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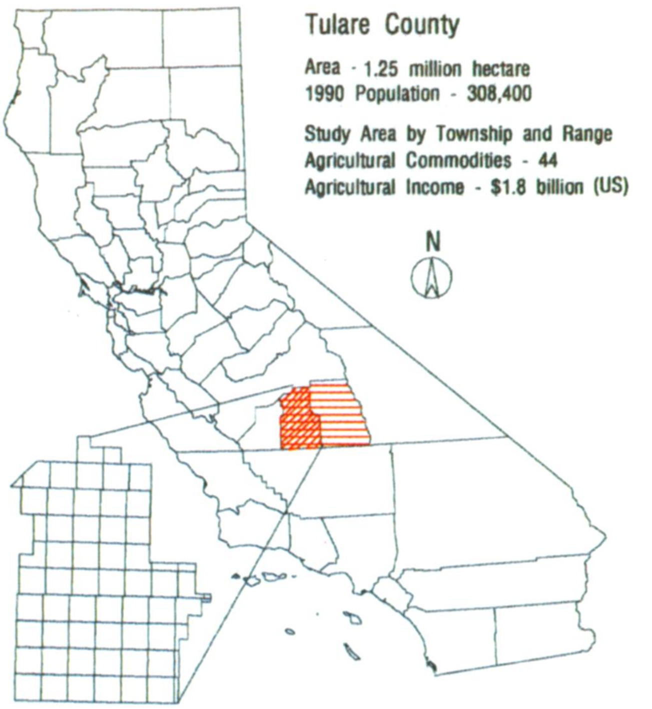
Assessing Groundwater Nitrate Contamination for Resource and Landscape Management

Groundwater nitrate concentrations increased and sometimes exceeded public health standards during the last 50 years in Tulare County, California, where ecological health and agricultural productivity are at risk. This study explained some of the spatial variation in groundwater nitrate concentration by spatial coincidence of soil leaching potential, agricultural land uses, and the groundwater elevation. Groundwater nitrate concentration increased where excess nitrogen loads in soils were greatest, soils rated highest for leaching potential, and groundwater elevation was higher. The high-risk nitrate leaching and contamination sites were most prevalent on townships where citrus, nut orchards, and vineyard crops were grown on coarse-textured soils. The assessment made use of available data at a spatial scale appropriate for devising management solutions, and the maps communicated the information effectively. Farmers and planners can use this information to adjust farm-management practices and land-use strategies to minimize nitrate contamination risks in groundwater.

INTRODUCTION

Groundwater supplies more than 40% of California's water demand, and is relied on for drinking purposes in about 70% of the cities with more than 10 000 people (1). Unfortunately, this critical natural resource is often contaminated with nitrates, which are some of the major contaminants. About 10% of the sampled wells in California and more than 7% of public water systems in Tulare County contained nitrate levels above the public health standard of 45 mg L^{-1} NO_3 during 1987 (2). The threats posed by high nitrate concentrations to human health (3) and agriculture (4) heightens the need to understand the landscape structural pathway for nitrate leaching and how to minimize the risk of contamination.

Figure 1. Location of study area within Tulare County, California.



Nitrates in groundwater come from diverse sources such as nitrogen fertilizer, animal wastes, municipal wastewater, landfill, septic tanks, urban runoff and soil organic matter. Nitrogen fertilizer application is of particular concern to the public (5, 6), and it is the dominant source of groundwater nitrate contamination (7). Rates of nitrogen fertilizer application correlated positively with nitrate leaching rates from irrigated agricultural land (8, 9) and grazed grassland (10). These rates depend on the amounts of nitrogen and water applied (11). Nitrate leaching is also influenced by soils and climate (5, 12).

Spatial data expressing the factors responsible for nitrate leaching can be related to the measured spatial variation of water quality for identifying potentially polluted areas. The most predictive factors can then be integrated to develop indicators of landscape sensitivity and level of threat posed by land use, similar to the indicators developed for pesticide leaching potential (13). Land units vary in their sensitivity to nitrate leaching according to soils and physiognomy, and they vary in vulnerability according to nitrogen load and land use. These indicators of sensitivity and vulnerability (pressure) can be measured with available data managed on a GIS (Geographic Information System), but they must be communicated simply and effectively to be worthwhile (4, 14). Once related to impact, measured by groundwater nitrate concentration among well samples, they can be extended to other areas for assessing one aspect of ecosystem health (15–17) at spatial scales appropriate for pattern recognition (18–21) and effective management solutions (4). Analysis and management at conventional small scales often fail to recognize and prevent cumulative impacts, and therefore invite catastrophic surprise (22–25).

