Organic Farming: Challenge of Timing Nitrogen Availability to Crop Nitrogen Requirements

X. P. Pang and J. Letey*

ABSTRACT

Groundwater has become increasingly degraded by NO_3, and this degradation has been partially attributed to the use of commercial inorganic N fertilizers. Conversion from conventional fertilizer management to organic farming has been proposed as a means to reduce groundwater degradation. Matching soil inorganic N supply with crop N requirement on a temporal basis is important to achieve high yield and low water degradation. Dynamics of N mineralization from two manures and N-uptake dynamics for two crops were derived from published data, and multi year simulations were done using the ENVIRON-GRO computer model, which accounts for N and irrigation management effects on crop yield and N leaching. The temporal N-mineralization and N-uptake curves did not match well. The potential N uptake for corn (*Zea mays* L.) exceeded the cumulative mineralized N during a significant period that would cause reduced yield. Wheat (*Triticum aestivum* L.) has a low and flat N-uptake peak, so that the cumulative mineralized N met N demand by wheat during the growing season. A crop with a very high maximum N-uptake rate, such as corn, would be difficult to fertilize with only organic N to meet peak demands without excessive N in the soil before and after crop growth. In order to satisfy crop N demand, a large amount of manure, which would leave much N or subsequent leaching, must be applied. It took two or more years after conversion to organic sources of N to reach maximum yield because of carryover of unmineralized manure and accumulation of mineralized N after crop uptake which was not completely leached during the winter. High initial applications to build up the organic pool followed by reduced inputs in subsequent years would be appropriate.

NITROGEN IS A MAJOR PLANT NUTRIENT required for high yields of most agricultural crops. Nitrogen in the NO_3 form is also mobile and susceptible to transport to groundwater, causing degradation of aquifer water quality. Prior to the availability of commercial N fertilizer, agricultural systems generally included crop rotations that included a N_2-fixing crop and animals, whereby the manure produced by the animals was returned to crop land for fertilizer purposes. Kurtz et al. (1984) referred to a debate after World War II when commercial N became available. They stated "the agricultural establishment that had been committed for decades to diversified and animal agriculture was suspected of being biased and unwilling to change (to commercial N)." Since that time, use of commercial fertilizer and other synthesized chemicals has become widely adopted by the agricultural industry.

Nitrate concentrations of groundwater have generally increased during recent decades, and the widespread use of commercial N fertilizer has been implicated as a causative factor. Organic farming is being promoted as being an environment friendly and more sustainable farming system. Ironically, scientists one-half century ago devoted much research emphasis to providing farmers information on the beneficial use of commercial fertilizer, whereas present research programs are focused on providing information for farmers to reduce the use of commercial fertilizers.

Conversion from commercial fertilizer (conventional farming) to organic forms causes changes in the soil other than fertility effects that can affect plant growth. For example, organic farming plots had a higher organic matter content, higher N mineralization potential, and higher microbial biomass levels than plots receiving commercial fertilizers (Power and Doran, 1984; Scow et al., 1994; Drinkwater et al., 1995).

Power and Doran (1984) reviewed the literature on N use and organic farming. They reported that almost universally those converting to organic farming required about 3 to 5 yr to stabilize production practices. Yields during the conversion period were often lower than those achieved later. Scow et al. (1994) also reported a lag period after a transition from conventional to organic farming, where there were lower yields under the organic farming treatments.

One objective of organic farming is to have low potential for groundwater degradation by nitrates. Measurement of mineral N concentrations in the root zone is commonly done in experiments involving organic farming. The total mass transfer of NO_3 below the root zone is not usually measured because of the difficulty in accurately measuring this value. Ignoring denitrification possibilities, the total mass of NO_3 transported to groundwater is a product of the concentration of NO_3 in the root zone and the amount of water that passes through and below the root zone. Power and Doran (1984) reported that organic farming seldom had pools of large concentrations of inorganic N within the root zone. Conversely, at times, large concentrations of inorganic N can occur within the root zone from commercial N application. Organic N is immobile but also unavailable for plants. The key to achieving high yields with minimal groundwater degradation is to have mineral N available at the time and in the quantity required by the crop.

First, we present an analysis of the dynamics of N mineralization of two manures and N uptake, using two manures and two crops as examples. Second, we report the results of multi year simulations, using a dynamic model to illustrate the consequences of N mineralization and uptake dynamics for crop yield and N leaching under selected management variables.

Dep. of Environmental Science, University of California, Riverside, CA 92521. Received 21 July 1998. *Corresponding author (john.letey@ucr.edu).

Published in Soil Sci. Soc. Am. J. 64:247–253 (2000).

Abbreviations: ET, evapotranspiration; MSEA, Management Systems Evaluation Areas.

MATERIALS AND METHODS

Dynamics of Nitrogen Mineralization and Nitrogen Uptake by Crops

We assume that the amount of mineralized N within the year is described by the relation

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

Where N_{min} is the amount of mineralized N, A_o is the total amount of N in the organic material, t is time, and λ is a coefficient representing the rate of decay.

