DOI: 10.1007/s00267-003-9138-x

Nitrogen Leaching and Denitrification in Continuous Corn as Related to Residue Management and Nitrogen Fertilization

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ABSTRACT / Maintaining crop production levels with reductions in terrestrial greenhouse gases requires strategic residue and nitrogen (N) fertilizer management. Our objectives were to: (1) quantify the effect of nitrogen N application rate on N losses; (2) examine the role of residue returned on N transformation and losses; and (3) verify the capability of the NCSWAP/NCSOIL model to simulate the dynamics of N and ^{15}N in the soil–plant system. Data obtained from a long-term continuous corn study on a silt loam soil, with two N levels (20 and 200 kg N/ha), with two types of residue management (residue harvested, −R; and residue returned, +R) was used to calibrate the model. The model accurately predicted ^{15}N in the plant and soil organic matter (SOM) at the 0- to 15-cm and 15- to 30-cm depths for both fertilizer rates and residue managements. Concentrations of ^{15}N in the corn and SOM were higher for the 20 than 200 kg N/ha treatments. Greater dilution of the ^{15}N with nontracer fertilizer added at the higher fertilizer rate was responsible for differences in ^{15}N concentrations in the plant. The predicted cumulative N loss during a 30-year simulation indicates more nitrate leaching past the 1-m depth for −R than +R treatments, while higher denitrification rates were predicted for the +R than −R. The simulated cumulative effect of residue returned on denitrification over 30 years predicted increased cumulative N losses from 1320 to 1705 kg N/ha and 1333 to 2574 kg N/ha for the low and high N application rates, respectively. Better synchronization of N release from residue and addition of N fertilizer with plant-N uptake would minimize leaching and denitrification.

Groundwater contamination due to nitrate (NO_3^-) leaching and greenhouse gas emission of the nitrous oxide (N_2O) are two environmental concerns for applied N fertilizers (Rhode 1990). Crop production systems that optimize yield, reduce greenhouse gases (GHG), and improve soil and water quality are desirable. Returning residue with reduced tillage maintains soil organic matter (SOM) and increases the capability of soil to provide N to growing crops (Maskina and others 1993). The SOM sustains many soil functions such as soil microbial and faunal activities (Doran 1980a,b, Biederbeck and others 1984, Ocio and others 1991). In a silty clay loam soil in eastern Nebraska, populations of total microbes were 1.7–4.4 times higher in soils treated with corn residue than untreated soil (Doran 1980a). Furthermore, nitrifier and denitrifier populations were 4–20 times higher on mulched as

KEY WORDS: Soil organic matter; nitrate leaching; ^{15}N; tracer N uptake; Biomass; NCSWAP simulation; denitrification

Published online January 20, 2004.

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compared to plots without mulch. Bengtsson and Bergwall (2000) reported that nitrate reducers and nitrifiers were more common in fertilized soils than the unfertilized control soils.

Increasing immobilization and decreasing denitrification of surface applied fertilizer and indigenous N with residue returned is a challenge for GHG reduction and soil and water quality improvement. Residues retained on the soil surface can increase N losses due to leaching and denitrification. Generally, 59%–66% of applied N is found in the plants, while 24%–28% of applied N remains in the soil and 10%–13% is probably lost by denitrification or ammonia (NH_3) volatilization (Porter and others 1996). Several researchers have attributed sizable fertilizer N losses to denitrification (Schindler and Knighton 1999, Jensen 1994, Luo and others 2000, Abbasi and Adams 2000a,b). Nitrous oxide, with a relative thermal adsorption 150 times that of CO_2, is a by-product of nitrification and denitrification (Rhode 1990, Frolking and others 1998, Lal and others 1998). It is estimated that 0.17–3.52 kg of N_2O can be emitted to the atmosphere per 100 kg of N in applied fertilizer (CAST 1992). Knowledge of the amount of N denitrified is important for understanding the fate of N fertilizer and consequent GHG emission and mitigation.

Isotopic tracer N (^{15}N) is used to study the fate of N fertilizer and to differentiate between soil N and fertilizer N uptake. Small additions of ^{15}N are particularly informative in evaluating the dynamics of soil N (Wolf and Russow 2000). Tracer N can be used to detect various sinks, including the crop, and available soil N or soil organic N pools (Kramer and others 2002). Tracer N is also used to monitor N uptake and retention in the soil, as well as N lost by leaching or denitrification. Smith and others (1982) found that slightly more than 50% of ^{15}N fertilizer was taken up by plants, less than 5% remained in soil as NO_3^-, about 35% was incorporated into SOM, and 7% was unaccounted for in a sorghum (*Sorghum bicolor* L.)–sudangrass (*Sorghum sudanese* L.) sequence. The use of ^{15}N in studies of soil-N transformations can provide valuable information on the processes of immobilization of inorganic N into organic forms and subsequent remineralization, leaching, and denitrification.

Because of the large number of variables involved and the complexities of interactions between crop, climate, and soils, it is only through the use of process-based computer models such as NCSWAP and NCSOIL (Molina and others 1983, 1997, 2001) that the long-term effects of crop residue management practices on carbon (C) and N transformation be explained. The purpose of the ^{15}N field study was to calibrate the NCSWAP/NCSOIL model and provide some insight into N dynamics. The specific objectives of the simulation were to: (1) quantify the effect of N application rate on N leaching and denitrification; (2) examine the role of residue returned on N transformations; and (3) verify the capability of the NCSWAP/NCSOIL model to simulate the dynamics of N and ^{15}N in the soil-plant system under field conditions.

