports represent 38% of animal N excreted ("Scenario C (study area)").
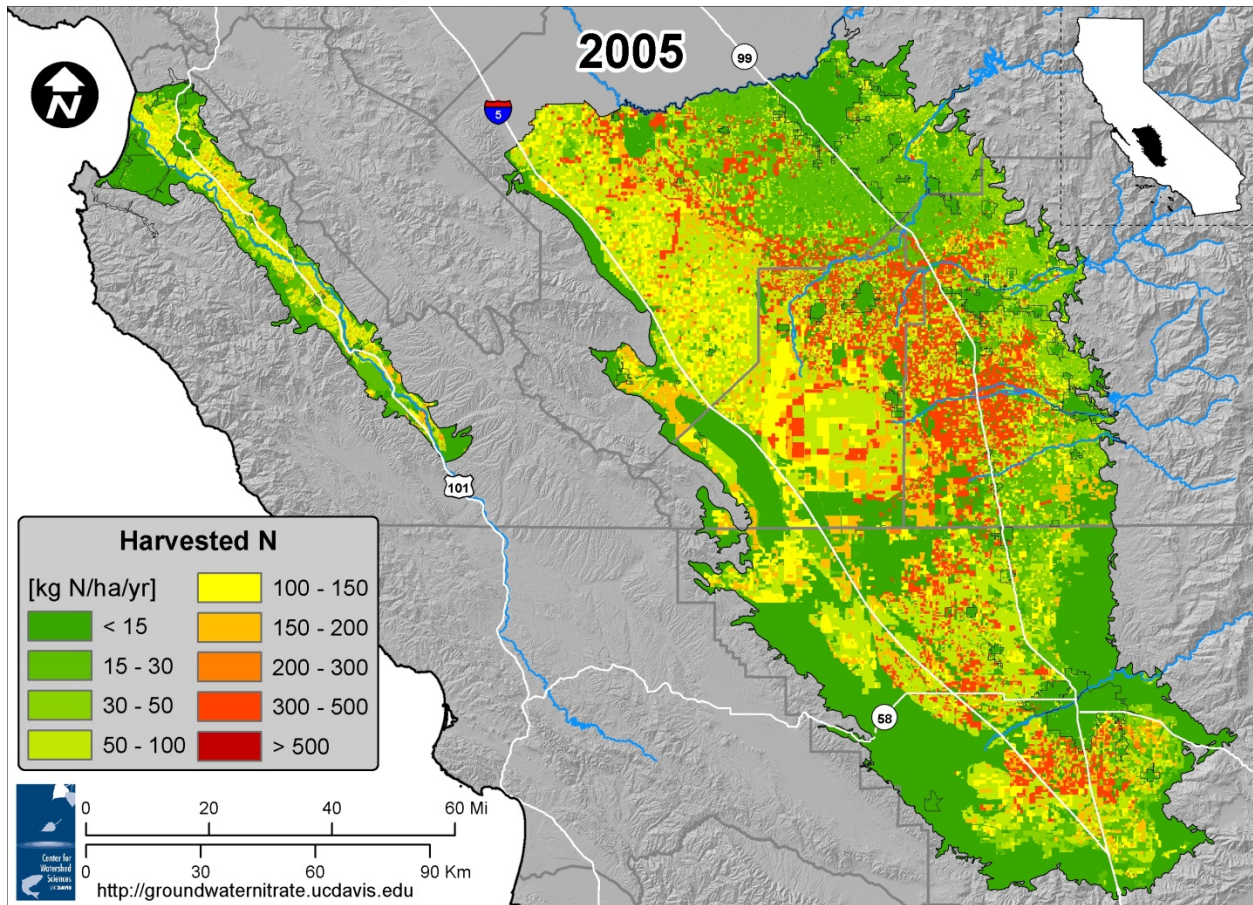
Figure 14. Simulated nitrogen harvested in 2005 from all cropland including alfalfa. The simulation assumes 1.7 annual crops in seven vegetable crops (broccoli, brussels sprouts, cabbage, cauliflower, celery, lettuce, spinach) and double-cropping of all corn acreage with winter grain.