Pratt et al. (1973) proposed that the yearly rates of mineralization be expressed as a series of fractional mineralization of any given application, or the residual of that application, and be referred to as a decay series. For example, a decay series 0.40, 0.25, 0.06 means that for any given application 40% is mineralized the first year, 25% of the residual (that which was not previously mineralized) is mineralized the second year, and 6% of the residual is mineralized the third and all subsequent years.

The value of λ can be selected such that the total amount of the annual mineralization equals the decay series. For example, a decay series of 0.40, 0.25, 0.06, the value of λ for the first year would be such that N_{min} equals 0.40 A_o. The value of λ is changed for subsequent years or for different forms of organic N to match the decay series. From Eq. [1] the cumulative amount of mineralized N can be plotted as a function of time. The slope of that curve represents the rate of N mineralization as a function of time.

The cumulative amount and rate of N uptake by a crop can be measured in the field. We selected corn and wheat as crops for illustrative purposes. Nitrogen uptake by corn as a function of time was taken from STCES of Iowa State University (1992) and by wheat from a report by Doerge et al. (1991). Chicken (*Gassus gallus*) and beef (*Bos taurus*) manure were selected as the organic forms of N in this study. The decay series reported by Pratt et al. (1973) were 0.90, 0.10, 0.05 for chicken manure, and 0.75, 0.15, 0.10, 0.05 for beef manure. Different sources of manure may have different decay rates than these values, but the purpose of this study was to illustrate principles rather than report the results for a specific manure.

The rate of mineralized N for the various manures and the rate of N uptake by corn and wheat are illustrated in Fig. 1. The results are for manure containing 400 kg ha^{-1} of N and the annual N uptake of 294 kg ha^{-1} for corn and 258 kg ha^{-1} for wheat. Time zero represents the planting date for each crop and also the time of manure application. Note that the N-mineralization and N-uptake curves do not match well. The maximum N-uptake rate by corn is 10 kg ha^{-1} d^{-1} and occurs around 60 d after planting in a very narrow time period (20 d). The peak rate of N uptake exceeded the mineralization rate. The maximum N-uptake rate by wheat is 3.5 kg N ha^{-1} d^{-1}, which is about one-third that of corn and occurred ≈125 d after planting. The peak N uptake by wheat occurs across a longer time period (80 d).

The cumulative amounts of mineralized N and N uptake as functions of time are illustrated in Fig. 2. A potential for N leaching occurs when the mineralized N exceeds the N uptake. Conversely, N deficiency occurs when the N uptake exceeds the mineralized N. The total N demand of corn rises sharply to its maximum around 60 d after planting. Even application of 400 kg organic N ha^{-1} of relatively fast-mineralizing chicken manure would not meet cumulative corn N demands. In order to satisfy crop N demand, a large amount of manure must be applied. This would leave much organic N available for subsequent mineralization and leaching. It is clearly shown in Fig. 2 that fresh beef manure, which represents a moderate rate of decay, is not suitable as a sole N source for crops, such as corn, with a very high maximum N uptake rate. Note that for corn the potential N uptake exceeded the cumulative mineralized N during a significant period for both manures, which would cause reduced yield. On the other hand, the amount of N mineralized both from chicken and beef manure on an annual basis exceeds the potential uptake. For wheat the cumulative mineralized N from chicken manure exceeded the cumulative N uptake during the entire growing season. For beef manure, the amount of N mineralized exceeded N uptake during the early stages of plant growth. Adequate N was provided for latter stages

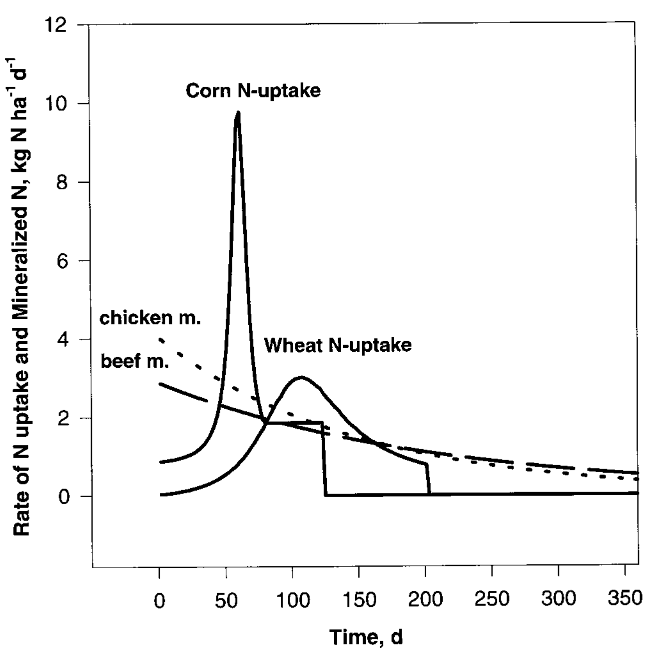

Fig. 1. Representative rates of mineralized N for chicken and beef manures and N-uptake rates by corn and wheat.

