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Simulating dairy liquid waste management options as a nitrogen source for crops

G.L. Feng [a], J. Letey [a,*], A.C. Chang [a], M. Campbell Mathews [b]

[a] Department of Environmental Sciences, University of California, Riverside, CA 92521, USA
[b] University of California Cooperative Extension, 3800 Cornucopia Way, Ste A, Modesto, CA 95358, USA

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Abstract

Large scale dairy operations are common. In many cases the manure is deposited on a paved surface and then removed with a flushing system, after which the solids are separated, the liquid stored in ponds, and eventually the liquid applied on adjacent crop land. Management of liquid manure to maximize the fertilizer value and minimize water quality degradation requires knowledge of the interactive effects of mineralization of organic N (ON) to NH_4^+, crop uptake of mineral N, and leaching of NO_3^- on a temporal basis. The purpose of the research was to use the ENVIRO-GRO model to simulate how the amount of applied N, timing of N application, ON mineralization rates, chemical form of N applied, and irrigation uniformity affected (1) yields of corn (Zea mays) in summer and a forage grass in winter in a Mediterranean climate and (2) the amount of NO_3^- leached below the root zone. This management practice is typical for dairies in the San Joaquin Valley of California. The simulations were conducted for a 10-year period. Steady state conditions, whereby an equivalent amount of N applied in the organic form will be mineralized in a given year, are achieved more rapidly for materials with high mineralization rates. Both timing and total quantity of N application are important in affecting crop yield and potential N leaching. Major conclusions from the simulations are as follows. Frequent low applications are preferred to less frequent higher applications. Increasing the amount of N application increased both the crop yield and the amount of NO_3^- leached. Increasing irrigation uniformity increased crop yields but had variable effects on the amount of NO_3^- leached. A winter forage crop following a summer corn crop effectively reduced the leaching of residual soil N following the corn crop.

Keywords: Nitrate; Manure; Groundwater; Organic nitrogen; Mineralization; Leaching

1. Introduction

Livestock and dairy production around the world is progressively moving toward congregating a large number of animals into small land areas. For example, dairies in California have a total herd size of 1.5 million cows. In 1999 the average size of California's 2200 dairy farms was over 650 milk cows, not including dry stocks, heifers, and calves (CDFA, 2000).

The feed rations for animals in the confined animal operations are formulated to maximize production. As

* Corresponding author. Tel.: +1 951 827 4327; fax: +1 951 827 5295.
E-mail address: john.letey@ucr.edu (J. Letey).

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a result, the large amount of nitrogen-rich wastes produced by the animals must be properly managed to avoid environmental degradation.

In the San Joaquin Valley of California, manure deposited on paved surfaces in dairies is removed with a flushing system. After separating out solids, the liquid manure is typically stored in ponds (lagoons) and eventually applied to adjacent cropland. Liquid manure applied to crop land serves as a fertilizer nutrient source for crops and may become a potential source of nitrate (NO_3^-) groundwater degradation if the land applications are not properly managed.

Forage crops are capable of removing large quantities of N from the soil. Results of field investigations on the application of dairy effluent to year-round forage crops have been reported by Woodard et al. (2002), Hubbard et al. (1987), Vellidis et al. (1993), and Newton et al. (1995). The general findings were that the amount of N removal by the crop and the NO_3^--N in the soil water below the root zone tended to increase with increasing loading rates of N.

Nitrogen is present in the liquid manure in organic N (ON) and NH_4^+ forms. The latter is immediately available for crops but the ON must be mineralized before it is available for plant uptake. ON and NH_4^+ are not very mobile in soil, however, NH_4^+ can be nitrified to NO_3^- in days to weeks which is freely transported through the soil by flowing water. Proper management of liquid manure to maximize the fertilizer value and minimize water quality degradation requires knowledge of the complex dynamic interactions described above.

Dairies may employ different strategies in applying the liquid manures on cropland that entail different N inputs and timing of the applications. When different approaches of manure applications are adopted, it is difficult to project the outcomes in terms of crop yields and nitrate leaching due to the dynamic and interactive processes involving the reactions of applied N, irrigation, and plant growth. The temporal accounting of these coupled N reactions can be accomplished by utilizing a computer model such as the ENVIRO-GRO model (Pang and Letey, 1998). The model allows the simulation of various dairy liquid waste management options on water and nitrate distribution in the soil profile as a function of time, the amount of deep percolation, the amount of leached nitrate, and crop yield relative to that of a non-stressed crop.

The main features of the model are as follows: The one-dimensional Richards equation, which describes transient water flow through soil, is combined with a plant water uptake function. The water uptake function is based on the potential evapotranspiration (T_p) and the matric and osmotic head potentials of the soil water. The convection-dispersion equation is used to describe chemical flow. The model allows additional water and/or N uptake from zones in the root system where they are adequate to compensate for deficiency in other sections of the root zone. Since potential water and N uptakes are related to plant growth, a feedback mechanism is programmed so that reduced growth results in reduced potential water and N uptakes.