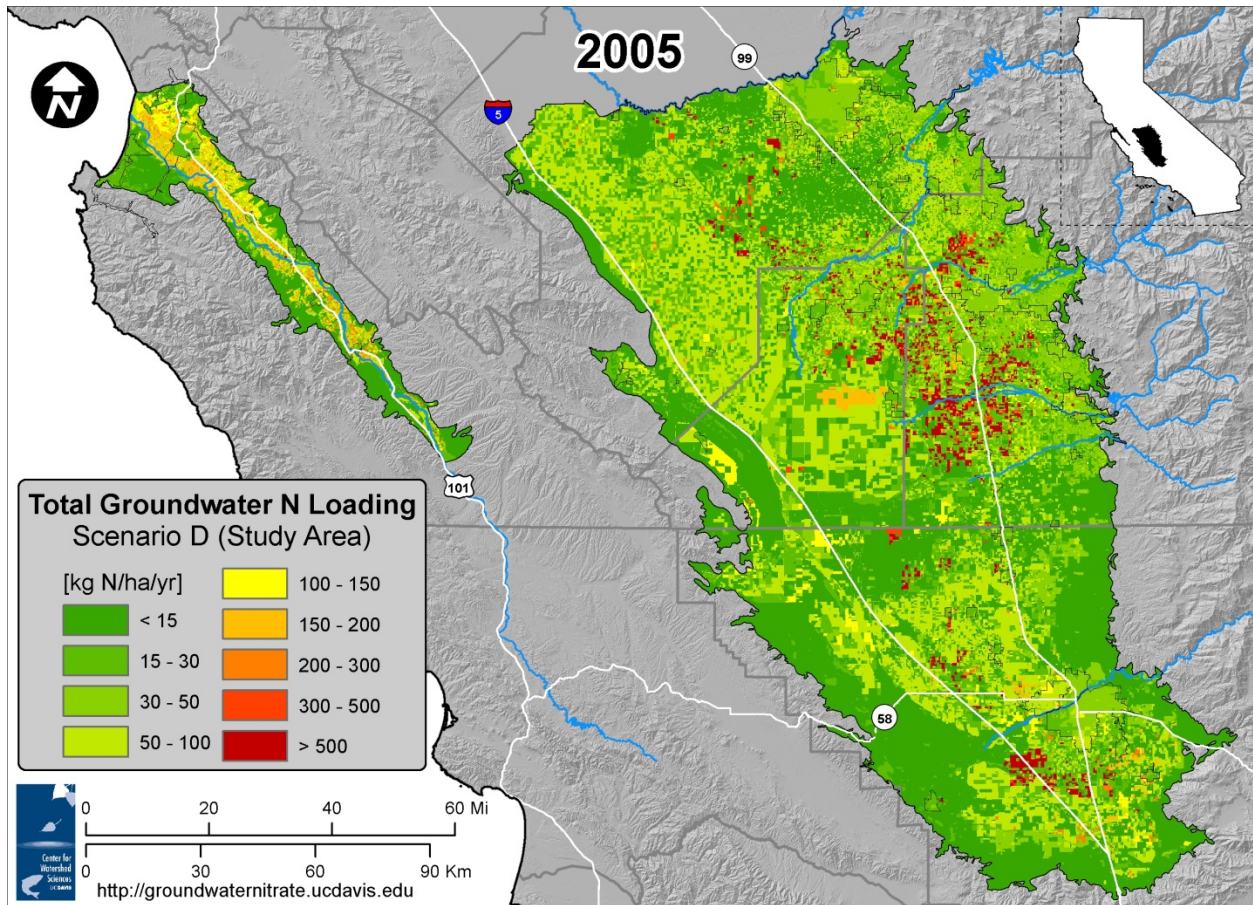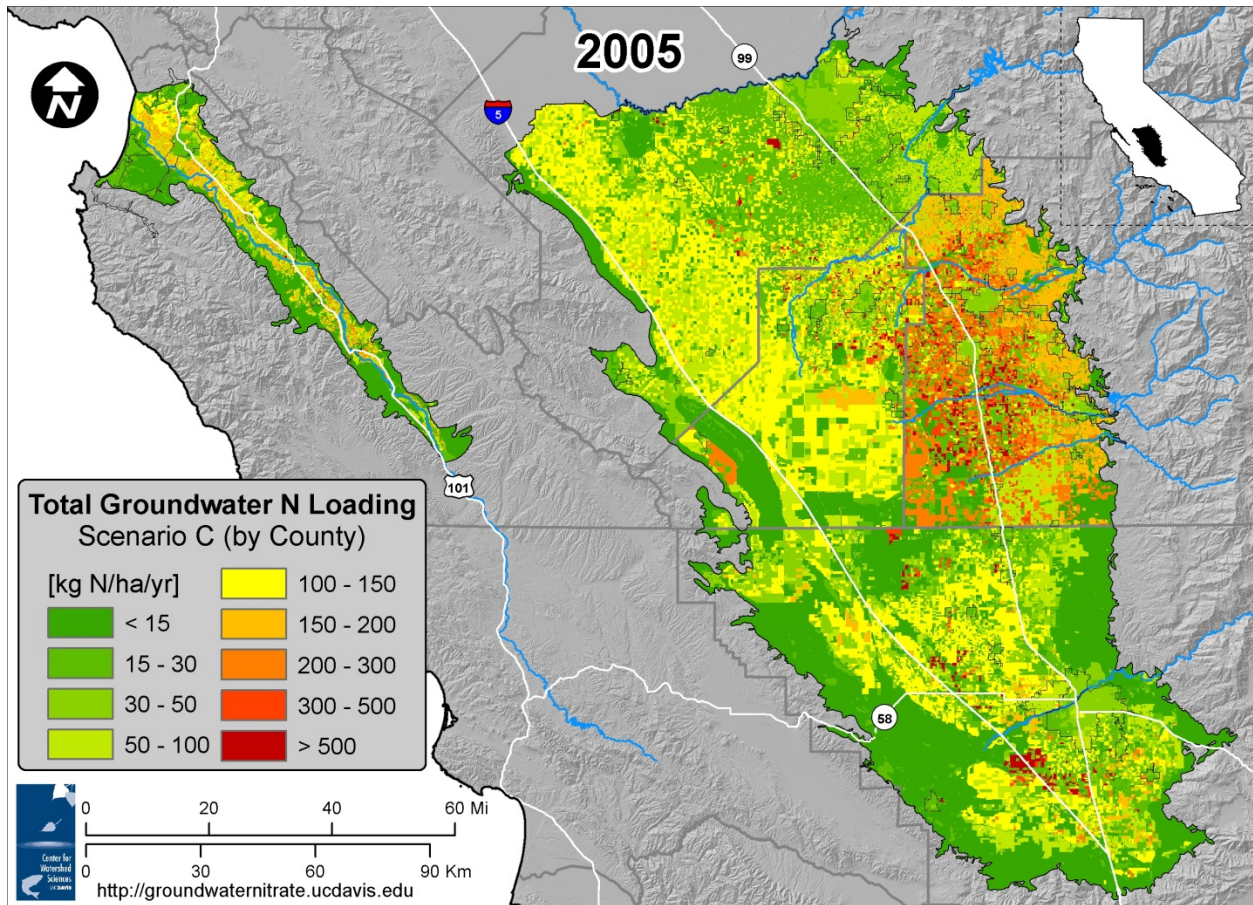
Figure 15. Simulated groundwater nitrate loading from all sources including cropland. Simulation of the hypothetical "Scenario D": All land applied manure N (62% of animal N excreted) is applied to corn, grain, and other field crops (not including alfalfa) under the direct management of dairies (no manure N exports).