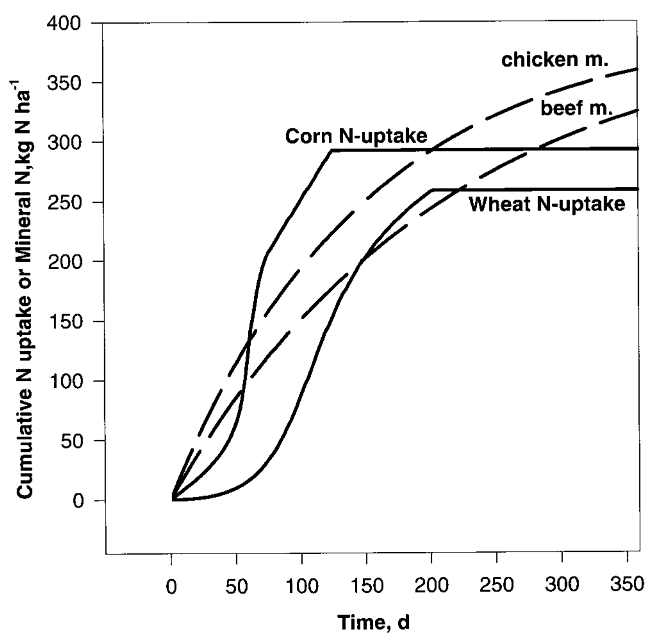

Fig. 2. Cumulative amounts of mineralized N from chicken and beef manures and cumulative N uptake by corn and wheat as functions of time.

when the N-uptake rates increased. Mineralization from manure continues after N uptake by crops stops, so there is an excess of mineralized N at the end of the year.

Factors to consider in using organics as the sole source of N are evident from the results presented in Fig. 1. The maximum rate of N uptake by a crop is important. A crop with a very high maximum N-uptake rate, such as corn, would be difficult to fertilize with only organic N. It would be virtually impossible to meet peak demands without excessive N in the soil before and after crop growth. Although the total N uptake of wheat is 88% of corn, the maximum uptake rate for wheat is only 31% that of corn. A significant conclusion is that in programming fertilization with organic materials for different crops, the N-uptake dynamics are equally or more important than the total N uptake.

A 1-yr analysis as depicted in Fig. 1 and 2 is not a complete analysis for the effects of organic N application. This is particularly true for organic materials that are not completely mineralized during 1 yr. The carryover of unmineralized organic matter to future years contributes to long-term N availability. The 3- or 4-yr delay in achieving high yields after converting from conventional to organic farming reported above is possibly associated with the need to accumulate a sufficient organic N pool in the soil that can be mineralized at a rate to meet peak N-uptake rates. This explanation is supported by Stanhill (1990) on the comparative productivity of organic agriculture for 26 crops at 15 sites. In comparing corn yields under organic and conventional farming practices, conventional had higher yields than organic fertilization when high yields were achieved. Conversely, organic farming yields were equal to or greater than conventional farming under adverse conditions or low yields. This may be attributed to a decrease in peak N-uptake rates, associated with reduced yields, which could more easily be matched by organic N applications. The data reported by Stanhill (1990) did not clearly reflect the transition phase effect reported by others.

Clearly there are complex interacting factors between organic N application and crop yields. A multi year analysis is required. Water management is a critical factor because the amount and timing of excess water application, which can cause leaching, has significant impacts on the potential groundwater degradation. In the following, we use a dynamic model that accounts for the interactions between the N supply, N uptake, and N leaching to illustrate the effects of selected N application and irrigation management practices on crop yield and N leaching.

Multi Year Simulations

The Model

The effects of application of manure on crop yield and N leaching were simulated using the ENVIRO-GRO computer model developed by Pang and Letey (1998). The ENVIRO-GRO model simulates the effects of irrigation, salinity, and N management on crop yield and leaching of NO_3 and salts through the soil. It integrates plant response to soil water matric potential, osmotic potential, and N stress. The model relates N uptake to N concentration, allows additional water and N uptake from a nonstressed portion of the root zone to compensate for a stressed portion of root zone, and adjusts the potential water or N uptake to account for reduced plant size. Pang and Letey (1998) used data from a field experiment with a wide range of water and N applications to corn to evaluate the model. The agreement between simulated and measured results was good, particularly for the "normal" irrigation and fertilizer applications. The greatest deviations occurred for the extreme irrigation and fertilizer treatments.

The ENVIRO-GRO model assumes that mineralization of organic N (e.g., animal manure) follows the first-order decay process and does not account for denitrification. The concept of a decay series proposed by Pratt et al. (1973) was used in multi-year simulations. In order to match the amount of the mineralized N from manure with the decay series proposed by Pratt et al. (1973), the mineralization rates of manure in the first, second, third, and subsequent years were assigned.

The effect of low temperature during the winter on manure mineralization was taken into account by reducing the mineralization rate from 1 October to 1 March. This was done by linearly reducing the value of λ in Eq. [1] to zero between 1 October and 15 December and linearly increasing λ from zero on 15 December to the potential λ value on 1 March.

