Soil Type, Crop, and Irrigation All Influence Optimal Nitrogen Management

John Letey and Peter Vaughan

Abstract

Many groundwater resources in California are degraded by high concentrations of nitrate. Most of this nitrate was transported to groundwater by water percolating below the root zone of agricultural fields. Consequently, soil type, crop, and irrigation that affect the rate of water percolation, in addition to application of nitrogen (N), dictate the probability of groundwater degradation. The dynamics of mineralization of plant unavailable organic N to plant available inorganic N (PAN) forms influence the probability of the N being transported to groundwater, and inclusion of soil temperature effects on mineralization rates is important as determined in this study. University of California scientists have developed the Nitrogen Hazard Index (NHI) and the ENVIRO-GRO (E-G) model as tools in developing Best Management Plans (BMP) designed to achieve high crop yields while minimizing groundwater degradation. The NHI allows farmers to input their crop, soil type, and irrigation system for a field and learn the relative risk of nitrate discharge below the root zone. Information is also provided for possible BMP strategies to decrease the probability of high nitrate leaching for their specific field. The E-G model, that requires the operator to be proficient in running such models, allows one to simulate the consequences of various management options on crop yield and the amount of nitrate leached. We report the results of E-G simulations that quantify the effects of irrigation, soil type, organic and inorganic N application amounts to corn yield and the amount of leached N. Simulation results indicate that nitrate management strategy based solely on applied amount of organic or inorganic N materials, and failing to include water management, is unreliable with respect to effective management of nitrate loading to groundwater. The results also reveal that monitoring N concentration immediately below the root zone, or in the aquifer, provides no information on the effectiveness of a given farm practice for reducing the amount of leached N. Indeed, erroneous conclusions might be made. Development of BMPs is proposed as being more effective and economical than tracking and reporting regulations for reducing the N load to groundwater.

Introduction

Many groundwater resources in California contain high concentrations of nitrate, and percolation from agricultural fields is a major contributor (Viers et al., 2012). Statements are frequently made that this is a result of excessive nitrogen (N) fertilizer application to crops. Excessive has more than one connotation and the term usually is not clearly defined. Excessive could mean more application than is removed by the crop. Unquestionably, more N is generally applied than removed by the crop. Another definition of excess is application of more fertilizer than required to achieve high yields and maximum profits. High yields and maximum profits almost always require application of more N than is removed by the crop. Whether farmers have historically applied more N than necessary to obtain maximum profits is subject to uncertainty. Other management factors such as irrigation have a great impact on the relationships between fertilizer application amount, crop yield, and deep percolation of nitrate. Strategies to reduce ground water degradation by nitrate that ignore the complex dynamic relationships with other management factors are likely to fail.

The fact that the nitrate reaches groundwater only because it is transported by water percolating through the soil is often disregarded in assessing the relationship between fertilizer application and nitrate degradation of groundwater. Water is required to meet evapotranspiration (ET) requirements of the crop. Irrigation or precipitation amounts that exceed the soil water holding capacity in the root zone cause leaching of soluble chemicals, including nitrate, to groundwater. The amount of N leached varies with time and depends on the amount of water flow and the N concentration in the soil-water at the time that leaching occurs.

The rate of N uptake by the crop varies with growth stage and may depend on the N concentration in the soil-water if N deficiency exists. Total plant dry matter production is usually linearly related to ET. Therefore, if plant growth is reduced by inadequate water, excess salinity or inadequate N; ET is reduced and this contributes to more leaching for a given irrigation regime (Pang and Letey, 1999). Feedback exists between plant growth and soil conditions. For example, if soil salinity reduces plant growth causing reduced ET, salt leaching is increased and serves as a partial protective mechanism. This is a positive feed-back mechanism with respect to salt leaching. However, if plant growth and ET are reduced by inadequate N or other factors, leaching of nitrate is increased and further reduces the nitrate content in the root zone and intensifies the problem. A consequence of this negative feed-back mechanism is that an attempt to decrease nitrate leaching by reducing N application may be counterproductive if the reduced N input causes reduced plant growth that causes increased N leaching. Significantly, groundwater degradation by nitrate is related to both time-dependent fertilizer and water management.

Nitrogen Results From Farmer Field Studies

The optimal (profit maximizing) N application amount is dictated by the amount of precipitation and irrigation. This statement is based on extensive research conducted on farmer fields in the 1970s. A total of 55 fields drained by tile systems and 31 fields that did not have a shallow water table and naturally drained were investigated (Letey et al. 1977; Letey et al. 1979). The rate of water discharge and the nitrate concentration in the water collected in tile systems allowed the calculation of the amount of nitrate discharge into the tile systems. The natural drainage studies involved drilling and analyzing soils removed at various depths, usually up to a depth of 50 feet. Procedures were developed to calculate the rate of water flow through the soil profile. This water flow rate multiplied by the nitrate concentration provided an estimate of the nitrate leached below the root zone. Information on fertilizer application was obtained from the farmers.

Similar results occurred for both systems. The correlation coefficient between the amount of N leached and the drainage volume was greater than the coefficient for the amount of N applied. This suggests that irrigation management is at least equal, and possibly more important, than fertilizer application in affecting the leaching of nitrate. As expected, the highest correlation coefficient was between the amount of nitrate leached and a combination of drainage volume and fertilizer application indicating that both are important.

Importantly, there was no significant correlation between the nitrate concentration in the drainage water with either the amount of fertilizer application or the drainage volume. The linear regression analysis for all the tile systems resulted in the equation $C = 29.4 - 0.0007N$, where C is the average nitrate-nitrogen concentration in mg/L and N is the fertilizer N applied in kg/ha (Letey et al.1977). Only concentration is usually measured with no measurement of the water flow rate that would additionally be required to calculate the discharge load. The numerical value of the concentration is of little value, and may even lead to erroneous conclusions as will be further documented later.

Farmers are very observant of crop behavior. They would not know how much drainage volume occurred on given fields, but they could measure yields. It was hypothesized that they would apply more N on fields that had deficiency in nitrogen because of the high drainage volumes on those fields. Indeed, the experimental data supported this hypothesis. A linear regression analysis for naturally drained fields resulted in the equation $N = 78.8 + 4.07W$ with $r = 0.618$ (significant at the 1 percent level); where N is the fertilizer applied (kg/ha/yr) and W is the drainage amount (cm/yr). The tile drain systems yielded $N = 275 + 2.85W$ with $r = 0.524$ (significant at the 5 percent level). Greater drainage flows, therefore, induced farmers to increase N applications

From the Past to the Future

Attributing the large quantities of nitrate that migrated to groundwater decades ago to excessive N application may not be correct. The causative factor is as likely to be related to irrigation management as to fertilizer management. Irrigation was almost entirely by gravity flow rather than pressurized irrigation systems. The irrigator has little control on the amount that infiltrates the soil in such systems because of non-uniform infiltration opportunity time within the furrow and spatial variability of hydraulic properties. Pressurized irrigation systems allow more precise control over the amount and uniformity of water application and partially negate the effects of soil properties such as infiltration rate.

Another factor contributing to purposely applying excess water can be attributed to the concern for salinating the soil. Historical accounts of salinating soils in irrigated semi-arid regions of the world are well known. Farmers were educated about the need to leach salts and they considered this in their irrigation practices. Leaching destructive salts also leaches beneficial nitrate. All of these factors contributed to the farmer needing to apply larger amounts of N to achieve high yields.

One reason for concluding that farmers apply more N than required for high crop yield is the perception that typically farmers apply more N than recommended by Universities and other research organizations. However, these recommendations are based on research that is commonly done on small plots with carefully controlled irrigation; conditions that may not be typical of farmer fields. The results reported above found that farmers tend to apply more N on fields that have greater drainage volumes This observation supports the conclusion that farmer application of N is influenced by field observations on yield.

Conversion of gravity flow systems to pressurized systems provides better opportunity to reduce deep percolation and should reduce the required amount of applied fertilizer. However, farmers and some scientists may not have considered the fact that the N application could be reduced without yield decrement with a shift in irrigation technology. Field observations can reveal deficiency in N application; but for most crops, excessive application is not observable. However, if a change in irrigation technology contributed to increased yields that require more N, the opportunity to reduce N application might be lessened.

Availability of soluble commercial N fertilizer has been cited as a cause for the historical large amount of nitrate reaching groundwater. Organic forms of N are sometimes assumed to decrease the potential for nitrate migration below the root zone as compared to inorganic forms. As will be demonstrated later, this assumption is not always valid.

If the cause of a problem is misdiagnosed, the prescribed cure may not be effective. Diagnosing the long term huge build up of nitrate in groundwater to historical excessive N application rather than to historical excessive water application can lead to poor, and possibly counter-productive, actions to improve the matter. Regulations designed to reduce groundwater degradation by focusing strictly on the amount of N application, and that do not account for the interactions between fertilizer and water management, as well as the timing of each, most likely will not achieve the desired goal. Furthermore each crop, soil, and irrigation technology poses individual challenges and opportunities that must be individually assessed. The nitrogen hazard index (NHI) was developed by University of California scientists and is available on line at http://ciwr.ucanr.edu/ and clicking on “Nitrogen Hazard Index”, followed by “Find Your Index Number”. A farm manager can input the crop, soil, and irrigation system and gain information that estimates the probability for nitrate to degrade groundwater from that field. Significantly, the relative effects of the crop, soil, and irrigation system toward contributing to the over all hazard are identified and allow one to focus management to mitigate those factors that are the largest contributors to the hazard. Guidelines are presented for management practices to minimize the degradation based on the specific crop, soil, and irrigation system.