The goal of the research reported here was to use the ENVIRO-GRO model to simulate how the amount of applied N, timing of N applications, ON mineralization rates, chemical form of N applied, and irrigation uniformity affected (1) yields of corn (Zea mays) in summer and a forage grass in the winter in a Mediterranean climate and (2) the amount of NO_3^- leached below the root zone. The results can be used to guide the selection of management options to achieve desired goals.

2. Simulated farm management system

The cropping system typically used by dairy farmers in the San Joaquin Valley of California consists of planting silage corn in the spring and harvesting it in the fall, followed by a forage crop that is planted in November and harvested in April. In the simulations, we matched the irrigation and N applications with the requirements for crop growth. Dairy lagoon water was used as the only N source for the crops. Simulated irrigation was applied every 15 days with a mixture of lagoon water and regular waters. The irrigation was based on the T_p of the preceding 15 days and the amount of lagoon water (i.e. N application) was based on the total potential N uptake (N_p) for a nonstressed crop during the succeeding 15 days.

The fractions of ON and NH_4^+ in lagoon water can be variable, but we chose equal concentrations of each, which is about the average case in the San Joaquin Valley. Simulations were also conducted using only ON to more clearly identify the effect of mineralization on the results. The applied N was assumed to be uniformly retained in the top 20 cm of soil at the time of application and that NH_4^+ would have been nitrified to NO_3^- prior to the next irrigation when it could be transported by water.

3. Factors considered in the model

3.1. Organic nitrogen mineralization

Mineralization of N can be described using the first-order decay equation:

$$N_{min} = A_0[1 - \exp(-\lambda t)] \quad (1)$$

where N_{min} is the amount of mineralized N, A_0 is the total amount of N in the organic material, t is time, and λ is the N mineralization coefficient.

Nitrogen mineralization is dependent on temperature (Frederick, 1950; Campbell et al., 1971). Stanford et al. (1973) estimated the rate constant at different temperatures. The relationship between mineralization rate and temperature is commonly described as a Q_{10} for a two-fold increase in the rate constant occurs for each 10 °C rise in temperature.

The large concentrated animal feeding operation wastes are applied on land year round and a given field may receive multiple applications in a year. Tracking of mineralized N over a long-term becomes problematic when ON is applied multiple times and the temperature changes seasonally. We developed a computation algorithm to account for mineralized N over time resulting from multiple ON applications and temperature that changes seasonally.

The first-order decay described by Eq. (1) was selected for ON mineralization. A standardized reference time t_0 must be selected as the reference point for counting. For convenience we chose 1 January as t_0. Inputs to the model, which are supplied by the user, are the times and amounts of ON applications and the values of λ for various time periods of the year based on seasonal temperature. The time of applications are specified relative to t_0. In multi-year simulations, the time counting in subsequent years are specified relative to the initial reference time. In other words, 1 January of the second year would be specified as day 366.

The algorithm keeps track of the N mineralization of each ON application and its seasonal changes of λ according to the input data. For each ON application the A_0 equals the total amount of ON of this application and t in the program is set as 0 for the N mineralization computation. However, the time for tracking application in mineralized N corresponds to the standard reference time.

When λ changes in the course of time, t in the program is reset to 0 and A_0 is reset to be the total amount of remaining ON from the original application. The computation continues until λ is changed again. This way each application of ON has its own mineralization series which is tracked with respect to time. The total mineralized N at a given time is the sum of mineralized N from each prior application.

Information on mineralization rate coefficients of ON in lagoon water is generally lacking. Van Kessel and Reeves (2002) determined the mineralization rate of 107 dairy manures collected in five states in the Eastern United States. The manures were mixed with soil and incubated at 25° C for 56 days to determine mineralization rate. The manures had highly variable N mineralization characteristics including 13 samples that had net immobilization. The mean mineralization from all samples had a 280-day half-life. Nine samples had a 90-day or less half-life. These data clearly established the fact that mineralization rates are highly variable and very difficult to establish for a specific situation. We chose the 90- and 280-day half-lifes for our simulations to determine the effects of mineralization rates on the results. The value of λ in Eq. (1) equals 0.0025 day for the 280-day half-life and is equal to 0.0077 day for the 90-day half-life.

Nitrogen mineralization rate varies with temperature. The λ value stated above was used for the months of May to October which are the warmest months. The value of λ for March, April and November, which have the intermediate temperatures, was set at half of the summer mineralization rate; and λ for December, January, and February, which are the coldest months, was set at one-fourth of the summer mineralization rate. More detailed refinements are probably not necessary based on the overall uncertainty of mineralization rates.