Inputs

Inputs to the model included potential evapotranspiration, crop water use coefficients, soil hydraulic properties, irrigation amounts and dates, and fertilizer amounts and dates. The value of potential evapotranspiration was typical to the San Joaquin valley of California. The crops considered in this study were corn and wheat. Water use coefficients of corn were taken from a report by Letey and Vaux (1985). Wheat water use coefficients were taken from Jensen (1981). The simulations had the crops planted on 1 May, corn harvested on 30 September, and wheat harvested on 15 October. The growing season irrigations were 75 cm for wheat and 63 cm for corn, representing 1.0 evapotranspiration (ET) for a nonstressed crop. The irrigation intervals were $\approx$2 wk during the growing season for both crops. There were 17 cm of simulated rain during the noncrop season. Total monthly rain was applied at the beginning of the month from November through April. The model calculated evaporation from the soil surface for the uncropped part of the year according to the two-stage approach (Nimah and Hanks, 1973). If surface matric potential was above a limiting value, evaporation was equal to the potential evaporation; otherwise, calculated evaporation becomes less than the potential based on hydraulic head gradient and soil hydraulic conductivity.

The fractional accumulative N uptake by corn as a function of time was taken from STCES of Iowa State University (1992) and by wheat from Doerge et al. (1991). The N-uptake curve in conjunction with the maximum seasonal uptake of crop produced the quantitative potential N-uptake rate as a function of time. The maximum seasonal N uptake was 294 kg ha^{-1} for corn (Broadbent and Carlton, 1979) and 258 kg N ha^{-1} for wheat (Doerge et al., 1991). One manure application per year was made on the day before planting for all simulations. There were four levels of each manure applied to each crop.

Constant and variable annual rates of manure application were evaluated. Manure applications of 300, 400, 500, and 600 kg N ha^{-1} were used for constant-rate application, and the variable rate applications were 400 and 300 kg ha^{-1} applied in alternate years. After several years of variable rate application, the rate was kept constant at 300 kg N ha^{-1}. Constant rate manure application simulations were conducted for both corn and wheat, whereas variable rate simulations application were conducted for wheat only.

The parameters related to soil physical properties that are required for the model were selected to be representative of a loam soil. Soil bulk density of 1.40 Mg m^{-3}, a saturated water content of 0.48 m^3 m^{-3}, and saturated hydraulic conductivity of 2.0 cm h^{-1} were selected. The parameters used in the Hutson and Cass (1987) hydraulic function were as follows: water content at the inflection point (θ_i) was 0.47 m^3 m^{-3}, the matric potential at the inflection point (h_i) was -0.0028 MPa, the air

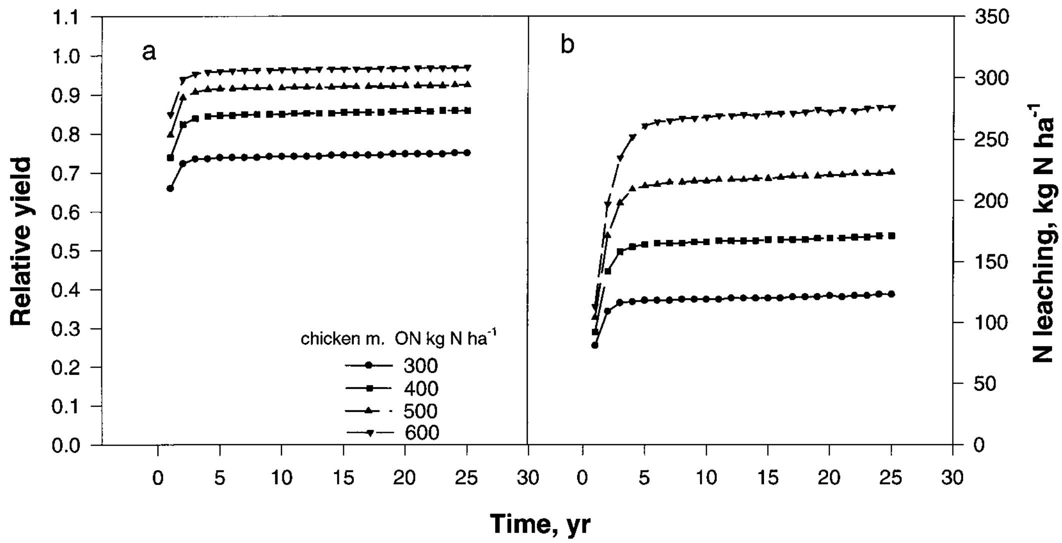

Fig. 3. Simulated (a) corn relative yield and (b) annual N leaching at four levels of chicken manure application for 25 yr.

entry matric potential (a) was −0.027 MPa, and the 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.