This study focused on how crop nitrogen application and uptake interact with soil properties to affect groundwater nitrate contamination. The specific objectives were to *i)* identify potential nitrate contamination sites in Tulare County; *ii)* describe the relationship between nitrate concentration in groundwater and influential factors such as soil types, groundwater elevation, and crop arrangement and cultural practices; and *iii)* develop meaningful, practical indicators which reflect the risks of groundwater contamination. We carefully combined variables and aggregated quantitative detail to broaden inference on factors, trends, and scales that are appropriate for identifying the most alarming patterns and the most promising solutions across a region, consistent with the top-down indicators approach (4, 26–29). We did not study the detailed cycling processes of water nor of nitrogen.

Study Area

Tulare County, California was selected as the study site (Fig. 1) because of its intense agricultural production and known groundwater problems. Townships were used as study units to suit the resolution and quality of the available data. The mountainous portion of the county beyond the crop-producing lands was excluded from the study.

METHODS

We digitized maps of agricultural, industrial, and residential land use (30) and soil attributes (31), and we linked these GIS data layers to crop statistics (32) and nitrogen application and plant uptake rates (33, 34). Nitrogen content in dairy animal waste was estimated from Mid-West Plan Service Handbook (35). Groundwater nitrate concentrations were collected from the California Department of Water Resources. The data were integrated into three broad indicators representing *i)* soil sensitivity to leaching; *ii)* groundwater vulnerability to nitrate contamination due to nitrogen loading; and *iii)* impact measured by groundwater nitrate concentration. The three indicators allowed separate assessments, as well as calibration.

Soil sensitivity to nitrate leaching was assessed with a modified GOSS model (36), although the model was originally developed to derive soil-pesticide interaction ratings. Unlike pesticides, nitrate leaching is enhanced in soils with high organic matter content (10, 37). Because the content of soil organic matter is low (~1%) in Tulare County, the effect of organic matter on nitrate leaching was assumed minimal. The soil K factor (erodibility), which was a function of slope, also was assumed inconsequential due to the flat relief of the study area. However, the soil hydrologic group class (i.e. water infiltration rate integrated with soil texture) serves to indicate the propensity for nitrate leaching. The modified algorithm of the model rated soil nitrate leaching potential as high to very low.

Soil hydrologic groups were weighted by area of each soil type on the township, and classified into four categories of hydrologic conductivity (HC, in cm hr^{-1}): very low (HC > 0.76), low (HC = 0.39 to 0.76), moderate (HC = 0.13 to 0.38) and high (HC < 0.13), designated A, B, C, and D, respectively. Class A of soil hydrologic groups included rocky and sandy soils and class D included heavy clays. A GIS map overlay of excess nitrogen load in soil and weighted soil leaching potentials was used to identify potential nitrate leaching sites in Tulare County. Regression and correlation analyses were also used to describe the relationship between groundwater nitrate concentration and groundwater elevation, and crop and soil indices.

Groundwater vulnerability to nitrate contamination was assessed strictly by land use, because groundwater under sensitive soils is not vulnerable until nitrogen and water are applied. Thus, our vulnerability index differed from that of Kellogg et al. (38), who combined soil sensitivity with land use. We estimated the excess nitrogen load in soil as the sum of the differences between applied nitrogen and that taken up by the crops, based on application and uptake rates multiplied by the land area of each crop per township, similar to Huang (39). Nitrogen load per township included artificial application to crops, ambient N-fixing by legumes, and local concentrations of animal waste at dairies and feedlots. Excess N was that remaining after crop uptake and export of animal manure for fertilizer. We used Wilcoxon's matched-pairs signed-ranks test and its large-sample approximation (40) to compare the contributions of alfalfa and dairies to excess N loads on townships. Excess N_A excluded N-fixing in alfalfa from the comparison, excess N_B excluded contribution of N from dairies, and excess N_C considered both N-fixing in alfalfa and N added by dairies (see Fig. 2).

