Long-term Nitrate Leaching Below the Root Zone in California Tree Fruit Orchards

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Objectives

The project is designed to provide data for determining the long-term rate of nitrate leaching to groundwater under different conditions of fertilizer application and to provide a field dataset useful for preparing a conceptual-numerical model that reflects field observations and accounts for spatial variability, preferential flow, and uncertainty. The dataset should be useful in assessing and improving current methods for the estimation of nitrate leaching. To achieve these objectives, the following approach has been taken for characterizing the field site:

I. detailed descriptive and geostatistical description of the site stratigraphy ("geologic framework");
II. detailed analysis of the unsaturated hydraulic properties and their spatial variabilities between and within hydrostratigraphic units ("hydraulic characterization");
III. detailed analysis of the microbial activity and geochemistry and the potential for denitrification ("biogechemical characterization");
IV. detailed one-time snapshot of nitrate distribution and its spatial variability in the unsaturated zone ("nitrate: validation dataset").

The field and laboratory characterization will be useful for the development and validation of various modeling tools that assess the fate of nitrogen in deep, heterogeneous vadose zones; and provide an education component for growers, farm advisors, and personnel from irrigation districts, water districts, and regulatory agency on the leaching potential and attenuation rates of agricultural chemicals in similar areas.

Workplan Review

To achieve the goals of this project, work is divided into four tasks: field sampling, laboratory analysis, modeling analysis, and extension. The original workplan was based on the assumption that additional funding will be available from the California Water Resources Center for a second graduate student research assistant during project years 2 and 3 (not included in the budget below). The California Water Resources Center Proposal was indeed funded beginning with fiscal year 1999/2000 and a student has been hired as a research assistant to the project since October 1, 1999 (primary goal: data analysis and soil physics modeling). Laboratory analyses have been performed by Jim MacIntyre (soil hydraulic measurements; Dr. Hopmans' lab), Andrea DeLisle, Michael Ridolfi, Cindy Bergens, and Tad Doane (chemical analysis; Dr. Horwath's lab), and Michelle Denton (soil physics, refinement of soil physical analysis technique, inverse modeling, data management; Dr. Harter's lab). Difficulties in recruiting qualified students led to a 12-18 month delay in the completion of the tasks for the remainder of the project. Stable isotope analysis is still in progress due to delays in protocol development. The analysis of the soil physical properties (protocol development, inverse modeling) has resulted in an extensive redevelopment of the multistep outflow method, for which we developed a new protocol (in preparation). The soil physics method development and implementation took significantly more time than anticipated, hence year #3 workplans have been substantially modified. Additional field sampling and stochastic analysis have been dropped, putting the focus on a geostatistical evaluation of the dataset. The adjusted completion dates (in parentheses) are reflected below. The project is increasingly integrated with other ongoing research of the PIs Harter and Hopmans. Their work continues to focus on evaluating spatial heterogeneity within alluvial vadose zones and its influence on transport of nitrate and other pollutants through the vadose zone under various agricultural uses. This interim report covers the period from January 2000 through June 2001. For the final report we request a 6 month no-cost extension until June 2002.

Year 1: January - December 1998

Task Description	Completion
Complete field work	2/98
Compile available information on fertilizer field project site	4/98
Chemical analysis of soil samples	6/00
Laboratory soil hydraulic experiments	begin in 1/98

Year 2: January - December 1999

Task Description	Completion
Stable isotope analysis	3/99 (12/01)
Evaluation of soil hydraulic properties from raw-data	6/99 (10/01)
Geostatistical analysis of field data	12/99 (02/02)

Year 3: January - December 2000

Task Description	Completion
Collect additional field samples	6/00 (cancelled)
Laboratory analysis of additional samples	9/00 (cancelled)
Stochastic modeling of the field site	10 /00 (cancelled)
Develop educational tools	11/00 (6/02)

Field Site Description

The research site is a 'Fantasia' nectarine orchard. The site is located on the east-side of the San Joaquin Valley, approximately 30 km southeast of Fresno, California, at the University of California Kearney Research Center. Groundwater contamination with nitrate is a serious concern in the region, particularly in the eastern half of the valley. There, most groundwater is pumped from several 100 feet thick Tertiary and Quaternary alluvial and fluvial sedimentary deposits that originate from the western slope of the Sierra Nevada. A series of large, interfingering alluvial fans laces the western edge of the Sierra Nevada. Current groundwater levels at the orchard site vary from 45 to almost 55 feet below the surface. Average annual precipitation at the site is 10 inches. In most years, negligible precipitation is recorded between late May and early October.