Initial Condition

The initial water content distribution was established by setting the soil profile at saturation (0.48 m^3 m^{-3}) and then allowing redistribution for 28 d with free drainage as the bottom boundary condition. This resulted in a water content of 0.34 m^3 m^{-3}, equaling −0.010 MPa matric potential at the bottom boundary and ≈0.28 m^3 m^{-3} at the upper boundary. This soil water content profile was then taken as the initial water content condition for all simulations. The initial inorganic N concentration was assumed uniformly distributed through the soil profile at the end of water redistribution, with a total N amount in the soil profile equal to 100 kg N ha^{-1}. The simulations were conducted for nonsaline soils and irrigated with nonsaline water.

Bottom Boundary Condition

The lower boundary condition at the 1.8-m depth was set as unit gradient (free drainage) since the temporal fluctuations of water content dampen with soil depth and a unit hydraulic gradient was achieved at this depth for the conditions of the simulations.

Each simulation was run for 25 yr. The two crops, two types of manure, and four levels of manure application yielded 400 simulations.

RESULTS AND DISCUSSION

Simulated corn relative yield and annual N leaching at four levels of chicken manure application for 25 yr are shown in Fig. 3a and Fig. 3b. Since corn has a narrowly peaked N uptake, the applications of chicken manure <600 kg N ha^{-1} did not meet crop N requirement. About half of the organic N from chicken manure was leached

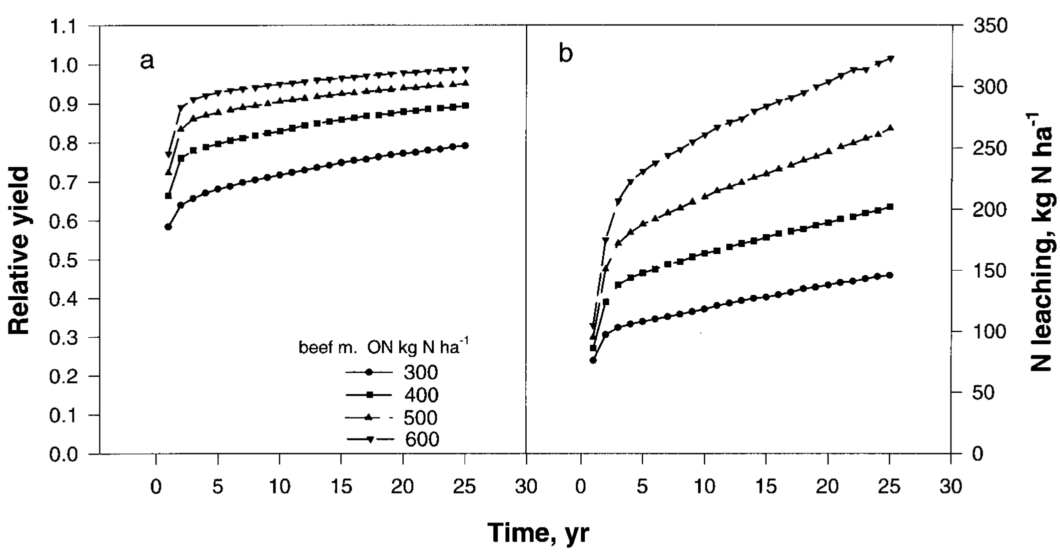

Fig. 4. Simulated (a) corn relative yield and (b) annual N leaching at four levels of beef manure application for 25 yr.

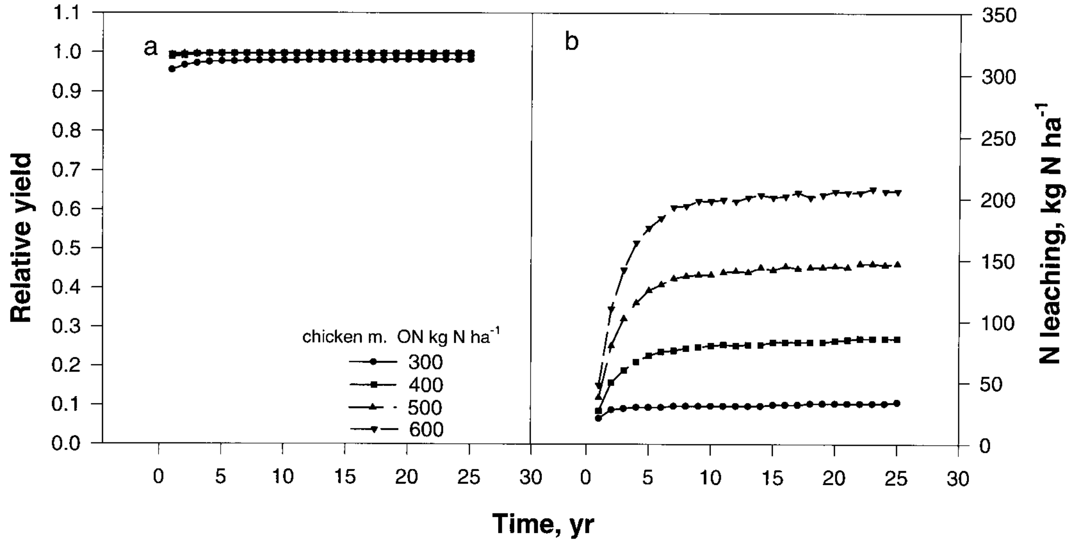

Fig. 5. Simulated (a) wheat relative yield and (b) annual N leaching at four levels of chicken manure application for 25 yr.

from the root zone because only half of the amount of applied manure was mineralized during the crop growth period and only one-third was mineralized before the peak N-uptake period. The remaining manure was mineralized during the rest of the year and was subject to leaching. It took ≈3 yr for the corn–chicken manure system to reach steady-state conditions. The increase in yield in years subsequent to the first year was the result of carryover of unmineralized manure and the accumulation of mineralized N after crop uptake which was not completely leached during the winter.