The California State Water Resources Control Board recently submitted a report to the Legislature with recommendations addressing nitrate in groundwater (State Water Resources Control Board, 2013). Quantities of nitrogen application were emphasized with little recognition of the interaction between fertilizer management and irrigation management. The report specified that nitrate high-risk areas be identified. However, these areas were based only on hydrogeological conditions. A map has been made identifying high risk areas of groundwater quality by MTBE, primarily from leaking of underground storage tanks. The assumption is that areas vulnerable to MTBE are also vulnerable to nitrate. This assumption is not justified because it ignores all of the dynamic interactions occurring in the root zone that control the movement of nitrate below the root zone. Only after migrating below the root zone would N movement be affected by the hydrogeological features that affect the movement of MTBE. There is no risk if the nitrate moving below the root zone is small. The probability of risk is related to the crop, soil, and irrigation system (NHI) that should be the focus rather than on hydrogeological “high-risk” areas.

Management at the farm level is the most important factor in reducing the continued degradation of groundwater from nitrate. A better report to the Legislature would have focused on best management practices and provided a plan by which improved farm management would be implemented. Management factors that influence yield of a specific crop and N leaching include the amounts and timing of organic or inorganic N applications and irrigation events. Other significant factors that are not specifically manageable include soil hydraulic properties and rainfall.

Objectives

A major objective of this paper is to present scientific factors concerning the dynamic interactions between soil, crop, and irrigation on the leaching of nitrate and crop yield.
A model, ENVIRO-GRO (E-G), developed by University of California scientists simulates the consequences of various management factors on crop yield and nitrate movement below the root zone. This paper uses E-G to illustrate the effects of organic and inorganic nitrogen application amounts, rainfall, and irrigation amounts on crop yield and leaching of nitrate on two soil types. The effects of soil temperature on the dynamic rate of organic matter mineralization and the implications of this on potential N leaching are new findings. The results of the study are discussed in context of the NHI concept and the recommendations in the State Water Resources Control Board report to the Legislature to protect groundwater from nitrate degradation (State Water Resources Control Board, 2013)..

The Model

The timing and amount of fertilizer and water application greatly affect the yield and amount of leaching. The E-G model (Pang and Letey, 1998) was developed to simulate (i) water, salt, and nitrate movement through soil with a growing plant; (ii) plant response to stresses associated with matric water potential, salinity, and N deficiency; (iii) water, salt, and nitrate leaching below the root zone; (iv) cumulative relative transpiration and N uptake; and (v) consequent crop yield relative to an unstressed crop. E-G does not account for denitrification or N immobilization. The model allows one to simulate the consequences of irrigation water salinity and management practices on crop yield and nitrate leaching.

This model has recently been reprogrammed to make it more efficient by Peter Vaughan**.** Modifications to E-G include addition of compensation for N uptake, a two-pool model for organic matter decay, mass balance calculations, comprehensive output routines, and improvement of transport calculations for salt and nitrate. The E-G program and User Manual are freely available at {This information will be available by the time this manuscript is published}.

The user must input certain information. This information includes the potential ET as a function of time, the amount and timing of water addition, the potential N uptake of the crop as a function of time, the amount and timing of N application, and certain soil and plant characteristics. The time and amount of soluble inorganic N application is adequate information. However, this is not sufficient information for organic forms of N because it is not immediately available for plant uptake. The rate at which the organic N is mineralized into inorganic N is required as input to the model. One purpose of this paper is to evaluate factors, including soil temperature, that affect the dynamic rate of organic N mineralization.

Organic Material Mineralization Rate

Pratt et al. (1973) proposed that the mineralization of organic materials applied to soil could be characterized by a decay series. This series consists of a sequence of numbers representing the fraction of the current organic N amount that will mineralize in successive years. For example, a decay series [0.40, 0.20, 0.10, 0.05] would have 40% of the organic N mineralized the first year; with 20% of the remaining organic N mineralized the second year, and so forth. These decay series remain an important practical tool for estimating the multi-year N mineralization that may be expected for manure, compost or other organic N materials (Cusick et al., 2006).

The application of organic-N material should be timed to provide mineralized N as it is needed by the crop; a situation that cannot be easily evaluated using decay series. A continuous decay function is preferable for predicting plant available nitrogen (PAN) produced and is required within models such as E-G that has variable time-stepping with intervals that are usually shorter than one day. The upgraded E-G model includes a two-pool decay model represented by:

$$N_r(t) = (1-\psi)N_0 e^{-\lambda_1 t} + \psi N_0 e^{-\lambda_s t} \qquad (1)$$

The initial organic-N applied is N_0 (kg/ha) which is divided into a fraction ψN_0 that is assigned to a slow-decay pool and a remaining fraction $(1-\psi)N_0$ assigned to a fast pool (Vaughan, unpublished manuscript). The decay coefficients are λ_1 and λ_s for the fast and slow pools, respectively. Numerical values for these coefficients and fraction can be derived from the decay series.

The relationship between decay series and equation 1 can be viewed as data points of the decay series and a continuous function that can be fitted to these points. Yearly remaining organic N (N_r) can be calculated from the decay series by assuming an initial applied amount. The resulting sequence of N_r values can be extended to ten years under the assumption that decay rates after the final year of the explicit decay series are determined exclusively by the slow pool. The presumed decay coefficient of the slow pool is 0.0101 representing a 1% per year decay rate commonly accepted for soil organic matter (Meisinger et al., 2008). By extrapolating the curve passing through the N_r values for exclusively slow-pool decay backwards to the application time, the value of ψ can be obtained. The remaining unknown, λ_1, can be determined by curve fitting equation (1) to all N_r values using a nonlinear least-squares algorithm.

Although it is known that mineralization is a temperature dependent reaction, temperature effects have not generally been considered in estimating mineralization rates. The CIMIS soil temperature data for 2000 through 2011 at Madera, CA site #145 were averaged to obtain daily values and these were fitted to a sine function (Fig.1). Note that there is an approximate three-fold difference in soil temperature between winter and summer. This temperature difference would be expected to impact the temporal rate of mineralization. Vigil and Kissel (1995) proposed an exponential function for describing mineralization rate in the temperature range of 5 to 30^o C

$$TF = 0.01\exp(0.13T_s) \qquad (2)$$

where TF is the temperature factor and T_s (ºC) is soil temperature. These factors were input data for calculating temperature-dependent decay rates in E-G.

Crop and Organic Material Selected for Demonstration

Corn (Zea mays) was selected as the crop for demonstration because a comparison has been made between simulated results using E-G and experimental corn field results. Pang and Letey (1998) compared the simulated results from E-G with field data reported by Broadbent and Carlton (1979) which included three water application treatments and four nitrogen application amounts. The mean relative yield for all treatments was 0.69 observed and 0.64 simulated. The mean N uptake was 158 kg/ha observed and 159 kg/ha simulated. The poorest agreement was found for the extreme irrigation treatments that would not ordinarily be applied in the farmer operation. Although nitrogen was not a variable, the simulations from E-G were compared to a field experiment in Israel that included four irrigation water salinities and four irrigation intervals on corn (Feng et al., 2003). The mean relative yield was 0.68 observed and 0.70 simulated. Thus, the model has been demonstrated to simulate results comparable to experimental values for corn.

The required model input information is also available for corn based on a study in the San Joaquin Valley. The total N uptake was measured as a function of time for 3 years (Feng et al., 2005). The potential N uptake rate as a function of time was computed from these data and the total N uptake was 300 kg/ha.

The organic material selected for illustration had 90% mineralized in one year and the other 10% in the slow pool that mineralized at a rate of 1% per year. This approximates chicken manure that Pratt et al. (1973) reported had a decay series on 0.90, 0.10, and 0.05. An organic that is almost entirely mineralized in one year was chosen to avoid the complication of large carry-over of unmineralized N during successive years that would continually accumulate and result in complex multi-year simulations.

The cumulative N uptake by corn and the cumulative amount of mineralized N from an application of manure containing 370 kg/ha of N were computed as a function of time when the manure is applied on Jan. 1, Apr 1, May 15, or Oct 1. Only the October and April applications are reported in Fig. 2. Mineralization amounts adjusted for temperature dependent effects (TD) and assuming constant temperature (CT) are illustrated. Note that application on Oct 1 allows sufficient N to be mineralized before the crop period to provide its requirement. However, the mineralized N that exceeds crop uptake is subject to leaching during that time period.

Application on Apr 1 does not allow sufficient N to be mineralized to meet crop requirements during the first year but may in following years if it is not leached. Note that the temperature adjustment alters the time sequence that N is mineralized.

Variables Selected for Simulations

The organic material had two application dates and adjustment for temperature (TD) or no adjustment (CT). Inorganic N was applied once between the pre-plant irrigation and planting. A clay loam and sandy loam soil that differ in hydraulic properties and water holding capacities were selected. Two ratios (AW/PET) of uniform irrigation amount (AW) to potential ET (PET) equal to 1.1 and 1.42 were applied. These would cause expected leaching fractions for a non-stressed crop of 9 and 30%, respectively.