3.2. Plant nitrogen uptake

The potential N uptake rate (N_p) as a function of time is required input data. The total N uptake for a well-fertilized corn crop was measured as a function of time

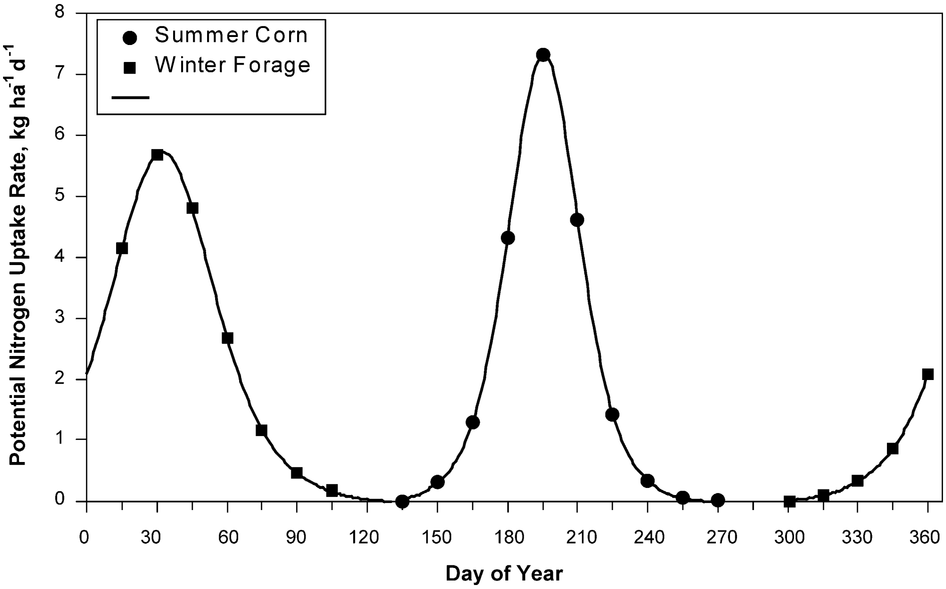

Fig. 1. The potential N uptake rate as a function of time for corn and forage crops.

in the San Joaquin Valley for 3 years. The total uptake varied slightly between years, so the data were standardized by setting the maximum uptake to 1 for each year. The standardized N uptake was plotted as a function of time. The sigmoid relationship between standardized N uptake (N_S) and time was found to fit the equation:

$$N_S = \frac{a+b}{1+\exp(-(t-c)/d)} \quad (2)$$

where the coefficients were $a = 0.018$, $b = 0.99$, $c = 1273$, and $d = 232$, and the r^2 of the regression equation between computed and measured N_S was equal to 0.99. The derivative of that curve was used to compute the standardized potential N uptake rate as a function of time. These values were multiplied by 300 to calculate the actual potential N uptake rate as a function of time when the total potential N uptake was 300 kg ha^{-1}.

The cumulative N uptake for several forage varieties were measured as a function time in the San Joaquin Valley. The winter forage N uptake varied among the four varieties evaluated. We selected the Triticale (T2700) for our simulations. The functional relationship between N_S versus time for this forage was identical to Eq. (2). The data fit this relationship with r^2 of 0.99 when $a = 0.015$, $b = 0.97$, $c = 2038$, and $d = 348$. The maximum N uptake for this forage was 300 kg ha^{-1}. The potential N uptake rate is depicted as a function of time for the corn and forage crops in Fig. 1.

The model computes the nitrogen uptake relative to that of a nonstressed crop (RN_{up}), thus a relationship between relative yield (RY) and RN_{up} is required to convert the results into yield. Pang and Letey (1998) found that the relationship between N uptake and yield reported by Sexton (1993) for corn grown in Minnesota was almost identical to the results measured in California by Broadbent and Carlton (1979). The relationship we used was RY equals $1.7RN_{up} - 0.70RN_{up}^2$. The data for the forage used in our simulations was RY equals $2.03\ RN_{up} - 1.03RN_{up}^2$ based on the field data reported above.

3.3. Limiting nitrogen concentration

A relationship between the concentration of NO_3^- in soil solution (C_N) and a crop N stress factor (γ) must be established. The following rationale was used to establish γ values. On a field basis, transpiration rate has units of m^3 m^{-2} day^{-1} and N uptake rate has units of kg m^{-2} day^{-1}. Nitrogen uptake rate divided by transpiration rate has units of kg m^{-3}, which are units for concentration. When $C_N \geq N_p/T_p$, γ was assigned a value of 1.0 (no stress). The concentration of N in the water carried to the root by the transpiration stream was adequate to meet potential N demand ($C_N T_p = N_p$). When $C_N \leq N_p/T_p$ (or $C_N T_p \leq N_p$), γ was assigned the value of $C_N/(N_p/T_p)$. The critical value of C_N (C_N^*) below which N uptake will be limiting is defined as N_p/T_p.