Figure 16. Simulated groundwater nitrate loading from all sources including cropland. Simulation of the hypothetical "Scenario C (by county)": hypothetically exported manure N from dairies (38% of animal N excretion) is land applied as soil amendment within the county of origin. Exported manure N applications are proportional and in addition to synthetic fertilizer applications to meet typical fertilizer application needs (Figure 4).
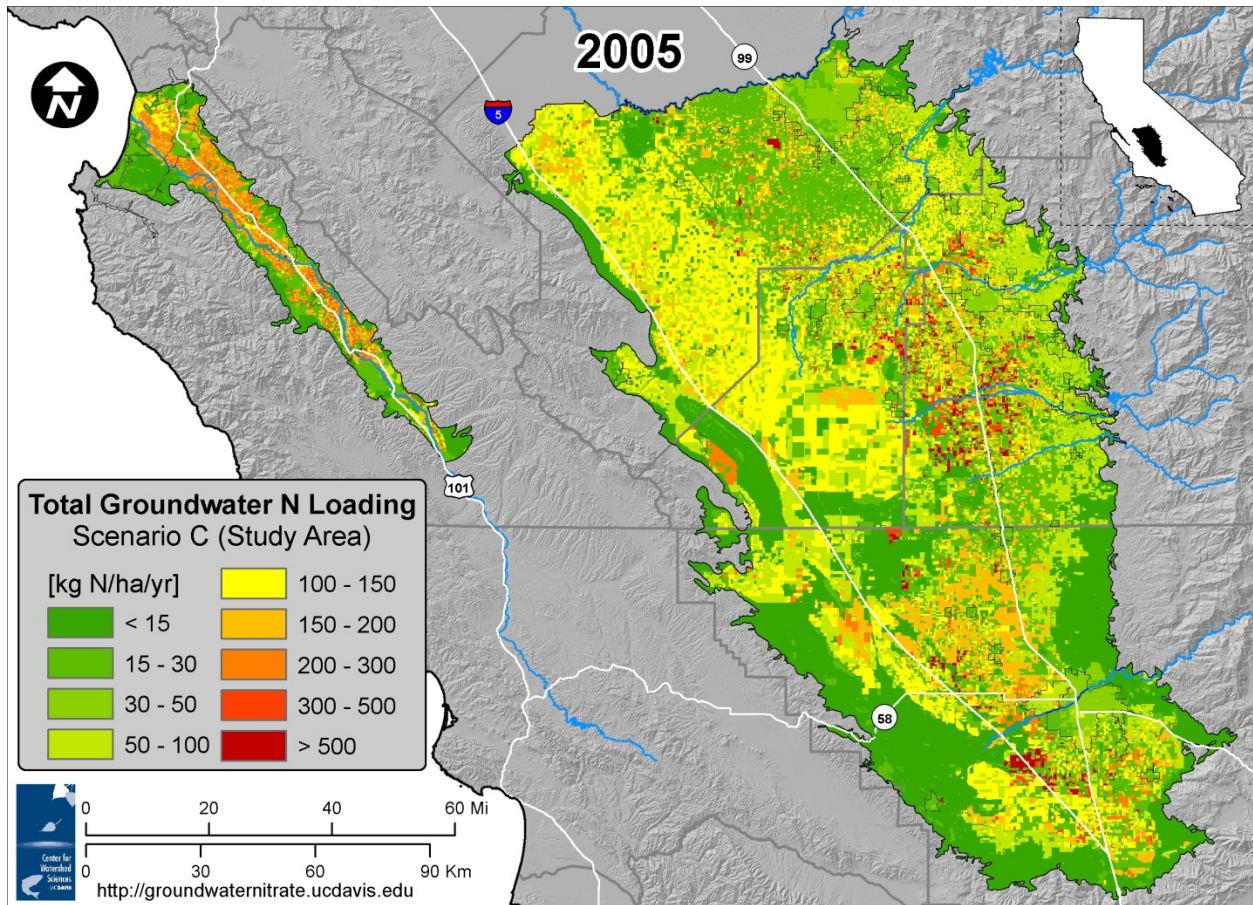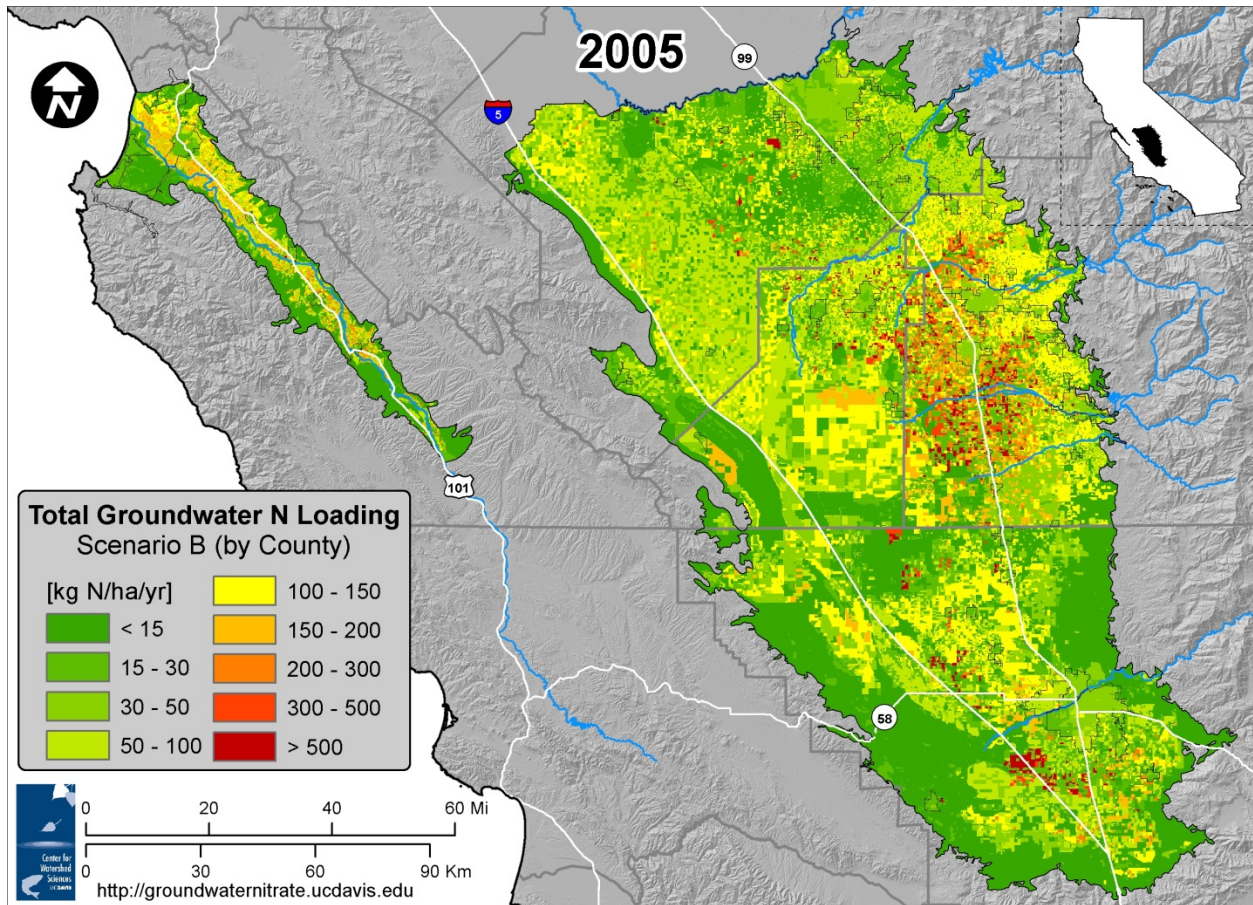
Figure 17. Simulated groundwater nitrate loading from all sources including cropland. Simulation of the hypothetical "Scenario C (study area)": hypothetically exported manure N from dairies (38% of animal N excretion) is land applied as soil amendment across the study area (not restricted to the county of origin). Exported manure N applications are proportional and in addition to synthetic fertilizer applications to meet typical fertilizer application needs (Figure 4).