The orchard was planted in 1975 and consists of 15 rows with 15 trees per row. Row spacing is 6 m, tree spacing within each row also is 6 m. As is common for many orchards and vineyards in the area, the orchard is flood irrigated every 10-14 days from April through September. On average, 10 irrigations totaling 1.2 m of water annually were applied to the orchard. Average consumptive use of the mature orchard is estimated to be 0.9 m. Average net infiltration to below the root zone is therefore estimated to be on the order of 0.3 m. Assuming average effective water content of 15%, travel time to the water table is on the order of 5-10 years.

A controlled fertilizer experiment was conducted in the nectarine orchard over a period of twelve years (Johnson *et al*., 1995). Five different application rates, 0, 100, 175, 250, and 325 pounds of nitrogen per acre were applied in three replicates (two replicates of the zero fertilization treatment) from 1983 to 1994. These fourteen subplots consist of five trees within a row. Border-trees received a 100-lbs/acre-nitrogen treatment. Treatments are limited to a continuous, 8 feet wide band around the center of each tree row. Treatments extended 10 feet to the east and west of the first and last tree in each subplot. Except for the 0 treatment plots, all trees received a broadcast application of 100 lbs/acre nitrogen in September of each year. In the subplots with treatments larger than 100 lbs/acre, additional fertilizer was applied by hand in the spring of each year. In 1995, no fertilizer was applied. In the fall of 1996, a single fall application of 100 lbs/acre was applied to the entire 20-year-old orchard. In 1997, the orchard received regular irrigations only through early July, when field sampling began.

One additional irrigation was applied in late September 1997, after approximately two-thirds of all cores were taken. The duration of the fertilizer experiment is considered long enough to affect the entire vadose zone profile. For our analysis, we chose three of the fourteen subplots for detailed investigations (one each of the 0, 100, and 325 lbs/acre treatment). In 1997, the first year of this project, 60 cores were drilled to a depth of 52 feet; samples were taken at one foot to two feet intervals and stored for later analysis (Harter, 1998).

The Geologic Framework
A detailed description of the geologic framework has been provided in the first annual report (January 1999). No additional work has been performed under this objective during the work period.

Hydraulic Characterization
Hydraulic characterization includes determination of soil moisture content at the time of sampling (determined for all samples; Klute, 1986), determination of the saturated hydraulic conductivity, measurement of the dependence between unsaturated hydraulic conductivity, moisture content, and soil water pressure, and determination of grain size distribution (hydrometer method, ASTM, 1985). The gradient in soil water pressure and the unsaturated hydraulic conductivity determine the rate of water flow through the soils. The soil moisture content determines the actual volume associated with the flow rate. For purposes of this project, the undisturbed core samples were divided into five textural and pedogenic classes:

1. clays and silty clays
2. silty loams, silty-clayey loams, and loams
3. sandy loams
4. paleosols and hardpan (coated and cemented loamy sands and loams)
5. sands

The principle of the multistep outflow technique is to observe water outflow from and soil water suction changes in an initially saturated soil core sample at increasing steps of dryness. A saturated sample is placed into a specially developed pressure/suction chamber (Tempe cell) and is subjected to a predetermined air pressure. Water flows out of the soil until soil water suction matches the air pressure. Subsequently, air pressure is increased by a specified amount, which causes additional water to drain from the core until a new equilibrium is reached. Using the measured data in a computer model representing the homogeneous soil core, the specific unsaturated hydraulic conductivity and soil water retention functions of each core can be determined. For each of the five groups, average values and spatial variability will be determined to characterize the site.

For this project, the original multistep outflow technique was modified to accept the 1.7" core samples such that they fit tightly insight the Tempe cell. The semipermeable membrane on the outflow side of the Tempe cell was modified from a 1 bar ceramic plate to a 2-micron nylon filter. Various changes in the pressure and outflow tubing have been made to allow for faster and safer connections, simplified trouble-shooting, and superior system testing. Special attention had to be paid to the development of air-bubbles in the outflow tubing to avoid erroneous measurements. A protocol has been established for applying the multi-step outflow technique on direct-push drilling cores. Experiments were completed on over 100 undisturbed core samples, representing major hydrostratigraphic units within the 50-ft vadose zone. The parameters necessary to mathematically describe these measured hydraulic conductivity and soil moisture retention curves are simultaneously determined through inverse modeling with an optimization algorithm using the Levenberg-Marquardt method. This parameter estimation was completed this year and an exhaustive report detailing the multi-step outflow technique and the parameter estimation is being completed.

Michelle Denton, on a grant from the Water Resources Center, together with Atac Tuli have prepared a protocol of the multistep outflow method for determining soil hydraulic properties. Michelle, with support from Jim MacIntyre, is also scheduled to complete the inverse models for the 120 multi-step experiments that Jim MacIntyre had completed. This task has turned out much more time-consuming than I had originally anticipated. I am hoping that Michelle will be able to focus the second part of the summer and the fall on a geostatistical analysis of the soil hydraulic data that she has generated. I anticipate that she will complete her thesis in the spring of 2002.