The agreement between simulated and measured experimental corn N uptake during the summer reported by Pang and Letey (1998) provides evidence that this relationship is appropriate for corn. However, during the winter, T_p can be very low compared to N_p which results in a very high N_p/T_p ratio and thus an excessively high calculated C_N^*. Under these conditions a value of C_N^* must be selected based on experimental information. The value of 5 mg L^{-1} was selected based on the measured NO_3^- concentrations in the soil water below the root zone reported by Woodard et al. (2002) from studies applying dairy effluent to forage systems in Florida.

4. Irrigation uniformity

The simulated results are for the condition that the irrigation and nitrogen applications were uniform across the field; however, this condition is rare in an agricultural operation. The approach proposed by Letey et al. (1984) was used to determine the impact of non-uniform irrigation on the results. Because nitrogen was applied with the water in our case, zones receiving more water also received more nitrogen.

For any point "*a*" (finite size but small enough to be considered uniform), infiltrated water (IW) can be related to the average water application on a field basis (AW) by:

$$\mathrm{IW}(a) = \beta(a)\mathrm{AW} \tag{3}$$

where $\beta(a)$ is a parameter whose distribution over the field must be determined. For computational convenience, the distribution function of β can be approximated by a discrete distribution in which β takes on only a finite number of distinct values which have known probabilities. Two arbitrary IW distributions in addition to the uniform case were chosen for analysis. For clarity in reporting the results the Christensen's uniformity coefficient (CUC), commonly used by irrigation engineers to express the degree of uniformity, was calculated for each distribution. CUC equals $100 \times [1 - (\Sigma x)/Mn]$, where x is the absolute value of the deviation from the mean, M, of the individual observations and n equals the number of observations. Two distributions which were symmetrical around the mean with CUC equal to 73 and 86 were used in the analysis. The simulation was conducted for a given amount of water and N application to each discrete fraction of the field and then the results were integrated for the entire field.

5. Simulated variables

Field-average water application equal to $1.15T_p$ for the 15-day period since the last irrigation was used in all simulations. During the period between crops, it was assumed that there was no evaporation from the field. The potential water loss between the time of the last irrigation and the harvest of the crop was applied as an irrigation at the beginning of the next crop season.

The several variables combinations which were simulated are summarized in Table 1 for uniform irrigation and Table 2 for nonuniform irrigation. The amounts of applied N were 1.0, 1.2, and 1.4 times the N uptake for a non-stressed crop. When the N was applied with each irrigation, the amount of N applied at each irrigation was related to the potential N uptake for the succeeding period of time until the next irrigation. In some cases the N was applied with one-third at time of planting and then one-third each at 30 and 75 days after planting. The N applied in all of the above stated simulations were equally divided between ON and NH_4^+.

Other simulations were conducted when the applied N was entirely ON. These simulations had the total N being applied at the time of planting, and also having the N equally applied at 0, 30, and 75 days after planting. All simulations were conducted with the summer time mineralization rate one-half lifes of 90 and 280 days.

The effects of irrigation uniformity were investigated by doing simulations with irrigation uniformity CUC values of 73, 86, and 100. The N sources were equally divided between ON and NH_4^+ and applications were with each irrigation and also at three times during the cropping season.

Table 1
Summary of the combinations of variables which were simulated under uniform irrigation

N amount	N composition	N application timing[b]	Mineralization half-life days
$1.0N_p$[a]	NH_4^+ and ON	Each irrig.	90 and 280
$1.2N_p$	NH_4^+ and ON	Each irrig.	90 and 280
$1.4N_p$	NH_4^+ and ON	Each irrig.	90 and 280
$1.0N_p$	ON	0, 30 and 75	90 and 280
$1.2N_p$	ON	0, 30 and 75	90 and 280
$1.4N_p$	ON	0, 30 and 75	90 and 280
$1.0N_p$	ON	0	90 and 280
$1.2N_p$	ON	0	90 and 280
$1.4N_p$	ON	0	90 and 280

[a] N_p is annual potential N uptake by crop.
[b] The numbers indicate days after planting.

6. Input data for the model

The simulations were conducted for a soil bulk density of 1.40 g cm^{-3} and a saturated water content of 0.48 $cm^3\ cm^{-3}$. The saturated hydraulic conductivity was chosen at 2.0 cm h^{-1}. The parameters used in the Hutson and Cass (1987) hydraulic function were as follows: water content at the inflection point (θ_i) was 0.48 $cm^3\ cm^{-3}$; the matric potential at the inflection point (h_i) was −0.0028 MPa; the air entry matric potential (a) was −0.0027 MPa; and exponent (b) of the equation relating matric potential to water content was 3.8. The exponent (bhb) for the equation relating hydraulic conductivity to water content was set as 15.0. These functions are typical for a loam soil.