Figure 18. Simulated groundwater nitrate loading from all sources including cropland. Simulation of the hypothetical "Scenario B (by county)": half of the hypothetically exported manure N from dairies (19.5% of animal N excretion) is land applied as soil amendment within the county of origin. These manure N applications are proportional and in addition to synthetic fertilizer applications to meet typical fertilizer application needs (Figure 4). The remaining half of the hypothetically exported manure N (19.5% of animal N excretion) is subject to the pathways explained under "Scenario A" (Figure 20).
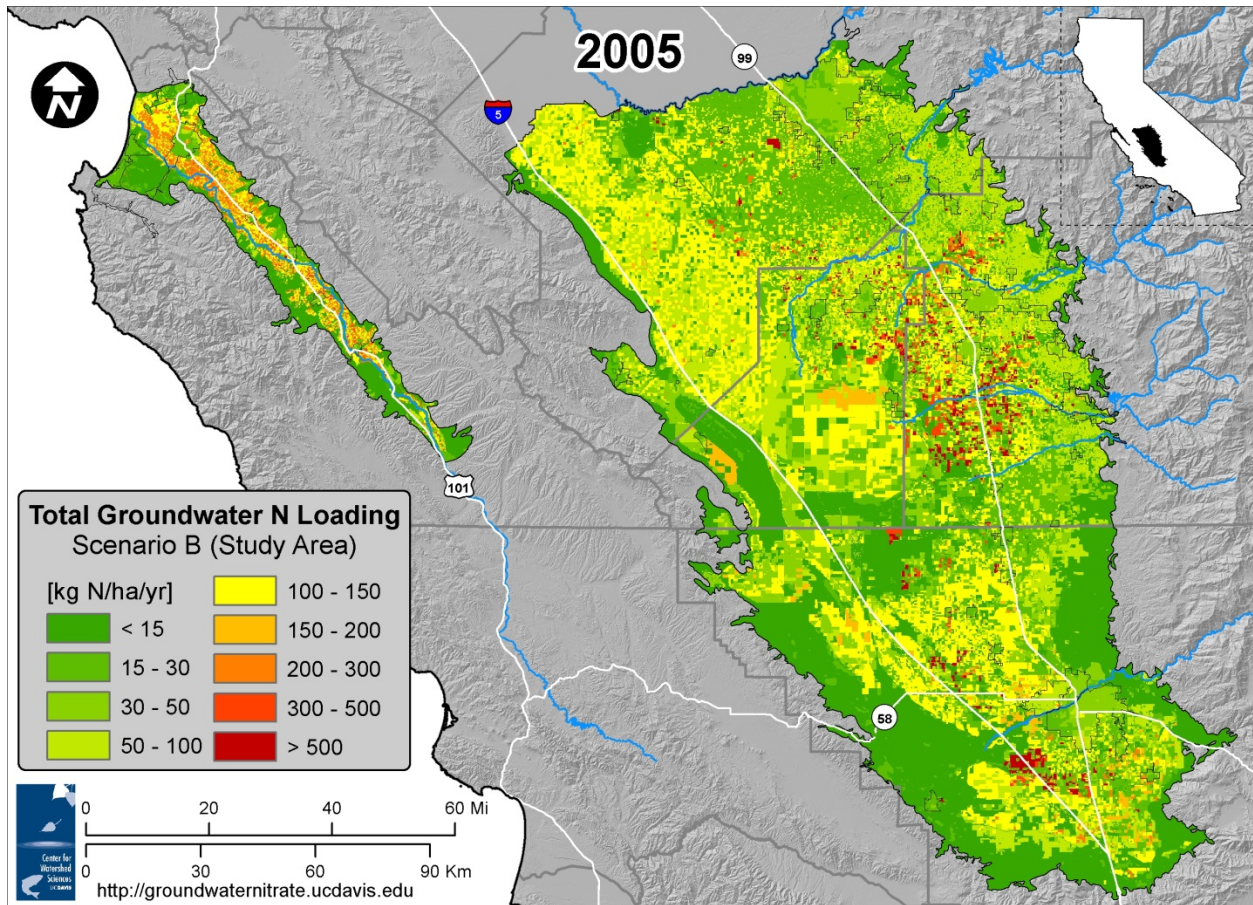
Figure 19. Simulated groundwater nitrate loading from all sources including cropland. Simulation of the hypothetical "Scenario B (study area)": half of the hypothetically exported manure N from dairies (19.5% of animal N excretion) is land applied as soil amendment across the study area (not restricted to the county of origin). These manure N applications are proportional and in addition to synthetic fertilizer applications to meet typical fertilizer application needs (Figure 4). The remaining half of the hypothetically exported manure N (19.5% of animal N excretion) is subject to the pathways explained under "Scenario A" (Figure 20).