The first annual results are highly dependent on the initial soil conditions at the beginning of the simulation and may not accurately reflect the long-term effects of the treatment. For example, Broadbent and Carlton (1979) found that for the first year, crop N uptake on the plot that received 0 N application was approximately 75% of the amount that was taken up from the plot that received the highest N application. This ratio dropped to about 25% after about three years of treatment. These results emphasize the importance of multi-year field experiments to accurately determine the treatment effects. We ran simulations for 10 continuous years. The effects of the initial soil conditions were dissipated after the first two years, but only the 10-year results are reported. However, one value of the model is that the effects of changing management can be determined on an annual basis.

The crop was seeded on May 15 and harvested on September 28. Irrigation was bi-weekly on the clay loam and weekly on the sandy loam because of the lower water holding capacity. The soil profile was not recharged with water at the end of the growing season, but this amount of water was applied as a pre-plant irrigation the next season. The time and amount of rainfall during the fallow season were those recorded at CIMIS station #145, Madera, CA during the calendar year 2006 which was a relatively wet year having 29 cm total precipitation compared to a ten-year average of 22 cm. The individual rain event numbers are reported in the Results section.

A range of N input amounts were selected for each combination of variables to determine the required amount to achieve maximum yield and the relationship between yield and application amount. The annual N leached was computed for each case. The direction (upward or downward) and rate of water flow and N concentration in the soil water at the 100-cm depth, that represented the bottom of the root zone, were computed and plotted as functions of time. Combination of water flow and N concentration allowed calculation of the amount of N leached, and the cumulative leaching amount as a function of time was determined.

Results

The results from the organic addition to the clay loam soil will be presented first. The RY and annual amounts of leached N are plotted as a function of applied amount of organic-N for AW/PET = 1.1 in Fig.3 and for AW/PET = 1.42 in Fig.4. Note that much higher applications of organic-N are required to achieve a given RY for the higher water application. The higher water application resulted in greater N leaching as depicted in Figs.3 and 4 and thus required higher applications to achieve a given yield. The farmer is primarily interested in yields, whereas the amount of N removed by the crop is important to potential groundwater degradation from nitrate.

The model does not compute yield *per se* but computes the relative N uptake (RNup) to the potential uptake of a plant that does not experience N deficiency. A relationship between RNup and relative yield (RY) is necessary to convert the results to relative yield. Based on the results of Broadbent and Carlton (1979) this relationship for corn grown in the San Joaquin Valley is

$$RY = 1.7N_{up} - 0.7N_{up}^{\;2} \qquad (3)$$

Because the relationship between yield and N uptake is not linear, the relative N uptake is less than RY for a given application.

Except for conditions of maximum yield, a reduction in the amount of N application does not induce an equal reduction in the amount of N leached. For example, for AW/PET = 1.1, reduction of N application below 360 kg/ha did not reduce the amount of N leached at all (Fig.3). For AW/PET = 1.42, reducing N application from 430 to 330 kg/ha only caused a reduction of 20 kg/ha in leached N (Fig.4). Two factors contribute to this behavior. First, the reduction in N uptake is greater than the reduction in yield of corn for a given application. The reduction in uptake increases N availability for leaching. Second, and more important, the reduction in yield causes a reduction in ET resulting in an increase of deep percolation that is a major contributor to the leaching of N. This result emphasizes the importance of properly understanding "excessive" N application If "excess" is defined as more than removed by the crop without consideration of yield, a reduction in N application will not result in an equal reduction of the leached N amount. Indeed, it might be very little or no reduction.

The date of organic application and whether or not the rate of mineralization is adjusted for temperature effect are important in affecting the results. For the clay loam soil, application in October produced higher yields than application in April, and correcting for temperature effects resulted in lower yields (Fig. 3). The greater time for mineralization from October to April made more mineralized N available for the crop season. However, this N would be subject to leaching from winter rains. As will be reported later, the rainfall pattern did not cause deep water percolation on this soil. Neglect of considering low winter temperatures effects on mineralization caused an overestimate of yield and underestimate of leaching in this case.

Results from the sandy loam soil are illustrated in Figs. 5 and 6. Note that the Leached N scale is twice the scale used for the clay loam soil and that the applied amounts are greater to achieve maximum yield. April application of organic produced higher yields than the October application on the sandy soil that is opposite to the clay loam soil results. This result is a reflection of the greater winter leaching on the sandy soil as compared to the clay loam soil. Coincidentally, the temperature effect had very little effect on the results on the sandy soil.

The effects of water application amount on the N concentration and the water flow at the bottom of the root zone at different times for the organic-N application of 370 kg/ha are illustrated in Fig. 7 on the clay loam soil. The same relationships are illustrated in Fig.8 for the sandy loam soil. A negative water flux represents downward flow and a positive flux represents an upward flow at the bottom of the root zone (100 cm depth).

Considering the clay loam soil first, water flow at the 100-cm depth during the non-crop season is very low for both irrigation treatments. The AW/PET = 1.1 caused only very low downward flow after pre-plant irrigation and at the latter part of the growing season. As expected the AW/PET = 1.42 resulted in more water flow at the bottom of the root zone. However, the flux was quite small until after about Aug. 1. Thereafter, peak flows were simulated biweekly consistent with the dates of irrigation. The N concentration was rather constant at all times, but was about 2.5 times higher for the AW/PET = 1.1 than the 1.42 application. Conversely, the annual amount of N leached was about 2 times lower for the AW/PET = 1.1 than the 1.42 application because of the lower amount of leachate. These results clearly demonstrate the fallacy of monitoring only the N concentration at the bottom of the root zone as an indicator of N being leached from the crop. Besides being expensive, it can lead to erroneous conclusions.

The water flow pattern on the sandy soil differed from the clay loam soil, particularly in the winter. The lower water holding capacity of the sandy soil allowed the rain to penetrate deeper and create a downward flux at the 100-cm. depth. This explains why the October application was less effective in producing yield than the April application. A large amount of leaching potentially occurs during the non-crop season. The amount of N leaching during the non-crop season is dictated by the soil properties, total amount and distribution pattern of precipitation, and the depth under consideration based on crop rooting patterns. E-G.can be used to simulate the leaching under any combination of these factors.

The sandy soil required weekly irrigation. Therefore, the water fluxes during the latter part of the growing season reflect the irrigation schedule. Similar to the clay loam soil, the N concentrations remained fairly constant and were higher for the lower irrigation. Opposite to the concentration, the amount of leached N was greater for the higher water application.

The cumulative amount of leached N and the amounts of irrigation or precipitation are shown in Fig.9 for the case illustrated in Fig 7. The rainfall pattern represents numerous small rain events during the winter except for two rains near Jan.1 and one on May 21. The 7.2-cm event on May 8 was the pre-plant irrigation. The leaching pattern for both cases is consistent with the time sequence of N concentrations and water fluxes that are illustrated in Fig.7. The rate of N leaching was relatively low for AW/PET = 1.42 until the end of July, after which there was a rapid rate of leaching. This is concurrent with a period of high water flow. The N leaching was higher for the lower water application rate between Jan. 1 and Aug. 1. This was the result of the higher N concentration in the soil water at the bottom of the root zone during that time period. Most of the yearly N leaching for AW/PET = 1.42 occurred during August and September when large water flux events occurred and N concentrations were significantly less than for AW/PET = 1.1.

Even though significantly more water was applied than lost though ET for AW/PET = 1.42 treatment; the water flow at the bottom of the root zone was very low until the end of July. This result was not anticipated but explainable after observation. Note on Fig.9 that the PET, and therefore AW, continually increased until about Aug.1. The AW amount was to recharge the soil based on the potential ET during the period from the previous irrigation. The "excess" water application prior to Aug.1 would have been consumed by the higher ET following irrigation and would not have reached the 100-cm. depth. After Aug.1, the ET decreases with time and the "excess" water would flow beyond the 100-cm. depth and promote leaching as observed.

The inorganic N treatment was all applied on the seeding date of May 15 following the pre-plant irrigation on May 8. The RY and annual leached N results are presented in Fig. 10. Far less N application was required for maximum yield as compared to the organic material and also resulted in less leached N. Higher applications were required on the clay loam soil as compared to the sandy soil to achieve maximum yield that also resulted in greater leaching. Higher applications with greater leaching were found for the higher water application for both soils. Detailed data on the water fluxes and concentrations will not be presented. However, the soil concentrations were lower for the inorganic application than the organic and the concentration was lower for the higher water application than the lower water application.

Unlike the organic treatment where mineral N is continually produced, the inorganic was applied near the surface each year only on the seeding date. Water percolating through the soil would transport the N downward. However, the high N uptake by corn during the first half of the growing season would extract the N from the soil and remove most of it before it reached the bottom of the root zone. The lower and more frequent water applications on the sandy soil would have reduced the depth of water penetration on the sandy soil and made the N more available to the crop. This factor could account for less leached N on the sandy as compared to the clay loam soil.