The lower boundary was set at 2 m with 5 cm increments of soil depth for computation. The bottom boundary condition was set as free drainage. The upper boundary condition was set as flux control conditions with infiltration of irrigation according to the input rate. The bottom of the root zone was set at 1.5 m where drainage and N leaching were calculated.

The values, in units of MPa, for the threshold matric water stress (h_t) was equal to −0.05 for both crops and the matric stress causing 50% growth reduction (h_{50}) was equal to −0.14 for corn and −0.26 for forage. Irrigation water, even with lagoon water mixed in, was assumed to be sufficiently low in salinity to not affect plant growth.

The initial water content distribution was established by setting the soil profile at saturation and then allowing redistribution for 14 days with free drainage as the bottom boundary condition. This resulted in a water content of 0.34 $cm^3\ cm^{-3}$ and the matric potential equal to −0.012 MPa at the bottom boundary and 0.32 $cm^3\ cm^{-3}$ at the upper boundary. This soil water content profile was taken as the initial water content condition for corn in the first year, thereafter continuous simulation was conducted. The initial inorganic N distribution was 150 kg ha^{-1} evenly distributed over the top 20 cm and 100 kg ha^{-1} evenly distributed over the 20–200 cm layer. The initial water and N distribution only affected the results for the first and sometimes second year of the multiyear simula-

Table 2
Summary of the combinations of variables which were simulated under nonuniform irrigation

N amount	N composition	N application timing[b]	Mineralization half-life days	CUC[c] values
$1.0N_p$[a]	NH_4^+ and ON	Each irrigation	90 and 280	73, 86, 100
$1.2N_p$	NH_4^+ and ON	Each iirrigation	90 and 280	73, 86, 100
$1.4N_p$	NH_4^+ and ON	Each irrigation	90 and 280	73, 86, 100
$1.0N_p$	NH_4^+ and ON	0, 30, 75	90 and 280	73, 86, 100
$1.2N_p$	NH_4^+ and ON	0, 30, 75	90 and 280	73, 86, 100
$1.4N_p$	NH_4^+ and ON	0, 30, 75	90 and 280	73, 86, 100

[a] N_p is annual potential N uptake by crop.
[b] The numbers indicate days after planting.
[c] Christensens uniformity coefficient.

tions in a manner similar to how the initial soil condition affects results in the field. The reason for running multiyear simulations was to determine the long term consequences of a management scheme and eliminate the effects of the initial conditions.

The T_p was taken as the reference ET_0 times a crop coefficient. ET_0 values for Fresno, California, and crop coefficients for corn were taken from a report by Letey and Vaux (1985). The crop coefficient for the forage crop was assumed to be 1.0.

7. Results

The organic N mineralization rate is plotted as a function of day of year for 5 years in Fig. 2 when $N_p = 1.4$, summer half-life is 280 days, and the N was applied with each irrigation. Note that steady state values are reached after about 5 years. The temperol rate of mineralization does not coincide with the temperol rate of N uptake (Fig. 1). Therefore, the timing of leaching events will significantly affect the results. Large leaching rates at the initial and final stages of corn growth would particularly cause much N leaching that could affect crop yields as well as ground water degradation. In our simulations no large leaching events were programmed.

The relative yield (RY) of corn and forage and the amount of NO_3^--N leaching (NL) are shown in Fig. 3 over a 10-year period. The simulated conditions in this case were uniform application of $1.2N_p$ with every irrigation of $1.15T_p$. The applied N was equally divided with 50% NH_4^+ and 50% ON, where the ON had 280- or 90-day summer-time half-life mineralization rate. Maximum yields for both crops were simulated throughout. The high yields during the first 1 or 2 years can partially be attributed to the programmed high initial inorganic nitrogen content in the profile at the beginning of the simulations.

Note that the NL with a few exceptions increases with time and approaches a steady-state value which is reached earlier for the 90-day than for the 280-day half-life. Eventually both reached approximately the same value. One of the important findings of these analyses is that when a given amount of organic N is applied consistently, the annual amount of mineralized N eventually equals the amount of total applied N regardless of the mineralization rate constant. This is a fortunate circumstance because accurate information on mineralization rates is usually lacking. The