RESULTS

Soil Sensitivity

Tulare County has 97 soil types, all of which are low in organic matter and soil erodibility (K factor). Very productive soils of loam, sandy loam and clay loam cover 78% of the county's valley floor. Mean Storie Index values (41) ranged 0.16 for clay soils (11% of area) to 0.32 for loam and 0.37 for some of the other soil types other than loam.

The pattern of soil leaching potential corresponded to soil hydrologic groups on the study area. According to the Goss model's predicted leaching potential for the upper soil horizon, areas of high leaching potential occurred on sandy and highly permeable soils in the northwest corner of the study area, at the cities of Tulare and Visalia, and along the foothills. The moderate leaching potential class occurred mostly in the south-central part of the county. The areas of lowest leaching potential were concentrated on the west side, because of low soil hydrologic groups on relatively impervious clay soils and claypans.

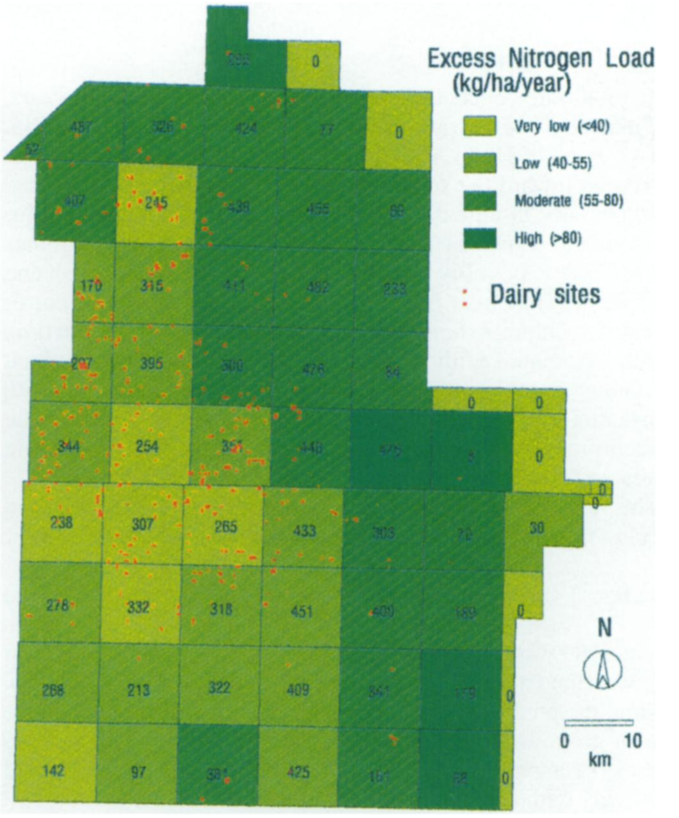


Figure 2. Total and excess nitrogen loads applied to Tulare County townships, indicating vulnerability of groundwater to nitrate leaching due to agricultural land use. Numbers denote total net nitrogen in tonnes per year.

Vulnerability to Leaching

Based on the spatial distribution of land use in Tulare County, the excess nitrogen load was greater on the townships of the northwest and along the foothills than on the west side (Fig. 2). Contrary to conventional thinking (4), and the much greater N loads per unit area (Table 1), excess nitrogen loads on townships were less where animal farms were clustered. Low excess nitrogen loads associated with alfalfa, barley, cotton-seed, carrots, and corn, whereas high loads associated with citrus, vineyards, and nut orchards. The ratio of excess N to agricultural product (kg ha^{-1}) varied sufficiently among crops in Tulare County to serve as an indicator of groundwater contamination (Fig. 3). Another indicator of threat is the typical amount of water applied relative to the yield (Fig. 3), which can be interactive with excess N. Both indicators measure vulnerability of groundwater to leaching of nitrogen compounds relative to the system goal of productivity, similar to indicators developed for the European Union (42). The ratio of excess N to N removed by the commodity can also serve as an indicator of nitrogen use efficiency (Fig. 3).