Discussion

Clearly, many complex interacting factors contribute to the crop yield and the leaching of N from a field. The timing of water and N application, as well as their amounts, greatly affects the results. Proper management of organic N application requires knowledge of the temporal rate of mineralization and not only the amount that will be mineralized in a given time period. The importance of converting conventional decay series mineralization data into rate of mineralization as a function of time is demonstrated by the results. Furthermore, adjustment to account for temperature is also important.

The NHI considers the crop, soil, and irrigation system as critical factors in assessing the relative risk of groundwater degradation by nitrate. The results of this study will be discussed in context of these three factors.

The results reported here for corn will differ in detail from other crops. Corn has an exceedingly high rate of N-uptake over a short period of time and almost none during the latter part of the season when the crop still has a high transpiration rate requiring irrigation (Fig.2). A crop with a very high maximum N-uptake rate, such as corn, is impossible to fertilize with only organic N to meet peak demand without excessive N in the soil before and after crop N uptake. Pang and Letey (2000) compared simulations of fertilizing wheat and corn with organic N and found that wheat had higher yields and lower leached N than corn. Even though both required the same amount of total seasonal N, the uptake rate for wheat was extended over a longer time period with lower peak rates. Crops with continual low N-uptake demand are more conducive to being fertilized by organics. Growing plants during the non-crop season facilitates the capture of mineralized N that is continually produced by the decay process. Feng et al. (2005) reported that growing a grass crop during the winter effectively reduced the leaching of N following a corn crop that had received dairy liquid waste.

The deep root system of corn is a positive feature. The crop can extract N over a considerable depth of soil before it leaves the root zone on its path to groundwater. The rapid N-uptake can be a positive feature for inorganic fertilizers that can be applied at high amounts near the soil surface. The N is rapidly taken up and removed early in the crop season leaving little for leaching later. Nitrogen is transported by water flowing to the root surface to meet transpiration requirements. The N-concentration in the soil solution required to meet crop demands by water flow depends on the ratio of potential N-uptake to potential ET. The high transpiration rate after N-uptake has essentially ceased, allows a very low soil solution concentration of N to exist. Both positive and negative features of corn relative to potential groundwater degradation from nitrate exist. Thus the crop was assigned an intermediate hazard index number of 3. However, more important than the number is the understanding of the dynamic interactions that occur in a corn field.

The soil type significantly affects the potential for groundwater degradation. Under the conditions of the reported simulations, the main effect of the sandy soil was to have greater leached N during the winter. The low water holding capacity allowed the precipitation to move beyond the root zone, whereas the clay loam retained the precipitation within the root zone depth. A major impact of soil type was not entirely manifested by the simulations. The soil dictates the amount of water that infiltrates the soil under surface irrigation systems. Sandy soils have high infiltration rates and more water infiltration is common through rainfall or surface irrigation systems. The simulations imposed the water scheduling so that the two AW/PET values were the same for both soils. The AW/PET = 1.42 is far more likely to occur on sandy soils than more fine textured soils. In every case the higher AW/PET induced lower yields and higher leached N than the lower AW/PET. The higher probability of N leaching is greater for the sandy soil than the clay loam. However, this factor was partially mitigated by altering the irrigation schedule so that smaller and more frequent irrigations were simulated with the sandy soil. This illustrates how the impacts, when understood, can be moderated by adjusting management. The model does not include a provision for denitrification. Therefore, the leached N values represent the worst case scenario for soils that may induce denitrification. Very little denitrification would be expected on the sandy soil. The clay loam soil would be assigned an index number of 3 and the sandy loam soil a number of 5.

The irrigation system is the third factor included in the NHI. Surface irrigation systems provide little control on the amount and uniformity of irrigation. All pressurized systems allow control on the amount of application. Micro-irrigation systems also have the potential for good uniformity. Uniform irrigation was assumed in the simulations. The uniform AW/PET = 1.1 can probably only be achieved with a well designed and managed micro-irrigation system. Without fertigation, as simulated in this study, the index number would be 2. The AW/PET = 1.42 would be typical of surface irrigation that has an index number of 5.

Uniform irrigation, wherein the same amount of infiltrated water occurs at all locations in the field, is essential to accomplish both high yield and low groundwater degradation. The extremes of choices in irrigating a field with non-uniform water application are to over-irrigate or under-irrigate the entire field. Over irrigation causes groundwater degradation and under irrigation causes poor yields. A trade-off between the two is required. Uniform irrigation allows, in principle, both goals to be achieved.

The findings in this study are completely consistent with measurements made on 86 farmer fields (Letey et al., 1977; Letey et al., 1979) providing confidence to there validity. First, the amount of N leached is more related to the amount of water percolating beyond the root zone than on the amount of N applied. Second, there was no correlation between the amount of N leached and the concentration of N in the water. The scientific evidence is overwhelming that irrigation management dictates nitrogen management options for achieving high yield with low groundwater degradation.

None of the State Water Resources Control Board recommendations to the Legislature identifies water management as a factor. The emphasis of the recommendations was on developing and implementing an N mass balance tracking and reporting system for N fertilizing materials.

The Law of Conservation of Mass specifies that, in one sense of the term, there is always mass balance. However, in a transient dynamic system in which there are several pools for N, the term “mass balance” lacks clear meaning. Continual additions and deletions from each pool exist. If the identical management is continually followed, such as the case for the simulations, a steady-state condition develops when the cycle repeats itself on a temporal basis. Implicit in some usage of “mass balance” for farm fields is to have a balance between the N added and the N removed by the crop. This narrow definition ignores the several other pools and reactions of N in the soil. A reduction of leached N equal to the reduction of N application is a frequent assumption by virtue of “mass balance”. This assumption is true if the higher N application is greater than necessary to get maximum production, but will not be achieved if the reduced N application induces a reduction in crop yield. Indeed, reductions in N application in some cases can cause only very low reductions in the amount of N leached.

Tracking requires measurement. Because leaching of N is the culprit, measuring the rate of leaching is vital. This requires the measurement of N concentration in the soil solution and rate of water flow at the bottom of the root zone. An accurate measurement of water flow is impossible. Particularly when one knows that these rates can fluctuation greatly with time as illustrated in Figs.7 and 8. The amount of leaching was primarily correlated with the water flow rate and not concentration. Indeed, higher leaching of N was commonly associated with a lower soil solution concentration.

Measuring nitrate concentrations in groundwater bodies provides valuable information. Concentrations measured today represent the consequence of actions decades ago. Whether the very high numbers are a result of excessive N application or excessive irrigation is not important. What is important is to improve present management to reduce future nitrate loads to the groundwater. A change in management that decreases the load will not be manifest in groundwater concentrations for decades. Having low water percolation beyond the root zone is the most effective approach to reducing the N load to groundwater. Ironically, the management practice of producing lower water flow at the bottom of the root zone requires the longer time to be manifest in a change in groundwater quality. Therefore, groundwater monitoring is not a reliable indicator of the effectiveness of present management practices. Proper irrigation management is essential before effective N management practices can be adopted. A tracking and reporting system will not achieve the goal, and might lead to costly ineffective practices

Developing Best Management Practices (BMP) rather than tracking and reporting is the effective rational approach to reduce N loads. The NHI concept was proposed by the Nutrient Technical Advisory Committee (TAC) appointed in 1994 by the State Water Resources Control Board as a resource for developing BMPs. Importantly, TAC proposed that fields with a low NHI number, which pose low threat to groundwater degradation, would be exempt from a formal BMP so that resources could be focused on cases where they would more effectively reduce degradation. Additionally, the NHI identifies whether the major threat is from the soil, crop, irrigation system, or a combination of them for each field. Therefore a BMP could be formulated that is tailor made for the specific field conditions. Although the Board accepted the report, it was never implemented because the index numbers for soils and crops were not available. These index numbers are now available for many soils and crops and the Board action in 1994 should be reviewed.

References

Broadbent FE, Carlton AB. 1979. Field trial with isotopes- Plant and soil data for Davis and Kearney sites. Final Report to the National Science Foundation, University of California pp 433-456.

Cusick PR, Kelling KA, Powell JM, Munoz GR. 2006. Estimates of residual dairy manure nitrogen availability using various techniques. J. Environ. Qual. 35:2170-2177.

Feng GL, Meiri A, Letey J. 2003. Evaluation of a model for irrigation management under saline conditions: I. Effects on plant growth. Soil Sci Soc Am J 67:71-76.

Feng GJ, Letey J, Chang AC, Campbell Mathews M. 2005. Simulating dairy liquid waste management options as a nitrogen source for crops. Agric Ecosyt & Environ 110:219-222.

Letey J, Blair JW, Devitt D, Lund LJ, Nash P. 1977 Nitrate-nitrogen in effluent from agricultural tile drains in California. Hilgardia 9:289-319.

Letey J, Pratt PF, Rible JM. 1979. Combining water and fertilizer management for high productivity, low water degradation. Cal Agr 33(2):8-9.

Meisinger JJ, Calderon FJ, Jenkinson DS. 2008. Soil nitrogen budgets. In J.S. Schepers and W.R. Raun (ed.) Nitrogen in Agricultural Systems. Agron. Monogr. 49. American Society of Agronomy, Madison, WI.

Pang XP, Letey J. 1998. Development and evaluation of ENVIRO-GRO, an integrated water, salinity, and nitrogen model. Soli Sci Soc Am J. 62:1418-1427.

Pang XP, Letey J. 1999. Pesticide leaching sensitivity to irrigation, salinity and N application: Model simulations. Soil Sci 164:922-929.