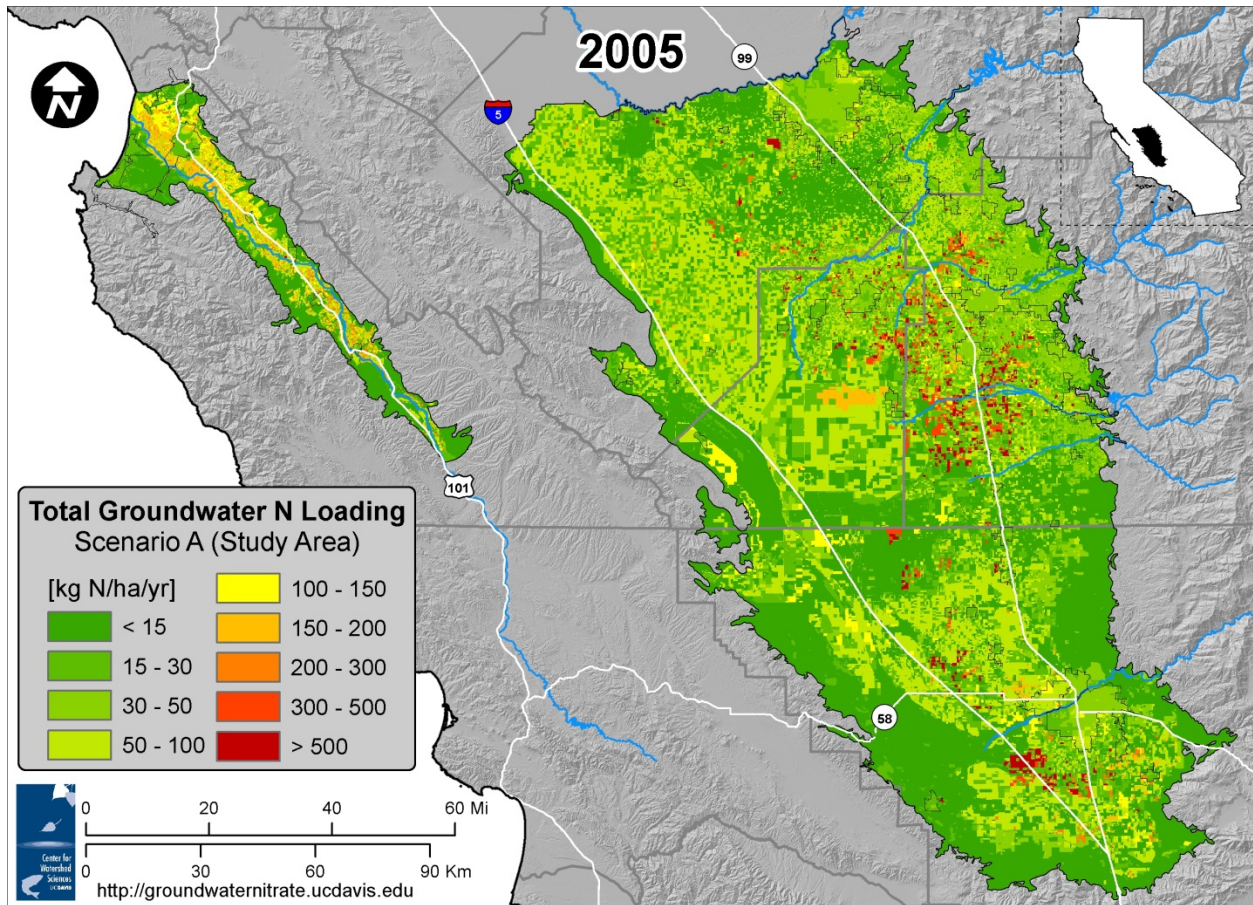
Figure 20. Simulated groundwater nitrate loading from all sources including cropland. Simulation of the hypothetical "Scenario A": All of the hypothetically exported manure N from dairies (38% of animal N excretion) is subject to one of the following conceptual pathways: a) applied to non-dairy cropland, with synthetic N plus manure N not exceeding the typical N fertilization rates shown in Figure 4, effectively replacing up to 78 Gg N/yr (86,000 t N/yr) of synthetic fertilizer N with manure N; b) transported to areas completely outside the study area, possibly after some processing; or c) intentionally processed and lost to the atmosphere.
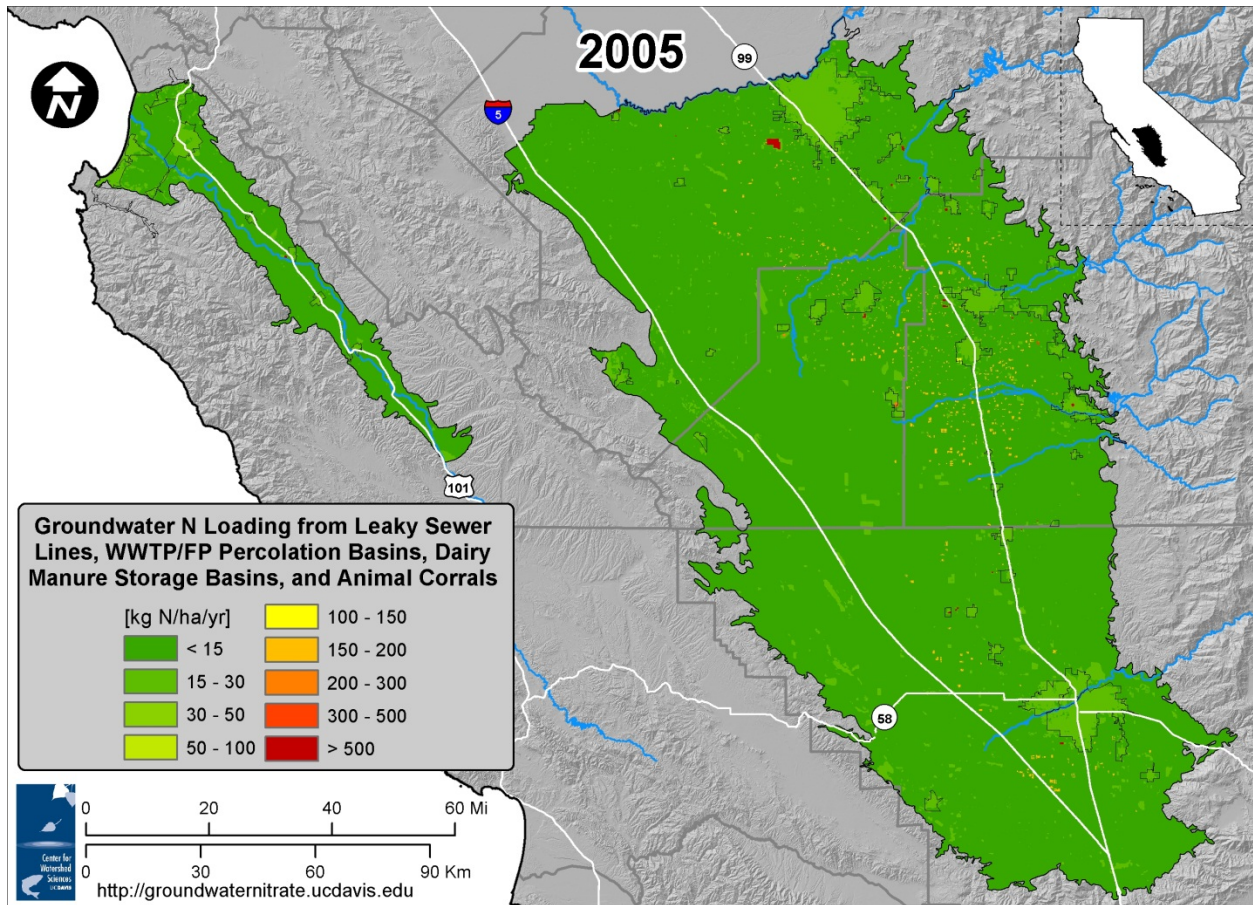
Figure 21. Groundwater loading from non-cropland sources including leaky sewer lines, turf areas, golf courses, WWTP/FP percolation basins, dairy manure lagoons, and animal corrals, in 2005. Septic systems loading (Figure 8) is not included here.