Alfalfa N-fixing, and dairies and feedlots, made significant differences in calculating excess nitrogen loads per township. The excess nitrogen load per township was greater when alfalfa N-fixing was excluded (N_A) from the calculation ($Z = 6.03$, $n = 47$, $P < 0.01$, where Z is the standard normal deviate, n is sample size, and P is probability of committing a Type I error), and when the contributions from dairies and feedlots were excluded (N_B) ($Z = 5.58$, $n = 40$, $P < 0.01$). That is, excess N_A > excess N_C > excess N_B.

Groundwater Impact

Data on nitrate concentration in groundwater spanned 50 years, and indicated concentrations were higher after 1970 ($Z = -4.045$, $n = 47$, $P < 0.001$). Average nitrate concentration in groundwater decreased toward the southwest part of the county. It increased exponentially in an eastward direction as surface elevation increased, and it increased at the northern and southern extremes of the County, possibly corresponding to where the Kaweah and Tule Rivers flow over two large aquifers. This trend also corresponded to more extensive citrus and nut orchard production, which associated with higher rates of excess N per product. Groundwater tables generally increased through time, but with substantial drops during drought periods. Groundwater nitrate concentration consistently increased as the groundwater table increased toward the ground surface.

The following model could explain 48% of the variation in average mg L^{-1} of nitrates in groundwater ($n = 45$, $P < 0.01$):

$$Nitrate = 3.4(SHG) - 2.33(SHG)^2 + 2.25(N_{exc}) - 1.95(\mathrm{SHG} \cdot N_{exc})$$

where SHG was the weighted average soil hydrologic group, and N_{exc} was the excess nitrogen load (kg ha^{-1}) on each township. Testing the predictor variables independently, nitrate concentration in groundwater correlated negatively with soil hydrologic groups (Pearson's correlation coefficient, $r = -0.3$, $P < 0.05$) and positively with excess nitrogen load due to land use ($r = 0.62$, $P < 0.001$). High nitrate concentration in groundwater occurred where excess nitrogen loads were high on highly permeable soils (Fig. 4). Excess nitrogen loads in soils were high due to the inefficient use of nitrogen in citrus and vineyard crops where soils are highly permeable. Groundwater elevation was not a significant component of the preceding model using spatial data. However, when averaged by latitude, groundwater nitrate concentration in townships increased exponentially with groundwater elevation, and was highest where groundwater tables approached the surface. Average groundwater nitrate concentration also correlated positively with crop water demand, water infiltration rate in soil and groundwater tables ($P < 0.05$ for all tests). It correlated negatively with percent of crop coverage and soil waterholding capacity ($P < 0.05$ for both tests).

Table 1. Annual water, nitrogen, and yield relationships among commodities grown in Tulare County during the 1980s (33–35, 56).

Commodity	Water use, cm ha^{-1}	N, kg ha^{-1} applied[a]	N, kg ha^{-1} removed	Excess N after removal by commodity kg ha^{-1}	Excess N after removal by commodity %	Yield kg ha^{-1}
Grapefruit	79.1	168.0	38.0	130.0	77	24 000
Lemons	79.1	168.0	57.0	111.0	66	30 000
Oranges	79.1	123.2	38.0	85.2	69	18 000
Avocados	79.1	112.0	20.0	92.0	82	5800
Olives	79.1	76.2	9.0	67.2	88	4600
Kiwis	79.1	112.0	35.0	77.0	69	9251
Apples	97.4	113.1	29.0	84.1	74	36 000
Apricots	97.4	105.3	34.0	71.3	68	18 000
Peaches/Nectarines	97.4	149.0	50.0	99.0	66	36 000
Plums	97.4	135.5	54.0	81.5	60	18 000
Prunes	97.4	124.3	54.0	70.3	57	18 000
Almonds	67.0	165.8	60.0	105.8	64	3000
Walnuts	97.4	157.9	52.0	105.9	67	2200
Pistachios	97.4	165.8	60.0	105.8	64	1142
Barley		97.6	85.0	12.6	13	4500
Wheat		166.7	79.0	87.7	53	4500
Grains, other	42.6	112.0	73.3	38.7	35	4000
Cotton seed	79.1	126.2	67.0	59.2	47	1900
Sugar beets	88.3	145.6	73.0	72.6	50	56 000
Corn	60.9	215.6	190.0	25.6	12	10 000
Grain sorghum	54.8	142.9	84.0	58.9	41	4500
Dry Beans	42.6	143.4	104.0	39.4	27	3000
Cole crops	36.5	184.8	60.0	124.8	68	
Carrots	36.5	134.4	76.0	58.4	43	42 000
Lettuce	36.5	171.4	48.0	123.4	72	30 000
Melons	70.0	107.5	36.0	71.5	67	22 400
Onions & garlic	36.5	143.9	86.0	57.9	40	36 000
Tomatoes	70.0	152.3	101.0	51.3	34	56 000
Peppers	70.0	181.4	46.0	135.4	75	24 000
Alfalfa	106.5	384.0	378.0	6.0	2	13 000
Mixed pasture	112.6	164.6	94.0	70.6	43	4500
Grapes	70.0	62.7	22.0	40.7	65	22400
Feed lots		1469.4	1322.0	147.4	10	
Dairies		2352.0	2116.0	236.0	10	