Pang XP, Letey J. 2000. Organic farming: Challenge to timing nitrogen availability to crop nitrogen requirements. Soil Sci Soc Am J. 64:247-253.

Pratt PF, Broadbent FE, Martin JP. 1973. Using organic wastes as nitrogen fertilizers. Cal Agr 27:10-13.

State Water Resources Control Board. Recommendations Addressing Nitrates in Groundwater. Report to the Legislature. 20 Feb 2013, 73 pp.

Viers, JH and 17 others. 2012. Nitrogen Sources and Loading to Groundwater, Technical Report 2, Assessing Nitrate in California's Drinking Water. Center for Watershed Sciences, University of California, Davis. 326 pp.

Vigil MF, Kissel DE. 1995 Rate of nitrogen mineralized from incorporating crop residues as influenced by temperature. Soil Sci Soc Am J. 59:1636-1644.

Figure 1. The daily average CIMIS soil temperature at the 15-cm depth from 2000 through 2011 at Madera, CA site #145.

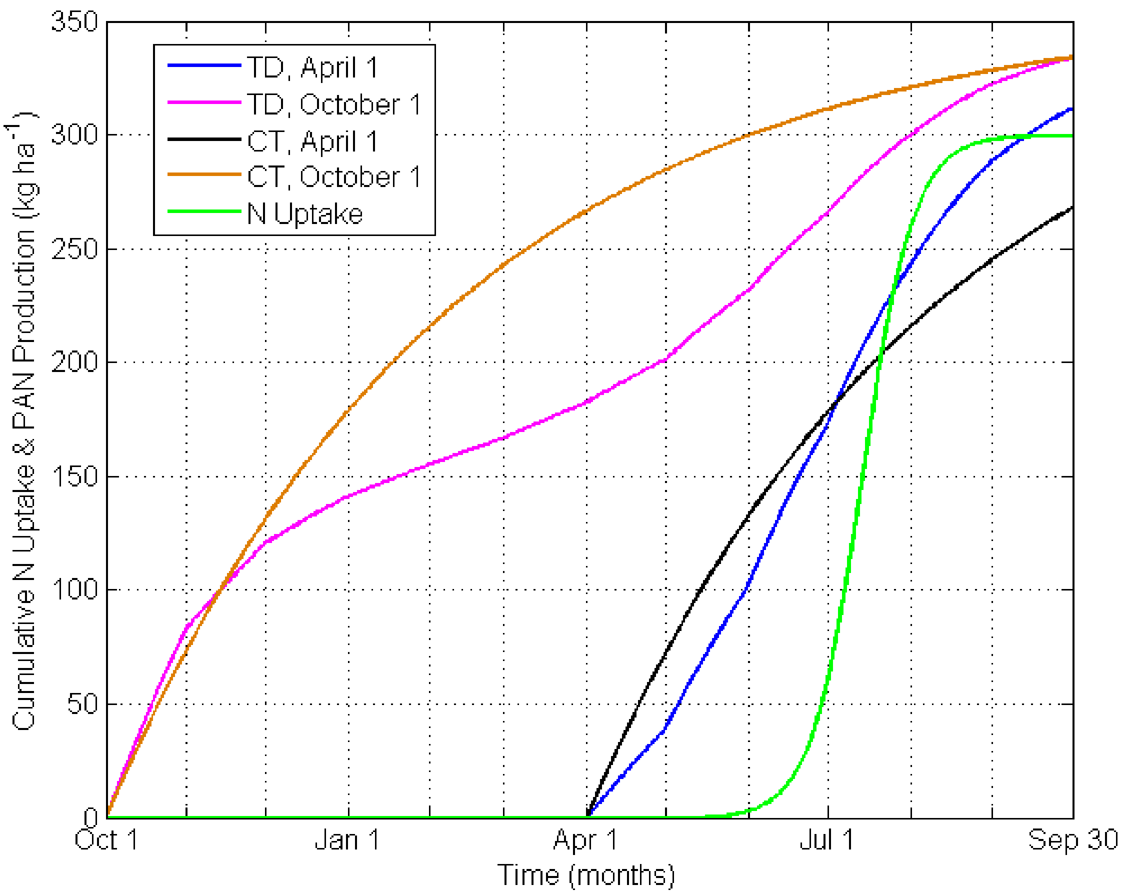

Figure 2. The cumulative crop N uptake and the cumulative amount of plant available nitrogen (PAN) production for organic material applied on April 1 or October 1. The temperature is assumed constant (CT) or mineralization is adjusted for temperature dependence (TD) at different times of the year.

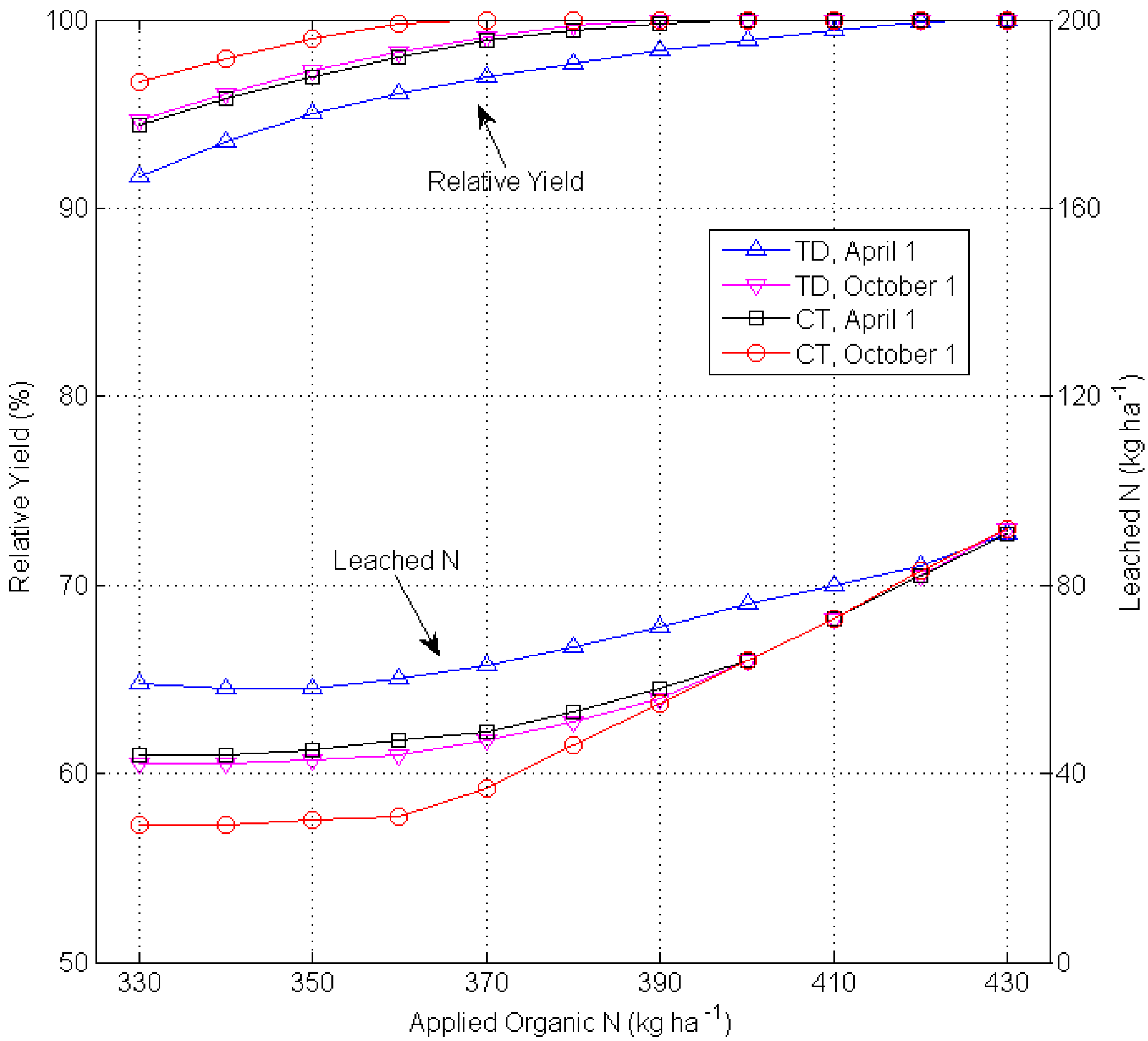

Figure 3. The relative crop yield and amount of leached N for different amounts of organic N applied on April 1 or October 1. Results for the clay loam soil and AW/PET = 1.1. The temperature is assumed constant (CT) or adjusted for temperature dependence (TD) for different times of the year.