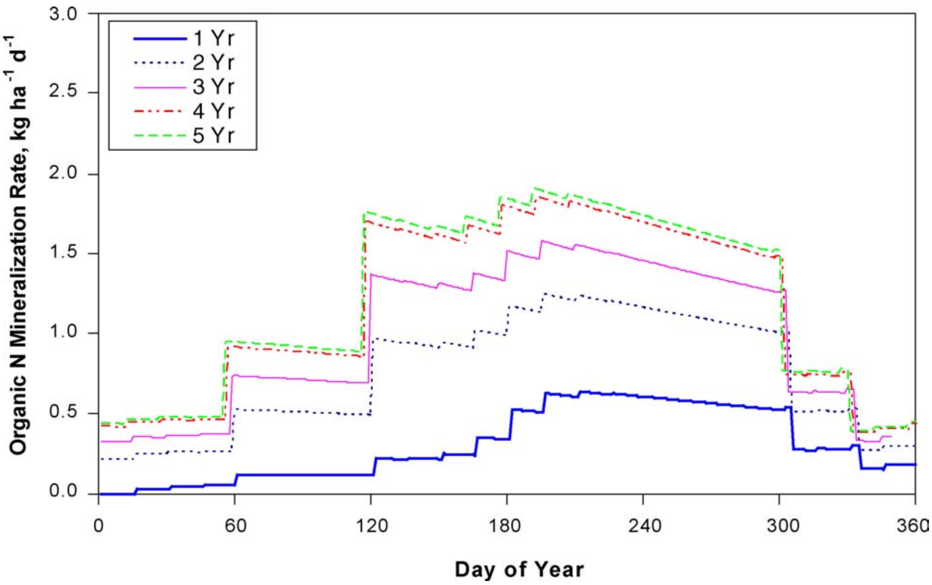

Fig. 2. The organic N mineralization rate as a function of time for 5 years when the time and amount of organic N application was biweekly to meet 70% of the potential N uptake and the half-life was 280 days during the summer. The results for years greater than five are identical to the fifth year results.

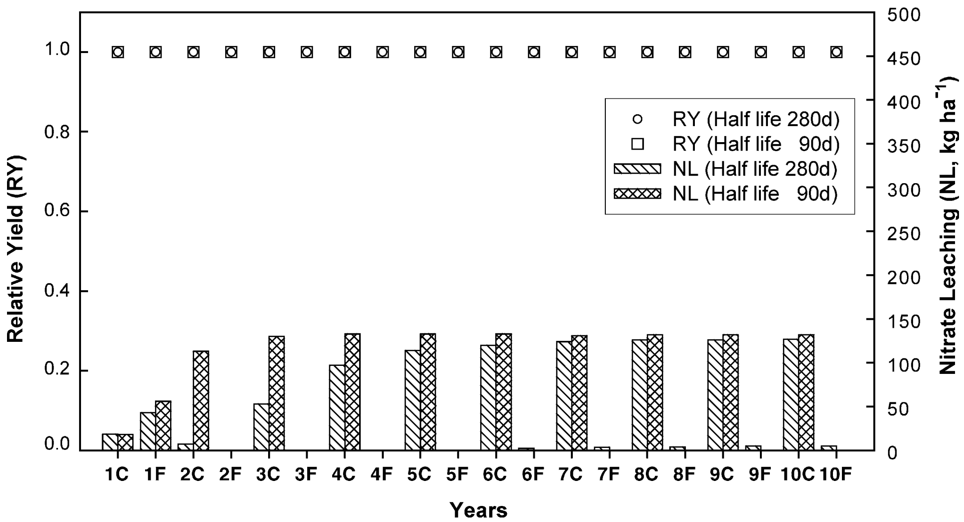

Fig. 3. The relative yield of corn (C), and forage (F) and the amount of nitrate-nitrogen leached during individual crop seasons as depicted over a 10-year period under uniform irrigation. The lagoon water was applied each irrigation with the total N equal to 1.2 times the potential N uptake. The results are depicted for summer time half life mineralization rates of 90 and 280 days.

mineralization rate constant determines the time period required to achieve steady state condition, but not the eventual quantitative steady state rate.

Note that after the first year essentially no NL occurs from the forage crop. (The first year results are greatly affected by the initial soil N distribution that was selected.) The low leaching under the forage crop can be attributed to two factors. The crop is grown in the winter months when the mineraliztion rate is very low. Therefore very little of the ON applied to the forage crop is mineralized and available for either crop uptake or leaching. The forage crop therefore was partially dependent on the mineral N remaining after the corn crop. The forage crop therefore utilized the available inorganic N sources which left little for leaching.

Much ON is mineralized between the period of forage production and maximum N uptake by the corn crop as well as after the time of maximum N uptake. These factors contribute to the significant amounts of computed NL under the corn crop.

Programming N application with time and amount consistent with crop uptake is simple when conducting computer simulations. Under a farm operation it is more common that the dairy waste only be added during some irrigations. For comparative purposes, we simulated applying the lagoon water during three irrigations for each crop, with equal amounts applied at the beginning, and approximately one-third and two-thirds through the crop season. All other conditions are the same as reported in Fig. 3. The results of the latter simulation are illustrated in Fig. 4. Note that in this case, corn yields were decreased and because of the reduced corn yields, more NL occurred. These results identify the importance of the timing as well as the total amount of N application. The decrease in corn yield is a result of having inadequate mineral N available during the relatively short time of peak N uptake requirement by the corn crop (Fig. 1). Much of the applied mineral N and also the amount of mineralized ON occurred after the peak crop requirement. Note that the forage was not affected because it benefited from the carry over from the corn crop. These results illustrate one of the challenges of managing organic N such that the availability of mineral N matches the crop N requirement on a temporal basis.