2.9 Concluding Remarks

In this technical report, we summarize and quantify the contributions of a wide range of nitrate sources to groundwater. The results, for the first time in one document, provide a comprehensive quantitative assessment of all groundwater nitrate sources and both, their overall regional contribution (Section 1.6) and the distribution of their local intensity (Section 1.8). Moreover, for the first time, sources are assessed continuously over a historically relevant period and into the future. The spatial source assessment covers 60 years of historic applications and projects 45 years into the future, at current management practices, and at anticipated urbanization rates.

Overall, cropland (not including alfalfa) is found to be the dominant source of nitrate in groundwater, contributing over 90% of all nitrate leached to groundwater. Other sources are locally important – often near urban areas - and may also lead to contamination of drinking water wells. These sources include septic systems in areas with relatively high density of unsewered homes, percolation ponds associated with municipal wastewater treatment plants and food processors, and manure storage

lagoons on dairies. Other sources, such as urban lawns, golf courses, leaky sewer lines may be locally important sources of nitrate, but are not considered a significant regional problem.

Cropland as the main source of groundwater nitrate in the study area is far from a single source. The study area features a globally unique diversity of dozens of major crops. It also experiences a wide range of soil and climate conditions and, more importantly, is managed by tens of thousands of individual farmers. Nitrate leaching undoubtedly varies within individual fields, between fields of the same crop, between farms, between counties, and between geographic sub-regions of the study area. With such inherent spatial (and temporal) variability, and given the additional complexity of the groundwater system itself (Boyle et al., 2012), it is tempting to lose sight of the overarching impact of agriculture on groundwater quality.

The large scale quantitative analysis of groundwater nitrate loading from cropland via the mass balance approach, aggregated from detailed data, allows for a clear identification of the major driving factors for groundwater nitrate loading – and of the constraints to addressing groundwater nitrate loading - independent of the large variability between crops, fields, and landowners in the study area.

The total amount of nitrogen intentionally or incidentally applied to study area cropland from various sources each year is about three times larger than the amount of nitrogen removed in the harvest,. This suggests significant system-wide inefficiencies in fertilizer use.