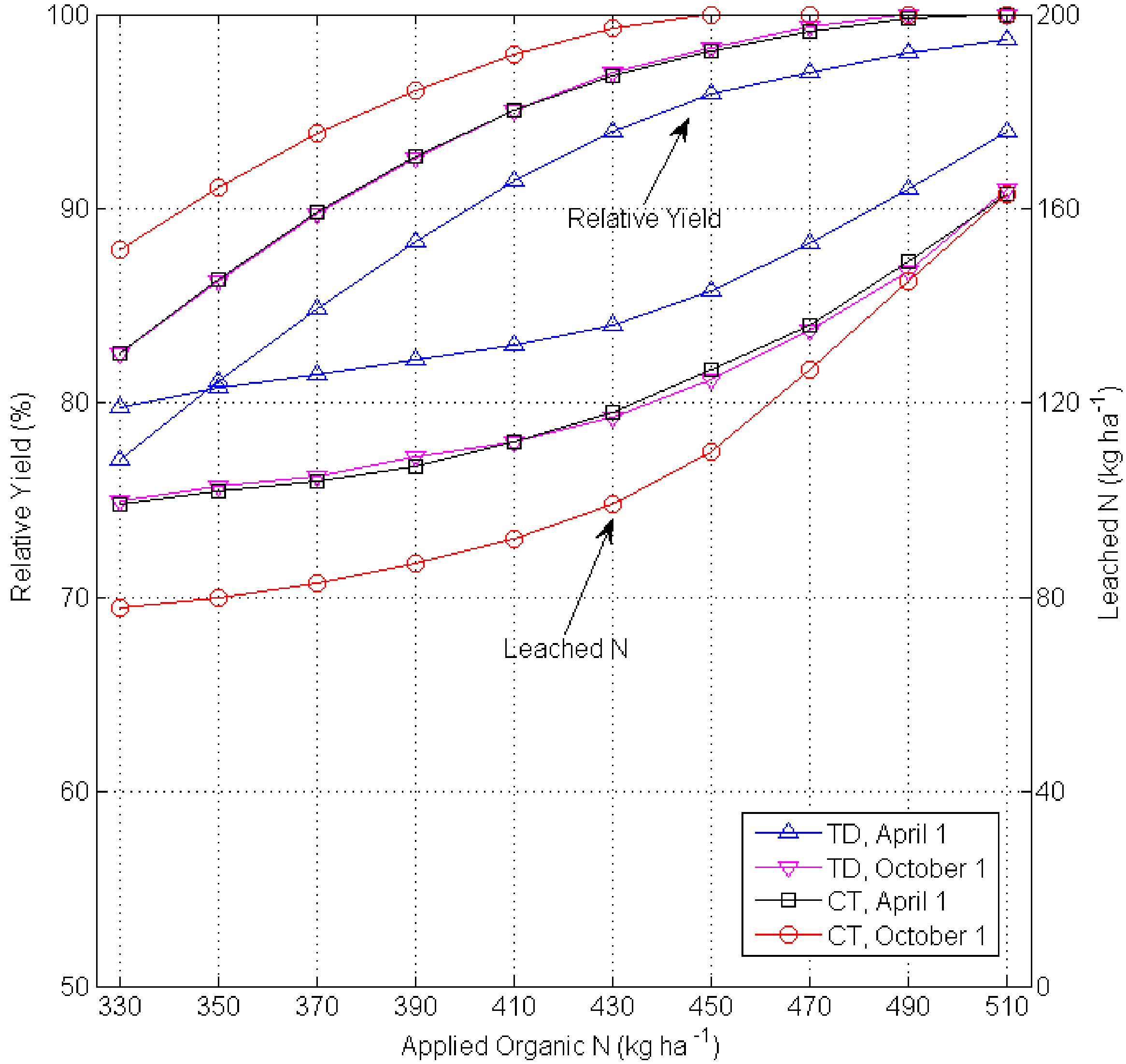

Figure 4. The relative crop yield and amount of leached N for different amounts of organic N applied on April 1 or October 1. Results for the clay loam soil and AW/PET = 1.42. The temperature is assumed constant (CT) or adjusted for temperature dependence (TD) for different times of the year.

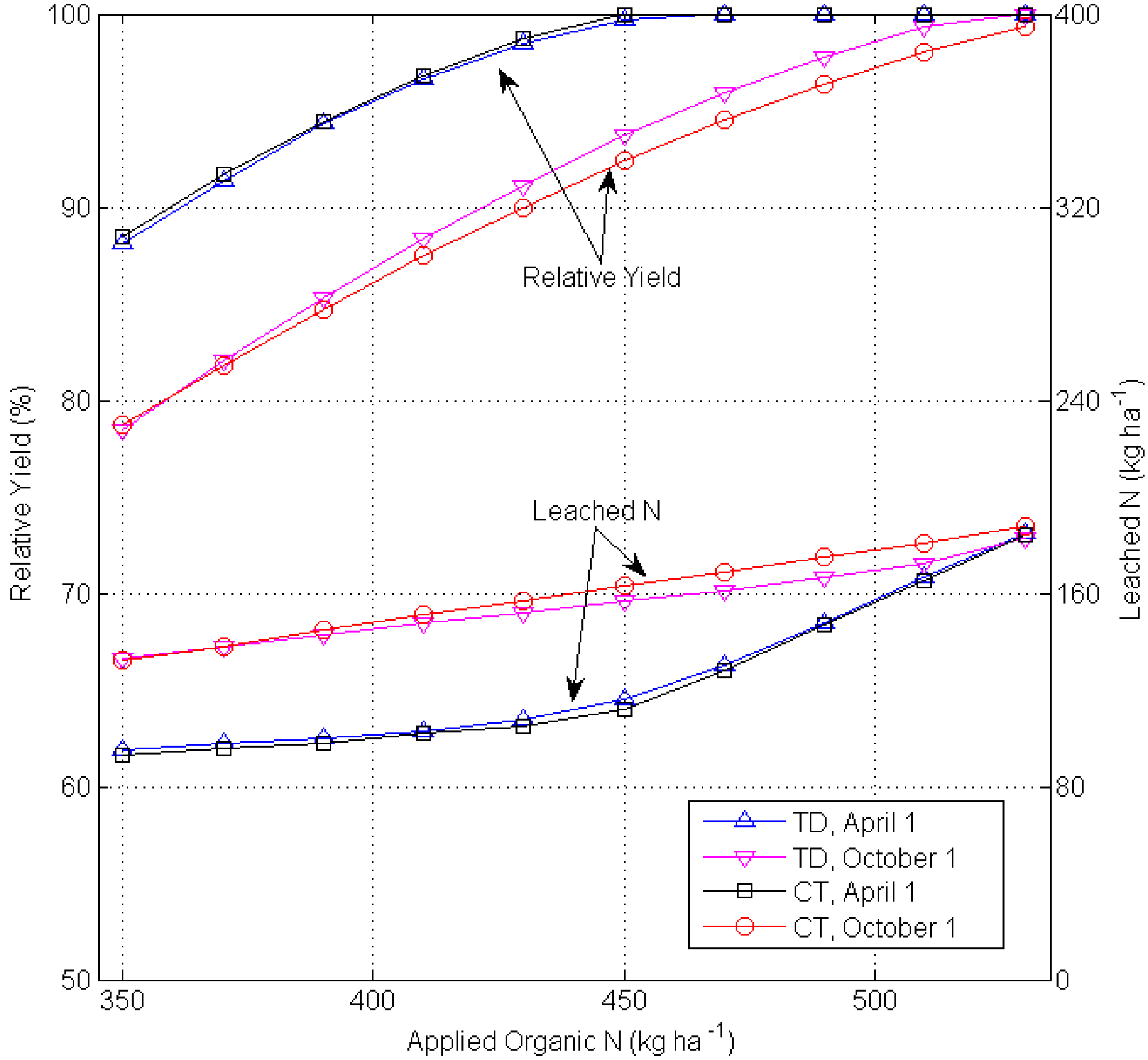

Figure 5. The relative crop yield and amount of leached N for different amounts of organic N applied on April 1 or October 1. Results for the sandy loam soil and AW/PET = 1.1. The temperature is assumed constant (CT) or adjusted for temperature dependence (TD) for different times of the year.