[a] Nitrogen applied to legume crops includes the nitrogen fixed from the atmosphere.

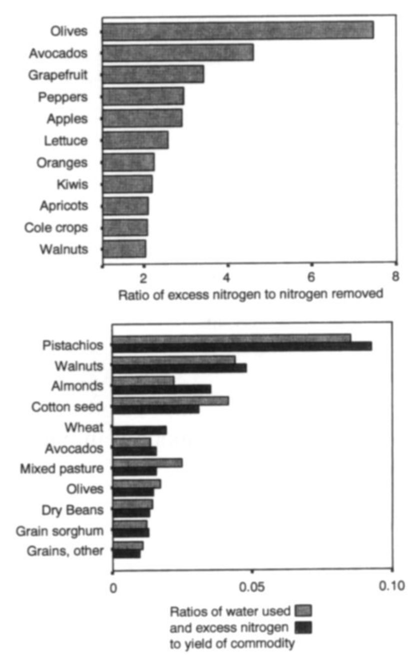


Figure 3. Environmental indicators of excess nitrogen relative to nitrogen removed by the commodity (top graph) and amounts of water used excess nitrogen relative to agricultural product (bottom graph). These ratios measure society's goal of minimizing groundwater pollution (4) against the goal of productivity.

DISCUSSION

The potential nitrogen leaching sites in Tulare County occurred mainly on the low foothill areas and the eastern Valley floor, and along the groundwater aquifers extending westward under the major streams, similar to the pattern found for pesticide leaching potential (13, 43). These soils are where orchard crops are grown on the sandy and sandy loam soils with high permeability. They are where the sensitive soils are made vulnerable to leaching by agricultural land uses, although the extensive citrus and vineyard crops on these areas actually generate only moderate levels of excess nitrogen (Fig. 3). The lower percentage crop coverage on these townships also pointed to soil sensitivity as the most important indicator of nitrogen leaching potential. The predicted leaching sites matched the actual areas of high impact fairly well.

The co-occurrence of predicted and actual nitrogen leaching areas provided a calibration of our spatial model (Fig. 5). We were therefore able to describe some of the factors responsible for nitrogen leaching into groundwater, and we established a set of indicators for assessing one aspect of ecological health across large areas. On and beyond Tulare County, land units rated highly for soil hydrologic groups and loaded heavily with excess nitrogen will pose the greatest risk of groundwater nitrate contamination.

Higher groundwater nitrate concentrations coincided where crop water demand, water infiltration rate in soil, and groundwater tables were also higher. Lower nitrate concentrations in groundwater associated with greater soil waterholding capacity in soils. Coarse soils usually have large pores and higher infiltration rates, so nitrate sources on these soils are easily leached if water is percolated through the soil profile. Nitrates will travel with other nutrients and water through the soil profile, the speed of which depends on the water infiltration rate through soil. Lateral nitrate movement may take place with sufficient water applied to sandy soils underlain by hardpan or claypan, but is less likely in Tulare County due to the dry climate.