Figure 4 presents the simulated corn relative yield and annual N leaching at four levels of wet beef manure application. Yield and N leaching increased with time during the 25-yr simulations. It took ≈25 yr for the corn–beef manure system to reach its maximum yield under the highest manure application (600 kg N ha^{-1}). For the other application rates (300, 400, and 500 kg N ha^{-1}), corn never reached its maximum yield. There was less yield and more N leached under beef manure application than under chicken manure for the same year and for the same rate of N application because of the lower mineralization rate of the beef manure. The accumulated unmineralized manure from previous years contributed to the increasing yield and N leaching in successive years.

The simulated wheat relative yield and annual N leaching at four levels of chicken manure application are presented in Fig. 5. Except for the 300 kg N ha^{-1} application, all application rates of chicken manure met the wheat N-uptake requirements (Fig. 5a). Application rates of 500 and 600 kg N ha^{-1} were excessive and resulted in large amounts of N leaching (Fig. 5b). Nitrogen leaching reached the maximum rate in the seventh year and stayed constant thereafter as water and N dynamics reached a steady state condition. The maximum N uptake rate of wheat was only about one-third that of corn (Fig. 1). This peak of N uptake occurred for a longer time (80 d) compared with corn (20 d). Note that higher yields and less N leaching for a given amount of

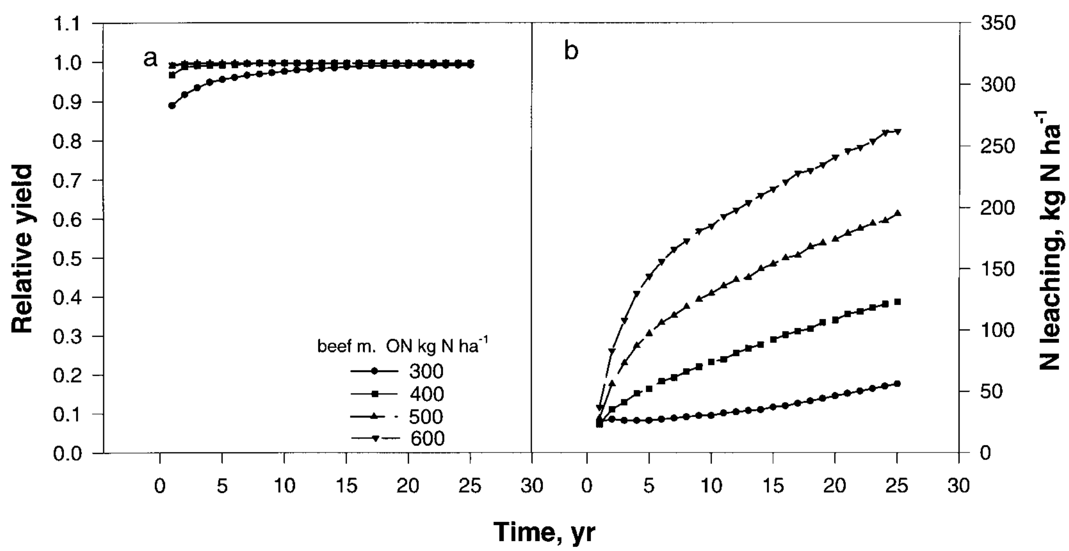

Fig. 6. Simulated (a) wheat relative yield and (b) annual N leaching at four levels of beef manure application for 25 yr.