Synthetic nitrogen fertilizer makes up slightly more than half of the total nitrogen applied to cropland suggesting limited flexibility in reducing overall nitrogen application to cropland. In the Salinas Valley, synthetic nitrogen fertilizer is over 80% of all nitrogen applied to cropland.

Land applied dairy manure now constitutes more than one-third of the total nitrogen land applied, increasing from 2% of total N applied prior to the late 1960s and about 15% of total N applied to cropland in the mid-1970s (Table 18). Dairies as sources of groundwater nitrate are therefore a relatively recent phenomenon compared to synthetic fertilizer. In addition, nitrate in irrigation water pumped from groundwater and nitrogen from atmospheric deposition have also become a significant, if only incidental, source of nitrogen applied to cropland (about one-tenth of all nitrogen applied).

Approximately half of the nitrogen incidentally or intentionally applied to cropland is leached to groundwater, whereas the relative groundwater loss was only about one-quarter of all N applied to cropland in 1960. The estimated amount of nitrate losses to groundwater represent a net fertilizer value, at 2011 prices, of about $200 million per year. The amount of groundwater nitrate loading is of such magnitude that, no matter the uncertainty about the exact amount of groundwater loading, the overarching finding is that cropland recharge has and continues to significantly degrade groundwater quality in the study area.

The estimated amount of groundwater nitrate loading in 2005 (195 Gg N/yr or 215,000 t N/yr) is more than double the estimated amount of groundwater nitrate loading from cropland in the mid-1970s

(82 Gg N/yr or 90,000 t N/yr), at similar recharge rates. This indicates that concentrations of nitrate in recharge have more than doubled over the past 30 years.

Importantly, the analysis also outlines significant constraints to reducing agricultural groundwater nitrate loading. If all cropland in the study area were under the CVRWB restrictions imposed on Central Valley dairy cropland, a restriction that would broadly reduce groundwater loading, the total allowable N application to cropland, at today's crop harvest output, would be on the order of 1.5 x 130 Gg N/yr (195 Gg N/yr or 215,000 t N/yr). This is about half of the current total N application to cropland (380 Gg N/yr or 420,000 t N/yr).

Significant reductions of cropland nitrogen applications cannot come from either atmospheric sources or irrigation water sources of N as these are incidental to the land. To the degree that changes in the economy of the study area are not desirable, continued application of urban and animal sources of N on cropland (effluent, biosolids, manure, and other organic materials) are also unavoidable. Large scale nitrogen-removal treatment of these sources would otherwise be needed. Together, these cropland N sources already provide about 90% (178 Gg N/yr or 196,000 t N/yr, Figure 3) of a 150% limit on the ratio of total cropland N applications to harvested N.

At the large-scale agricultural systems level, this suggests that significantly reducing groundwater nitrate loading in the intermediate to long-term is a two-pronged challenge:

First, significant reductions in synthetic fertilizer use would be needed, partly (or sometimes fully) replaced by nitrogen from organic sources, while crop yields are maintained or even improved. The necessary reduction in synthetic fertilizer use would largely be dictated by the ability to export organic sources of nitrogen out-of-state.

Second, nitrogen fertilizer from organic sources (largely dairy manure, but also biosolids and effluent) would be processed such that these can be economically distributed within the study area and – more importantly – such that these nutrients would effectively and efficiently replace synthetic fertilizer at a large scale across the study area. Alternatively, nitrogen from organic sources would be exported out-of-state or, perhaps, recycled in leguminous crops (alfalfa) currently not receiving significant amounts of fertilizer.

Dzurella et al., 2012 reviews current practices to (at least partially) address the challenge in improving cropland nutrient management. The conversion of manure and other organic N sources into a synthetic fertilizer-like product, remains unaddressed in this report, but needs to be considered. The utilization of manure and organic wastes as an energy source, in bio-digesters or as biochar, does not remove significant amounts of nitrogen from the waste stream. But it may provide a manure or waste

processing framework that is also amenable to separate nitrogen and salts[17] into a shippable, nutrient-accountable, and marketable product. Much more research and development is needed here.

The dual challenge of reducing overall N inputs to cropland by reducing synthetic fertilizer use while converting manure N to a product that can effectively mimic synthetic fertilizer is not unique to the study area. To the degree that the study area represents over 40% of California's irrigated agriculture and half of its dairy herd, the challenge for California agriculture as a whole remains nearly identical. Beyond California, this is also a global challenge, driven by population growth, economic improvements in threshold countries, and the likely doubling of the demand for food, especially milk and meat products, fiber, and biofuel production over the next four decades, while expansion of global cropland area is expected to be very limited. Already, irrigated agriculture produces 40% of global food and fiber supplies on 20% of all cropland. Without significant shifts in national and global consumer food choices, global markets, in the long-term, will continue to provide incentives for further intensification of irrigated crop and animal production systems, in California, in the United States, and in agricultural regions around the world.

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[17] Salt is another significant water quality concern associated with land application of manure. In the long-term, salinization of groundwater resources, unlike nitrate contamination, is detrimental not only to drinking water but also to irrigation water quality.

3. Acknowledgments

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