Biogeochemical Characterization

Soil extracts are analyzed for inorganic N (NO_3-N, NH_4-N), soluble C and soluble N (Horwath & Paul, 1994). Microbial biomass C is determined by the chloroform-fumigation extraction method (Horwath & Paul 1994). The measurement of inorganic N, microbial biomass N and denitrification potential (fractional abundance of ^{15}N and ^{18}O, Boettcher *et al.*, 1990) of the soil from different depths will complement other physical soil characteristics determined for the soil cores. Biogeochemical data are needed to estimate the properties within the soil profile that will influence the fate of nitrate. Within the framework of our research we assume that ammonification, nitrification, and denitrification are the dominant processes affecting the fate of nitrate in the soil. The processes that affect the fate of nitrate are in themselves affected by other parameters including mineral nitrogen, soluble carbon, microbial biomass, and other soil physical properties mentioned earlier. Approximately 1000 soil samples were taken to measure these processes, which affect the fate of nitrate. To date we have extracted soil samples to determine the concentration of mineral nitrogen, both nitrate and ammonium, soluble carbon, and microbial biomass. We have finished the analysis of mineral N, including nitrate and ammonium, on all of the core samples taken during 1998. We have also completed the analysis for dissolved organic C, microbial biomass C, and bromide. Ongoing is the analysis of stable isotope N content of nitrate in selected core samples. The isotope analysis was severely hampered by a malfunctioning freezer that contained most of the samples reserved for that analysis. As a result, many samples thawed out. We are currently analyzing the unaffected samples and will be evaluating the effect that the thawing may have had on the sample integrity of the thawed samples. I anticipate that the analytical work will be completed by the end of 2002.

Nitrogen 'Snapshot'
Our initial focus has been to determine whether significant differences can be observed in average vadose zone nitrate concentrations underneath the three subplots 2 years after completion of the long-term fertilization research project and a one-time 100 lbs/ac application throughout the orchard during that interim period.

The average nitrate concentration in deep soil water of the first (0 lbs/acre) and second subplot (100 lbs/acre) were not significantly different (5 mg/l and 7 mg/l, respectively). Variability of nitrate concentrations in both subplots was very large, ranging from less than 1 mg/l in many samples to over 100 mg/l in some soil samples. Underneath the 325 lbs/acre nitrogen treatment, however, average nitrate-nitrogen concentrations in soil water were almost three times higher (17 mg/l) than in the two other subplots. Almost a third of the nitrate-N samples exceeded concentrations of 10 mg/l (the maximum allowable groundwater quality limit). The high soil water nitrate concentration levels are similar to groundwater nitrate concentrations found in many areas with elevated nitrate-nitrogen contamination levels.

Due to the large localized variability of the nitrate concentrations throughout the 50' profile, no significant nitrate trends were observed with depth indicating that denitrification is not a dominating factor in this research orchard. Isotope analysis and computer modeling will help to further identify any denitrification processes, while assessing the impact of geologic heterogeneity, lateral flow mixing (between different subplots), and vertical mixing due to the changes in nitrogen management during the year before drilling on nitrate concentrations throughout the deep vadose zone.

The amount of water stored under unsaturated conditions in the vadose zone is equivalent to 12 acft per acre or more than 5 years worth of irrigation recharge (estimated to be 2 acft/ac per year or less). The total nitrogen storage in the vadose zone below the root zone is 190 lbs (0 lbs/ac treatment), 240 lbs (100 lbs/ac treatment) and 620 lbs/ac (325 lbs/ac treatment). This corresponds to annual nitrogen losses of 30-40 lbs/ac in the first and second subplot, and over 100 lbs/ac in the third (325 lbs/ac) subplot.

The nitrate-nitrogen found underneath the zero lbs/ac subplot is attributed to 1) lateral movement of soil water (the subplots are only 10' wide, while the vadose zone is 50' deep), 2) background concentration in irrigation water, and 3) significant influx of N during the one-time 100 lbs/ac application 9 months prior to drilling. For the same reasons, the total nitrogen found underneath the high fertilization subplot is thought to be a diluted mixture with net annual nitrogen losses being potentially as high as 250-300 lbs/ac. If the high nitrogen treatment had been applied to the entire orchard, our preliminary estimates indicate that nitrate-nitrogen concentrations in the percolating water recharging the aquifer would have been as much as three to fives times higher, on average. Such concentrations would exceed the groundwater quality standard five- to tenfold. The detailed nitrate "snapshot" is therefore direct evidence for the importance of proper nutrient management in tree orchards with respect to protecting groundwater quality.

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