The temporal effects reported above are largely associated with the mineralization of organic N. To more completely understand the dynamics of N mineralization on crop yield and nitrate leaching, simulations were conducted for the same conditions as depicted in Fig. 4 except all of the N was applied in the organic form. Results of this simulation are illustrated

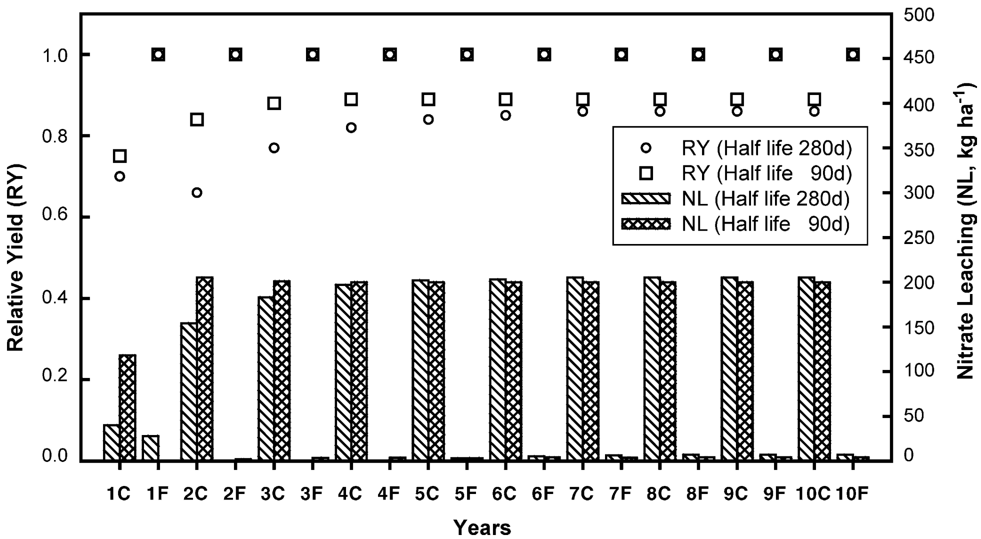

Fig. 4. The relative yield of corn (C), and forage (F) and the amount of nitrate-nitrogen leached during individual crop seasons as depicted over a 10-year period under uniform irrigation. The lagoon water was applied three times during the growing season with the total N equal to 1.2 times the potential N uptake. The results are depicted for summer time half life mineralization rates of 90 and 280 days.

in Fig. 5. Note, in comparing the results depicted in Figs. 4 and 5 that the main difference between the presence or absence of mineral N occurs during the first few years of the simulation. After the organic N has been applied for sufficient years to achieve steady state, the response was very similar to a combination of organic and mineral N as long as the total amount of N applied was identical.

Simulations where higher and lower N applications than those depicted in Figs. 3–5 were conducted. The main findings were as expected that higher N applications generally lend the higher yields and NL

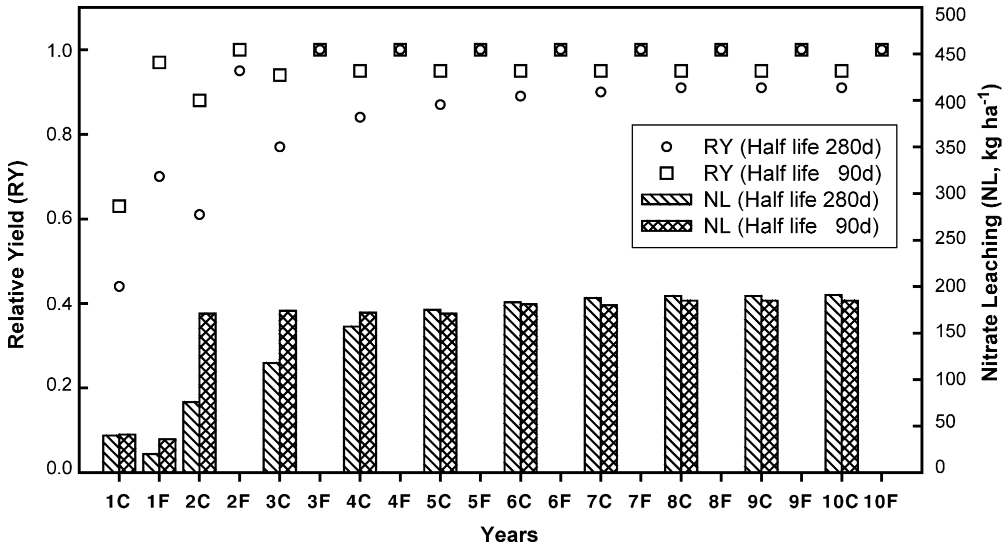

Fig. 5. The relative yield of corn (C), and forage (F) and the amount of nitrate-nitrogen leached during individual crop seasons as depicted over a 10-year period under uniform irrigation. Only organic N was applied three times during the growing season with the total N equal to 1.2 times the potential N uptake. The results are depicted for summer time half life mineralization rates of 90 and 280 days.