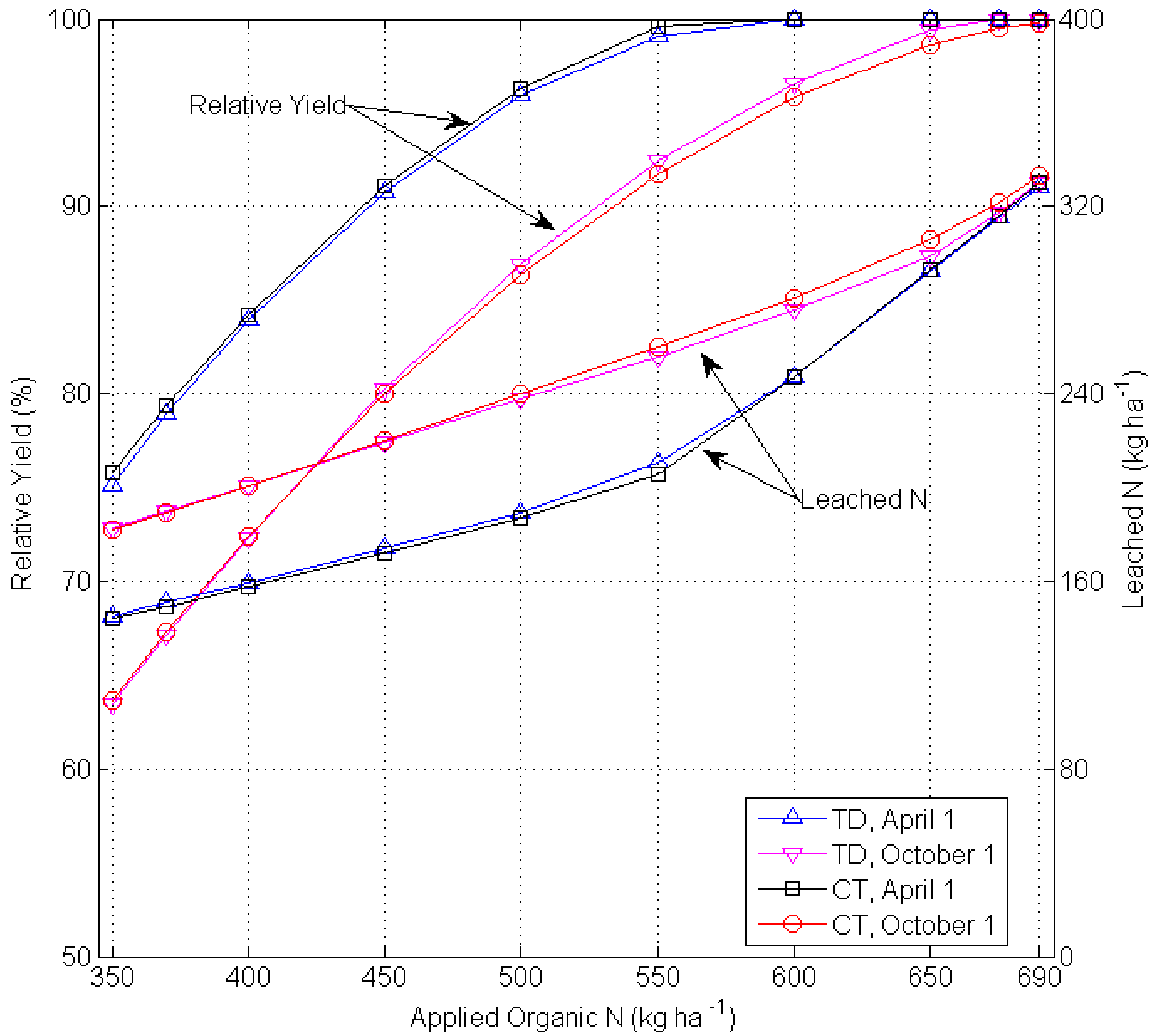

Figure 6. The relative crop yield and amount of leached N for different amounts of organic N applied on April 1 or October 1. Results for the sandy loam soil and AW/PET = 1.42. The temperature is assumed constant (CT) or adjusted for temperature dependence (TD) for different times of the year.

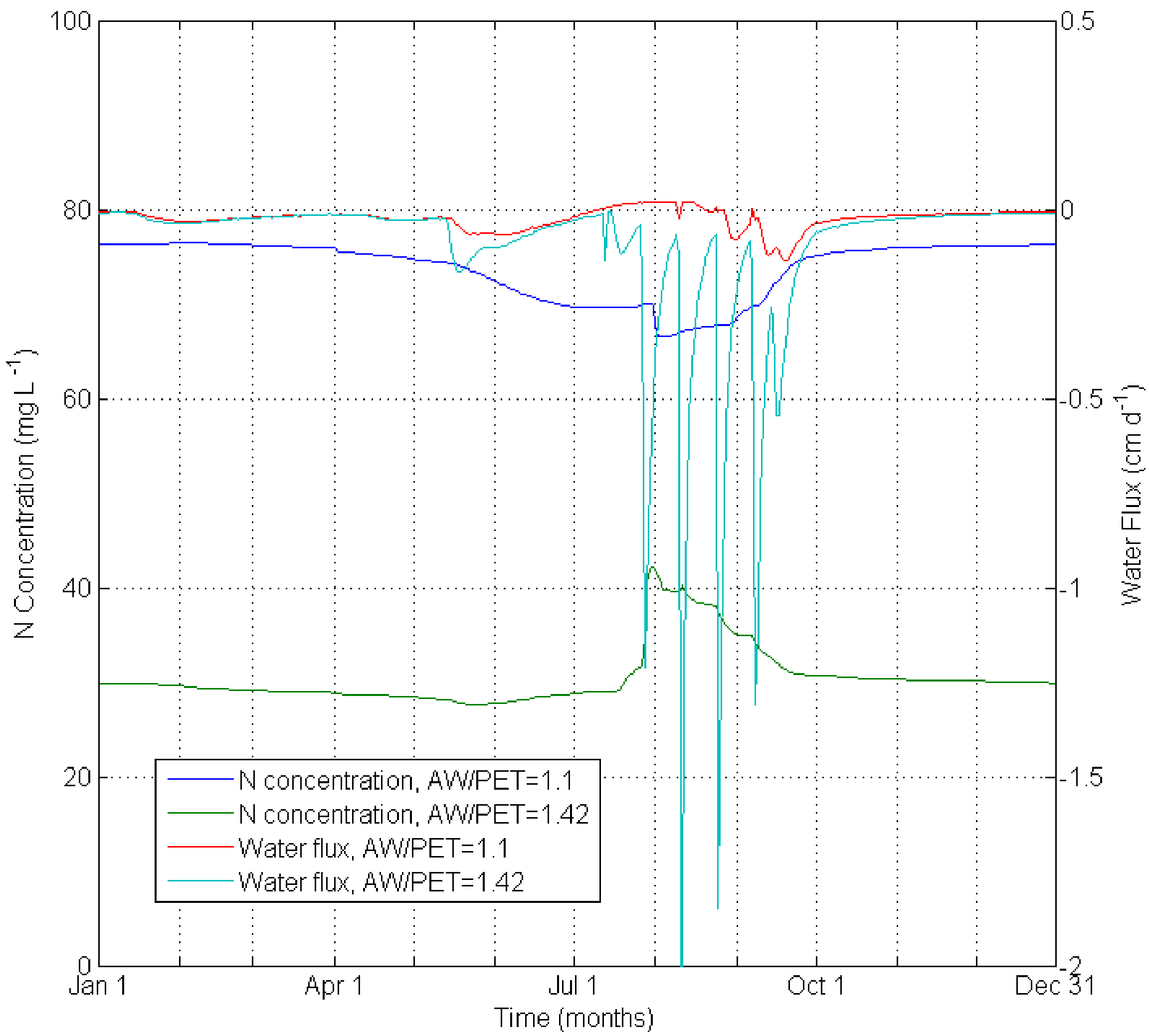

Figure 7. The N concentration and water flux in the clay loam soil at the bottom of the root zone at different times of year for the two water treatments. The results are for application of 370 kg/ha of organic N on April 1with temperature dependence. A negative water flux represents downward water flow.