Higher groundwater tables likely have higher nitrate concentrations because they can intercept the soil root zone where nitrates concentrate. Groundwater nitrate concentration also correlated with crop water demand, indicating that irrigation water supplied to cropping systems contributed to groundwater through percolation. Frequency and amount of irrigation typically increase with greater crop water demand.

The trend of increasing groundwater nitrate concentrations is likely due to increased nitrogen fertilization rates (44), increased water application rates, changes in crop patterns across the landscape, or to accumulating nitrogen following a long lag time between previous nitrogen application and its appearance in groundwater. Like annual field crops, animal farms were commonly regarded as a major source of nitrates in groundwater. Increasing numbers of animal farms in the county might increase groundwater nitrate concentration. However, citrus and nut orchards and vineyards contributed greater nitrogen loads per township due to their production on coarse soils (Fig. 2). The combined resource-use intensity of orchards, vineyards, and animal farms in the county will certainly increase groundwater nitrate concentrations. However, this input might lessen by adjusting the crop spatial arrangement or cultural practices.

Our derived GIS maps depict soil sensitivity, groundwater vulnerability and contamination in a manner that allows a simple, top-down interpretation of the spatial interrelationships between groundwater nitrate concentrations, cropping systems, and soil attributes. The areas predicted to be most contaminated deserve highest priority and greatest care in agricultural planning and management. Our indicators should be applied beyond Tulare County, adding to the resolution of those used by the USDA (4). Other areas might receive greater nitrogen loads than Tulare County (45), and greater excess nitrogen (39). Some other areas are also potentially more sensitive to percolation through soils (38) and more vulnerable to nitrate leaching (39). Our graphic indicators of environmental threat (Fig. 3) can provide water resource managers with information to improve the efficiency of water application and nitrogen use. They can alert researchers to crops which can most reduce nitrate pollution by improving resource use efficiency. However, the complex ecological relationships and chemical reactions in soils, and the many possible nitrate transport mechanisms, warrant verification analysis that sites indicated to be vulnerable to groundwater contamination actually have leaching problems.

Management Recommendations

Based on this research, we recommend that agricultural fertilizer and water management be altered on the areas with high risk of groundwater nitrate contamination. Reducing fertilizer use, where possible, offers the greatest potential for reducing the input of nitrogen compounds into the groundwater (7, 42). Our indicators in Figure 3 can help guide managers in identifying priority crops for which research and outreach efforts directed toward improving nitrogen and water-use efficiencies can contribute most to reducing nitrogen pollution in groundwater. Additional priority can be given to these crops where they occur on soils with high permeability and high groundwater tables.

Risk of nitrate contamination in groundwater also can be reduced by developing ecologically sound spatial structures among agricultural components, while avoiding any negative impact on productivity. The spatial arrangement of each commodity is important because each has a unique way of contributing excess nitrogen to soils. For example, our comparisons of land-use patterns indicated that growing alfalfa around dairies could reduce nitrate leaching potential. A careful soil-based selection of animal farm sites and alternative crop management methods might minimize nitrate pollution. Service ditches and canals on the agricultural landscape also can be managed to support aquatic vegetation capable of denitrification (46), and tail water ponds with aquatic vegetation can be strategically located to denitrify some of the excess load of nitrogen compounds (47–50). The spatial distribution of agricultural crops and other landscape elements is more manageable than is that of soil types and groundwater tables, so it offers greater opportunity for adjustment to minimize nitrate pollution in groundwater.