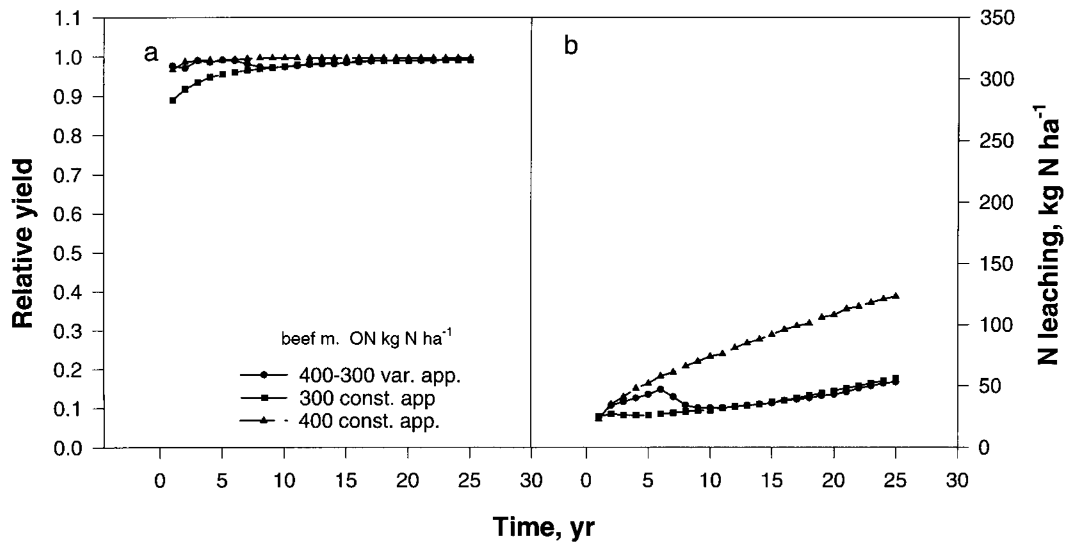

Fig. 7. Comparisons of simulated (a) wheat relative yield and (b) annual N leaching with 6 yr of variable rate manure application between 400 and 300 kg N ha^{-1} vs. constant manure application.

organic N application were achieved for wheat than for corn.

Figure 6 presents simulated wheat relative yield and annual N leaching at four levels of beef manure applications. For the 300 kg N ha^{-1} treatment, wheat yield increased with years and reached maximum yield at 16 yr. For application rates greater than 300 kg N ha^{-1}, yields were maximum after the second year (Fig. 6a). Nitrogen leaching increased with time for all N application rates (Fig. 6b).

It was important to determine if the dual goals of high yield and low N leaching could be achieved by applying a variable annual rate of manure. Figure 7 shows the comparisons of simulated wheat relative yield and annual N leaching with 6 yr of variable rate manure application (between 400 and 300 kg N ha^{-1}) versus constant manure application. After 6 yr of variable rate application, the rate was kept constant at 300 kg N ha^{-1}. Wheat yields were close to maximum during the 6-yr period and then decreased with time to the values of a constant application of 300 kg N ha^{-1} (Fig. 7a). Meanwhile, the N leaching increasing with time during the first 6 yr and then decreased to values of those from a constant 300 N ha^{-1} application (Fig. 7b).

The results reported on relative yields and N leaching (Fig. 3–7) are based on computer model simulations. No experiments have been conducted with all of the simulated variables that allow comparison between experimental and simulated results. Pang and Letey (1998) did compare simulated to experimental corn yields with variables of inorganic N applications of 0, 90, 180, and 360 kg N ha^{-1} and water applications of 21, 63, and 105 cm. The agreement between simulated and observed results was quite good, with a Willmott's *d* index (Willmott, 1981) equal to 0.94 for relative yield and 0.93 for N uptake. An index equal to 1.0 is perfect agreement between simulated and observed results. Deep percolation was not measured in the experiments so no comparison to simulated values is possible. However, the good agreement for yields and N uptake provides some assurance that the simulated N leaching is also a good estimate of the actual case.

The USDA funded and organized the Management Systems Evaluation Areas (MSEA) Project to evaluate the impact of farming systems and N inputs to crop production and groundwater quality beneath the crop. The MSEA research sites were established in several Midwestern states and a summary of the results were reported by Power et al. (1998). One of the findings was that high rates of previously applied manure often resulted in high amounts of N leaching. Thus, our simulated results are consistent with field observations. Another finding was that N leaching was most common in years when yields were substantially below normal due to poor growing conditions. One of the features of the ENVIRO-GRO model is that factors, such as deficient N or water, which reduce plant growth also decrease evapotranspiration. Thus, for the same water application more deep percolation of water is simulated under poor plant growth. This feature is consistent with the field observation that N leaching was most common in years when yields were substantially below normal.

A wide range of water management options could have been chosen for the simulations, and each option would potentially produce different results. The simulations were presented for uniform irrigation. With everything else held constant, uniform irrigation leads to higher yields and less N leaching than nonuniform irrigation (Letey et al., 1990). Simulated irrigation amounts matched the crop ET for a nonstressed plant, leading to higher yield and lower leaching than would have occurred if the simulated irrigation had not matched the crop ET as well. The assumption of no denitrification contributed to simulated results of higher yields and higher N leaching than would have occurred with denitrification. Incorporation of a cover crop rather than fallow between the cropping seasons would have led to less N leaching than the simulated results. Applications of manure several days before planting, rather than at the time of planting as was simulated, would have had the effect of shifting the mineralization curves in Fig. 1 and 2 to the left. This would have increased the potential for N leaching early in the season, but would have increased the amount of N available for crop growth in the absence of leaching.

Inasmuch as the simulations were conducted under a specific set of management variables and no model can completely capture all of the intrinsic features of nature, the absolute values reported are not as important as the more general findings of the study. This study reveals the complexities of using organic matter as a sole source of N fertilizer and identifies factors that must be considered. The N-uptake dynamics of the crop are very important. Crops with high uptake rates for a short time are not well adapted to be fertilized solely by organic matter. The mineralization rate of the organic matter has significant effects on potential yield and N leaching. Materials that are not completely mineralized in 1 yr create a cumulative organic pool with time that must be considered in future organic matter applications. High initial applications to build up the organic pool and cut back in subsequent years would be appropriate, as illustrated in Fig. 7.