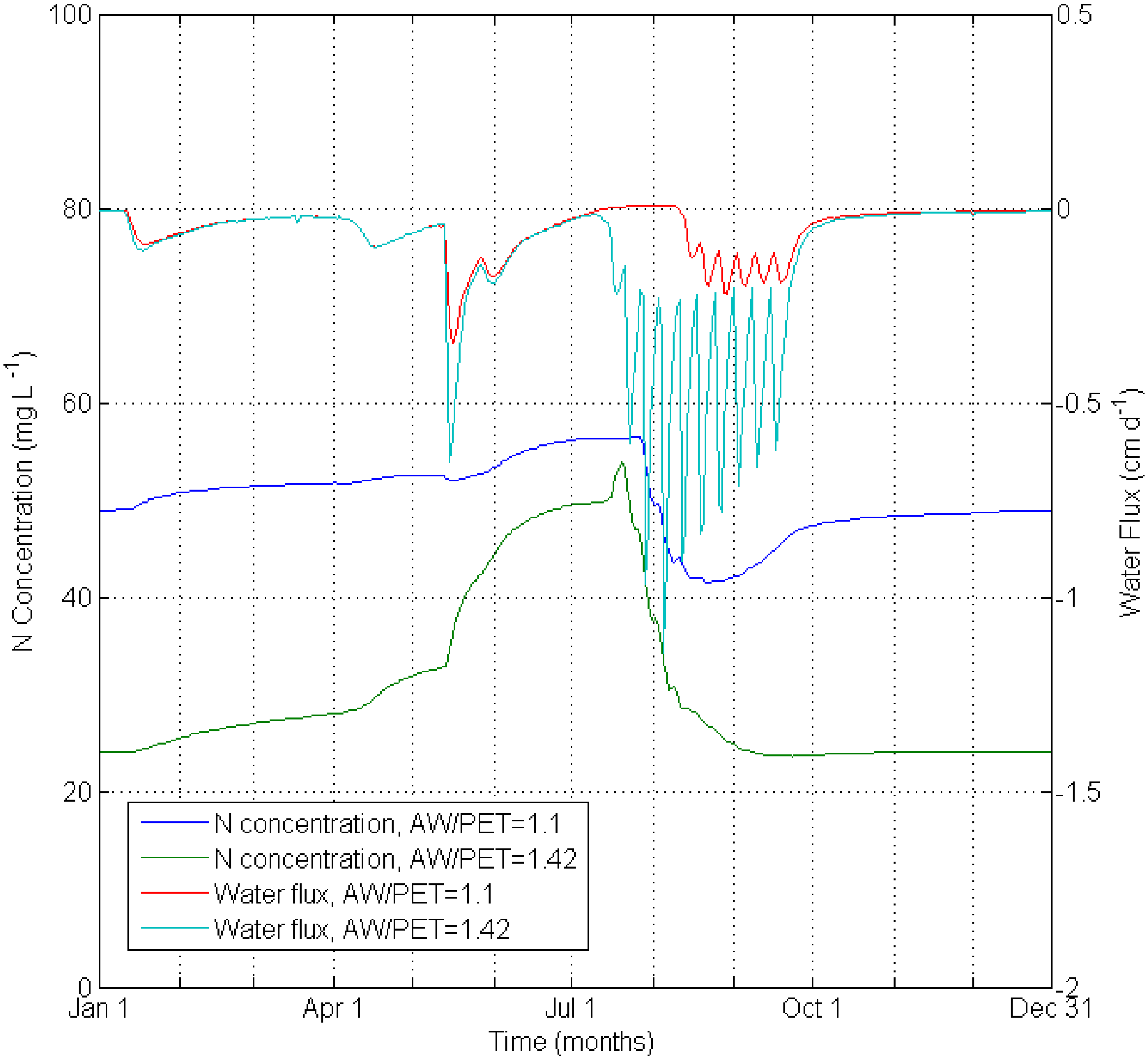

Figure 8. The N concentration and water flux in the sandy loam soil at the bottom of the root zone at different times of year for the two water treatments. The results are for application of 370 kg/ha of organic N on April 1 with temperature dependence. A negative water flux represents downward water flow.

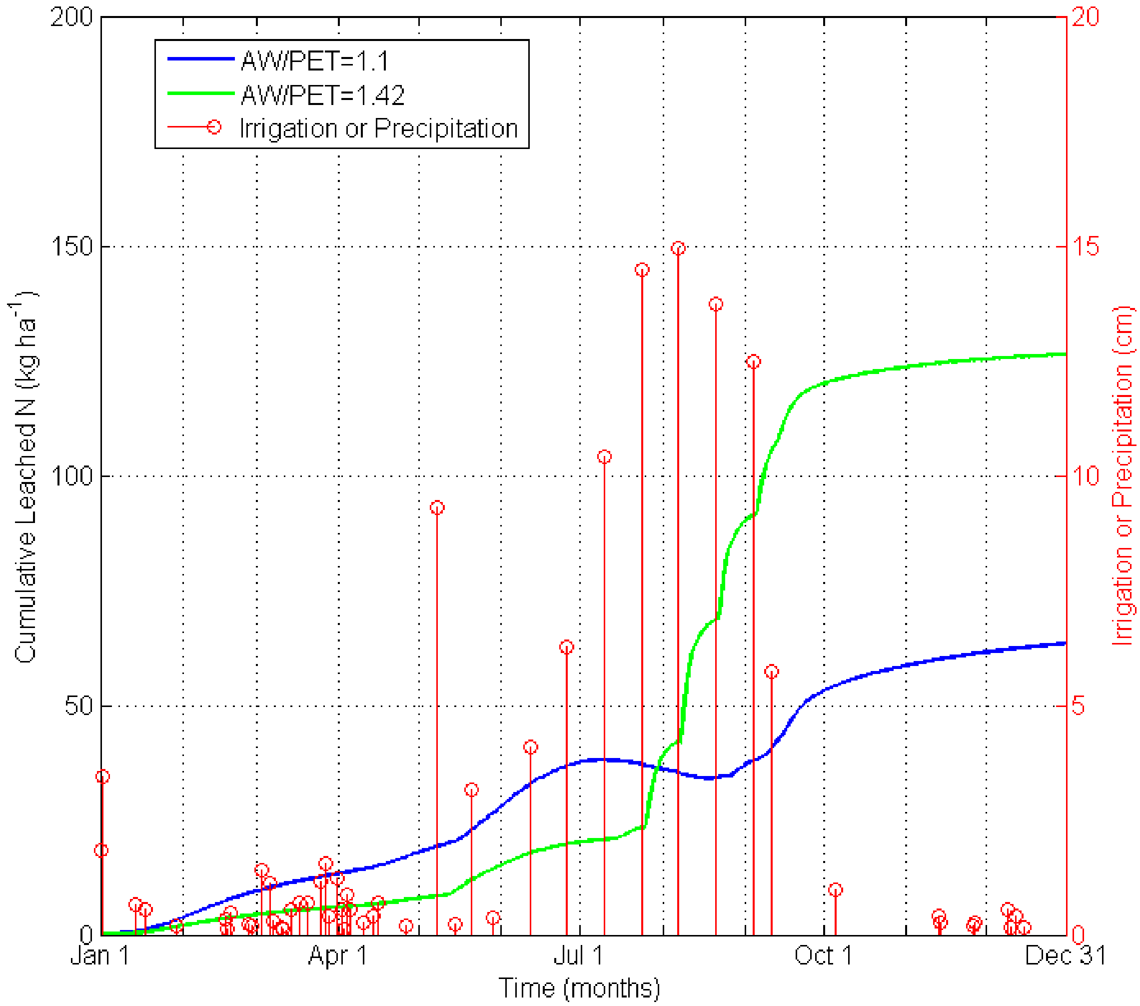

Figure 9. The cumulative leached N and precipitation or irrigation amounts at different times of the year for the two water treatments. The results are for application of 370 kg/ha organic N on April 1 with temperate dependence.

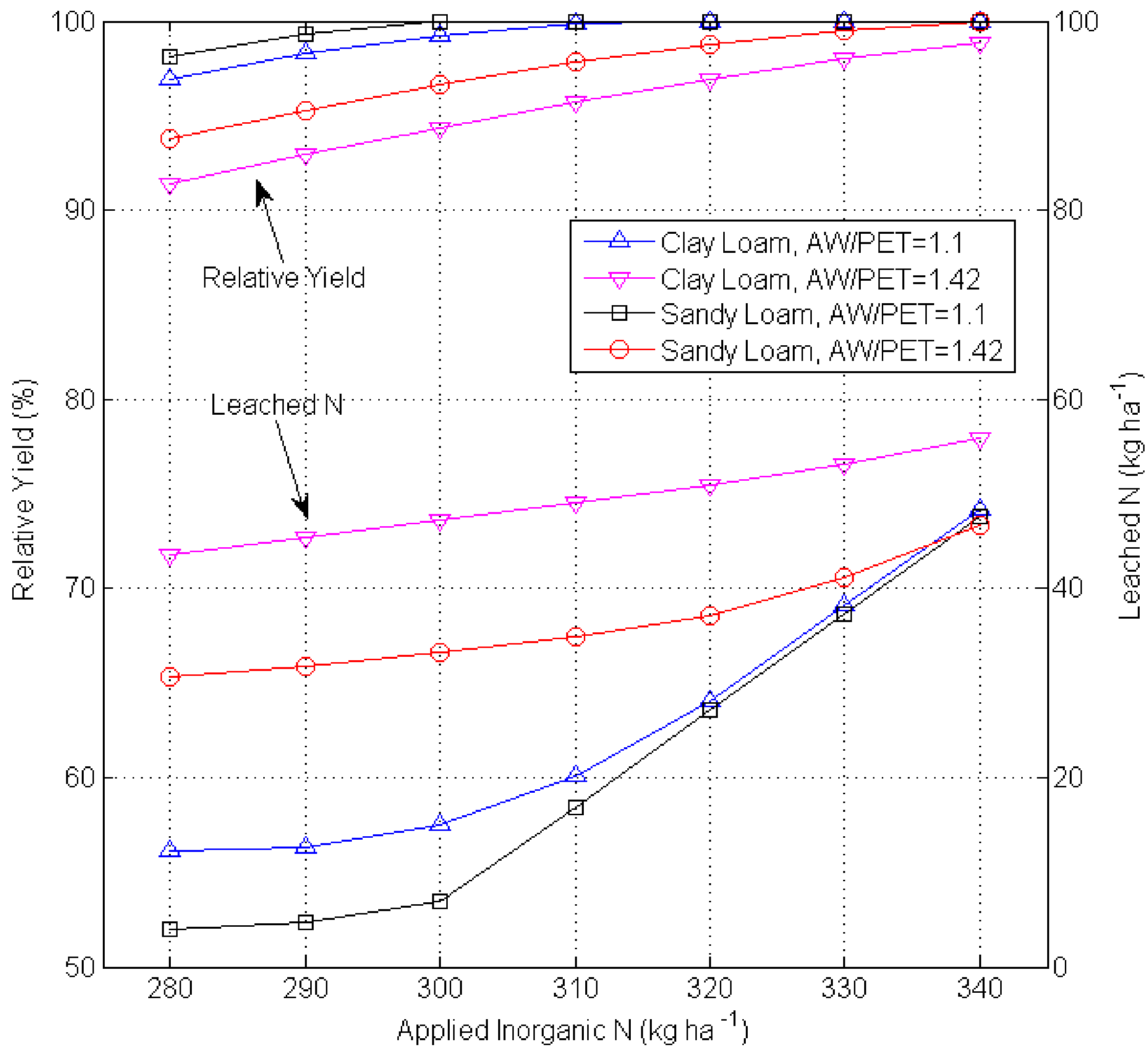

Figure 10. The relative crop yield and amount of leached N for different amounts of inorganic N application for the two soils and two water treatments.