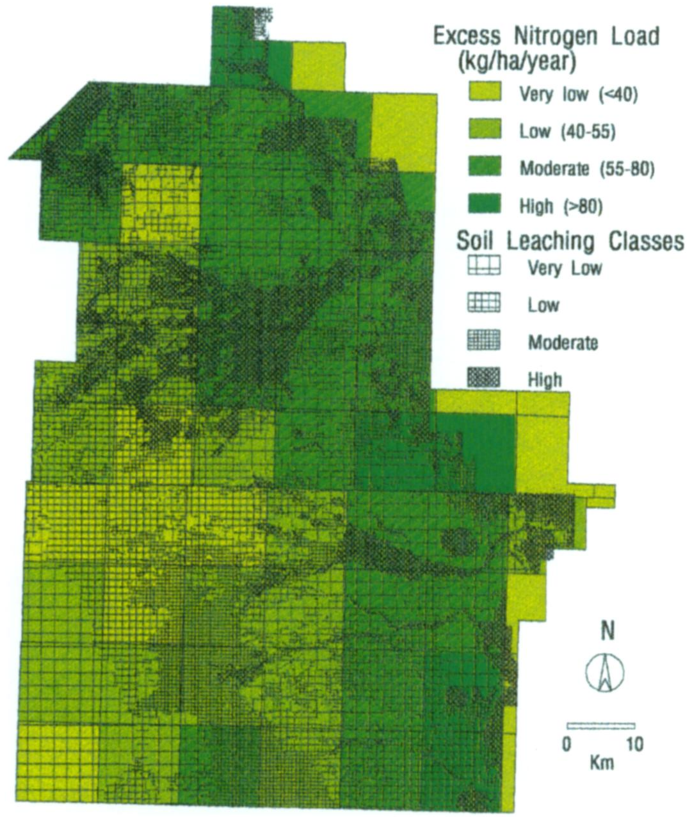


Figure 4. Co-occurrence of soil sensitivity and excess nitrogen loads due to agricultural land use across the Tulare County study area. The dense cross-hatch on the darker green indicates locations where nitrate leaching problems are most likely.

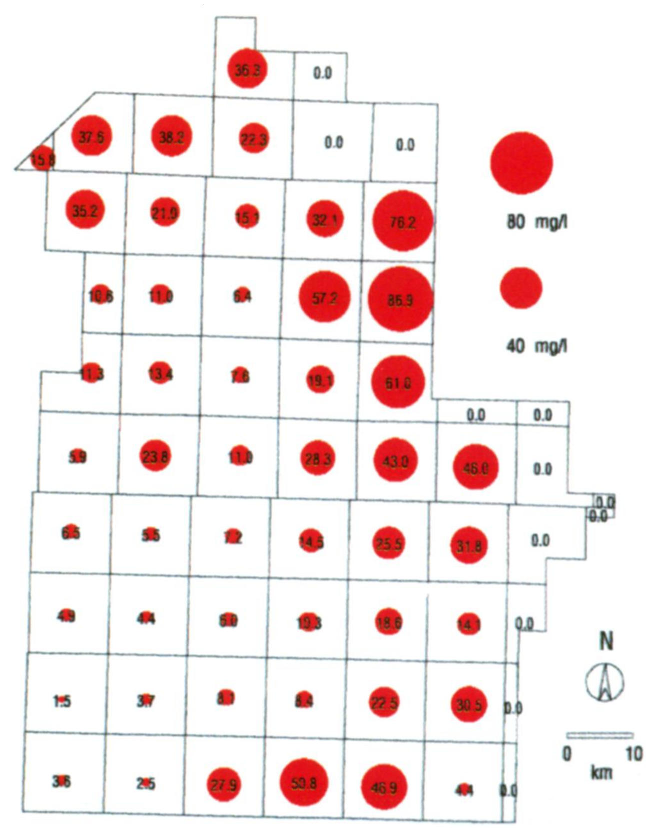


Figure 5. Impact of land use across the Tulare County study area, measured as average groundwater nitrate concentrations in sampled wells.

Finally, soils receiving high nitrogen loads can be treated to reduce leaching. For example, alfalfa has a deep rooting system and is noted to be an effective scavenger of inorganic nitrogen that may have accumulated under prior annual crops (51, 52). The use of deep-rooted crops such as alfalfa initially restrict nitrate leaching, but following alfalfa, large amounts of mineralized nitrogen can leach into subsurface drainage (53). Therefore, crops with high nitrogen demand could follow alfalfa in the rotation to minimize nitrate leaching. Another example is the use of legume cover crops in vineyards and orchards as a replacement for some synthetic nitrogen fertilizer inputs (54). New guidelines for management alternatives can minimize potential human and crop health risks by reducing and mitigating for the largest environmental input of nitrogen (7), thereby improving agricultural sustainability (16, 55).

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