Table 3
Simulated effects of irrigation uniformity on yield and nitrate leached

N application	CUC = 73				CUC = 86				CUC = 100			
	RY_c[a]	NL_c[b]	RY_f[c]	NL_f[d]	RY_c[a]	NL_c[b]	RY_f[c]	NL_f[d]	RY_c[a]	NL_c[b]	RY_f[c]	NL_f[d]
	N applied with every irrigation											
$1.0N_p$	0.85	64	0.92	15	0.91	37	0.94	3	0.95	0	0.97	0
$1.2N_p$	0.92	127	0.97	42	0.98	111	1	23	1	114	1	0
$1.4N_p$	0.92	178	0.97	76	0.98	163	1	58	1	182	1	48
	N applied 0, 30, and 75 days after planting											
$1.2N_p$	0.77	134	0.96	6	0.83	146	1	8	0.84	202	1	3
$1.4N_p$	0.83	158	0.97	34	0.91	162	1	39	0.93	232	1	51

[a] Relative yield of corn.
[b] Amount of N leached under corn (kg ha^{-1}).
[c] Relative yield of forage.
[d] Amount of N leached under forage (kg ha^{-1}).

and the opposite for lower N applications. The temporal effects were not sensitive to total N application.

The results presented thus far are for uniform irrigation. The effect of the irrigation uniformity on results for the fifth year of simulation when steady state conditions had been approached are reported in Table 3. The simulated results are for N application with every water application and also for N application three times during each cropping season. The average water application was $1.15T_p$.

In general, RY increases with increasing irrigation uniformity. However, the difference between a CUC equal to 86 and uniform irrigation is not great. Increasing the N application rate tended to increase RY and NL.

The effect of irrigation uniformity on the amount of NL is variable. Indeed, when the N is applied three times during the cropping season, increasing irrigation uniformity resulted in a simulated increase in the amount of nitrate leached. Non-uniform irrigation results in parts of the field being ''under irrigated'' and other parts of the field being ''over irrigated''. Since the nitrogen was applied with the water, the sections of the field receiving the least amount of water also received the least amount of nitrogen. However, water rather than nitrogen was the limiting growth factor and no deep percolation of water occurred on the drier parts of the field. This would allow a small fraction of applied nitrogen to accumulate in the drier parts of the field thus leading to an overall field average reduced nitrate leaching.

Application of only organic N once at the beginning of each crop was compared to application three times during each crop growing season. The general results are as follows. During the first year, the yields for both corn and forage were higher for the one time application but in succeeding years, there was no difference between the two options. Under the steady state condition, application of $1.2N_p$ resulted in a relative corn yield of 0.9 and maximum yield for forages. Increasing the nitrogen application to $1.4N_p$ increased the relative corn yield to 0.97. However, increasing the N application to $1.4N_p$ also increased the N leached by about 85 kg ha^{-1} $year^{-1}$.

8. Conclusions

One major conclusion from this study is that when applying ON ultimately steady state conditions are achieved, whereby an equivalent amount of nitrogen applied in the organic form will be mineralized during a year. Steady state conditions are achieved more rapidly for materials with higher mineralization rates. This finding also underlines the importance that the results from short-term field experiments must be interpreted with caution. The experimental results will be very dependent upon the initial N status of the soil, mineralization rate of applied material, and whether organic N had been applied to the field several years prior to the experiment. When transitioning to an ON fertilizer source, higher amounts should be applied during the initial years and then decreasing amounts in successive years as steady state mineralization is approached.

A second conclusion is that the timing and total quantity of N application are both very important in affecting crop yield and potential N leaching. Many crops have very high N requirement over a relatively short period of time and will experience reduced growth if adequate N is not available during that period. Because mineralization of N is a continuous function, the timing of N availability with crop requirement is difficult to synchronize (Pang and Letey, 2000). Significantly higher simulated yields were achieved when N was applied with every irrigation to meet crop demands as compared to equal applications three times during the crop season (Figs. 3 and 4).

Increasing irrigation uniformity resulted in increasing yield for a given N application amount. Increasing irrigation uniformity increased, decreased, or had almost no effect on the amount of N leaching depending on the specific scenario. Because the N was applied with the water, nonuniform irrigation also caused nonuniform N application which contributed to the variable effects on N leaching.

Planting a forage crop during the winter effectively reduced the leaching of residual soil N following the corn crop. Application of ON during the winter when mineralization is slow provides very little mineral N for winter crop, but it becomes a major N source for the summer crop.

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