Except for very high applications, the simulated results revealed a lag of two or more years to achieve maximum yield with manure. This may explain the field observations of a lag in achieving high yield when converting from conventional to organic farming. The lag would be most pronounced for crops with a very high uptake rate across a short time.

A combination of organic and inorganic fertilization may be optimal. The organic material is applied to improve microbial activity and other beneficial soil properties, and inorganic N fertilizer is applied to supply the large amount of available N required during peak N-uptake periods for the crop. Indeed, this was found to be the case in the Sustainable Agricultural Farming Project at the University of California, Davis where low-input systems (organic materials with a small amount of supplemental inorganic treatment) gave good results (Temple et al., 1994).

One might make the case that N was exclusively supplied from organic forms prior to the availability of commercial sources and farming could revert back to those systems. One major difference is the development of high-yielding crops, such as hybrid corn, which have a high N demand for a short time, which is a feature that is not readily compatible with organic farming.

One justification for organic farming is the expectation of reduced N leaching and groundwater degradation. Relatively low concentrations of mineral N occur in soils from organic application, but these low concentrations are subject to leaching during the noncrop part of the year or when excess water is applied during the crop season. Matching the time of mineral N availability with N uptake is not readily possible. The opportunity for a good match is highest for crops that do not have high N-uptake rates for a short period of time and also have low total N uptake. Doerge et al. (1991) reported N-uptake rates and total N uptake for 12 crops. Field corn and wheat, which were selected for our study, represent examples at both ends of the spectrum.

REFERENCES

Broadbent, F.E., and A.B. Carlton. 1979. Field trials with isotopes—Plant and soil data for Davis and Kearney sites. Final report to the National Science Foundation. Univ. of California, Riverside.

Doerge, T.A., R.L. Roth, and B.R. Gardner. 1991. Nitrogen fertilization management in Arizona. College of Agriculture, University of Arizona, Tucson.

Drinkwater, L., E. Dkletourneau, F. Workneh, A.H.C. van Bruggen, and C. Shennan. 1995. Fundamental differences between conventional and organic tomato agrosystem in California. Ecol. Appl. 5: 1098–1112.

Hutson, J.L., and A. Cass. 1987. A retentivity function for use in soil-water simulation models. J. Soil Sci. 38:105–113.

Jensen, M.E. 1981. Design and operation of farm irrigation systems. Amer. Soc. Agric. Eng. Monogr. 3. ASAE, St. Joseph, MI.

Kurtz, L.T., L.V. Boone, T.R. Heck, and R.G. Hoeft. 1984. Crop rotations for efficient N use. p. 295–306. *In* R.D. Hauck (ed.) Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, WI.

Letey, J., and H.J. Vaux. 1985. Water duties for California agriculture. A report submitted to the California State Water Resources Control Board, Sacramento, California. Agreement no. 2-043-300-0.

Letey, J., A. Dinar, C. Woodring, and J.D. Oster. 1990. An economic analysis of irrigation systems. Irrig. Sci. 11:37–43.

Nimah, M.N., and R.J. Hanks. 1973. Model for estimating soil, water, plant, and atmospheric interrelations: I. Description and sensitivity. Soil Sci. Soc. Am. Proc. 37:522–527.

Pang, X.P., and J. Letey. 1998. Development and Evaluation of ENVIRO-GRO: An integrated water, salinity, and N model. Soil Sci. Soc. Am. J. 62:1418–1427.

Power, J.F., and J.W. Doran. 1984. N use in organic farming. p. 585–600. *In* R.D. Hauck (ed.) Nitrogen in crop production. ASA, CSSA, and SSSA, Madison, WI.

Power, J.F., A. Dale Flowerdale, R.A. Wiese, and D.G. Watts. 1998. Agricultural nitrogen management to protect water quality. Information development expanding awareness (IDEA) no. 4. USDA, Washington, DC.

Pratt, P.F., F.E. Broadbent, and J.P. Martin. 1973. Using organic wastes as nitrogen fertilizers. Calif. Ag. 27(6):10–13.

Scow, K.M., O. Somasco, N. Gunapala, S. Lau, R. Benette, H. Ferris, R. Miller, and C. Shennan. 1994. Transition from conventional to low-input agriculture changes soil fertility and biology. Calif. Agric. 48(5):20–26.

Stanhill, G. 1990. The comparative productivity of organic agriculture. Agric. Escosyst. Environ. 30:1–26.

STCES of Iowa State University. 1992. How a corn plant develops. Spec. Rep. no. 48. Iowa State University of Science and Technology Cooperative Extension Service, Ames, IA.

Temple, S.R., O.A. Somasco, M. Kirk, and D. Fraedman. 1994. Conventional, low-input and organic farming systems compared. Calif. Agric. 48(5)14–19.

Willmott, C.J. 1981. On the validation of models. Phys. Geogr. 2: 184–194.