Materials and Methods

Field Experiment

A long-term field study was initiated in 1980 on a Waukegan silt loam soil (Fine-silt over sandy or sandy-skeletal, mixed, superactive mesic Typic Hapludolls) at the University of Minnesota Research and Outreach Center, Rosemount, Minnesota, USA. The soil was formed from silt loam loess (50–80 cm thick), overlying neutral to calcareous outwash sand and gravel (at about 100 cm depth) with a uniform slope of less than 1% (Clay and others 1985, Clapp and others 2000). The climate is continental with a subhumid moisture regime, where average annual precipitation ranges from 813 to 864 mm, and average temperatures in January and July are −11 and 22°C, respectively. The number of growing degree-days ranges from 1200 to 1900 for days in which monthly average air temperatures range from 10 to 30°C.

Previous crop and field history prior to 1980 consisted of two years of corn (*Zea mays* L.) in rotation with one year of soybean (*Glycine max* L.), five years of oats (*Avena sativa* L.) interseeded with alfalfa (*Medicago sativa* L.), and most recently 20 years of pasture before this study was established (Clay and others 1989). The initial soil properties for the surface (0–15 cm) soil were as follows: cation exchange capacity of 2.37 cmol (NH_4^+)/kg of soil, clay content of 242 g/kg, silt content of 600 g/kg, pH of 6.5 (0.01 M $CaCl_2$), soil organic C (SOC) of 30 g/kg, and C/N ratio of 10.7 (Clay and others 1985).

The main experiment consisted of four tillage residue (corn stover harvested or returned) treatments. Two tillage treatments, rototill, and no-till, were randomly combined with the two residue managements. The fertilizer treatments for the main plots initiated in the spring of 1980 and continued until 1992 were low N (20 kg N/ha) and high N (200 kg N/ha) application rates of $(NH_4)_2SO_4$. The fertilizer was surface applied after planting to each plot (6 × 9 m). The experimental design was a 2 × 2 × 2 factorial randomized split–split plot design with four replications. Experimental design and procedures have been reported previously (Clay and others 1989, Clapp and others 2000, Linden and others 2000).

Subplots or ^{15}N microplots (1 × 3 m) were established in the center of larger plots (6 × 9 m) to study the long-term effect of N fertilizer and residue management on corn yield (Clay and others 1985, 1989). Tillage management of these subplots was different than in the larger plots. Subplots were rototilled annually in the fall with a garden sized rotary tiller at a depth of 7–10 cm. Microplots were fertilized with 0.8 g $^{15}N/m^2$ as $(^{15}NH_4)_2SO_4$ mixed with natural abundance $(NH_4)_2SO_4$ in solution to give values of 40 and 4 excess atom-% ^{15}N for the 2 and 20 g N/m^2 application rates (Clay and others 1985). These rates resulted in the same ^{15}N mass per area being applied to all plots regardless of N fertilization rate. Two residue management treatments, residue harvested (−R) and residue returned (+R) were initiated in October 1980. Residue as stover plus grain was removed from the −R plots after physiologic maturity and weighed. In the residue returned (+R, stover only) treatments, all stover was removed, weighed, chopped, and returned to the soil surface of ^{15}N microplots before fall tillage. Aboveground dry matter yield for the microplots was measured annually after physiologic maturity near the end of September. An average of 670 g/m^2 of residue dry matter was returned to the top 15 cm of soil in each microplot. Detailed procedures and measurements have been reported previously (Clay and others 1992, Linden and others 2000). Total N and ^{15}N uptake in the aboveground biomass for each treatment were determined annually.

Soil samples were taken at two depths (0–15 and 15–30 cm) for total C and N, and tracer (^{15}N) annually from 1980 through 1986 and every other year from 1987 to 1992. Tracer N was determined using an elemental analyzer interfaced with an isotope ratio mass spectrometer (Carlo Erba model NA1500 and Fisons model Optima, Middlewich, Cheshire, UK).[1] In 1980, soil samples were taken at four depths (0–15, 15–30, 30–45, and 45–60 cm) during the growing season to monitor NO_3-N movement in the soil.

Model Description

The model NCSWAP (nitrogen and carbon cycling in soil, water, air and plants) is a simulation model of the soil–water–air–plant continuum that integrates water flow dynamics, temperature, solute transport, crop growth, total and tracer N and C transformations, tillage, and residue effects. NCSWAP is a large model encompassing several submodels including NCSOIL. The NCSOIL model is used as a subroutine to simulate N and C transformations in the soil. The NCSOIL model has been previously described in detail by Molina and others (1983, 1997).

The NCSWAP model also has been previously described in detail by Molina and others (1997, 2001). Briefly, the model uses the crop as a biological integrator of the soil status and managerial and meteorological variables. A reference crop growth-curve for optimum growth at a given site and year is modified to accommodate N, water, and temperature influences in layers of the soil profile. NCSWAP simulates below- and aboveground photosynthate inputs into the soil profile. The soil conditions, roots, and rhizodeposition are updated daily (if dry) or every 0.2 days during water infiltration and redistribution. The model requires five input files. One file is for initial soil profile conditions, and four files are for annual crop inputs, temperature, precipitation, and management practices. The soil profile is defined as 100-cm deep and consisting of 20 layers, each 5-cm deep. Total nontracer and tracer C and N transformations in SOM are calculated for each layer of the soil profile. Four pools represent the SOM in each layer: pool I is microbial biomass, with two components—labile (I_L), with a half-life of 2 days, and resistant (I_r), with a half-life of 17 days; pool II, which is potentially mineralizable, half-life of 115 days; and pool III, which is recalcitrant. The sum of pools I–III is the SOM, and it corresponds to total organic matter minus residues.

Model Parameterization

Initial conditions such as soil depth, bulk density, texture, hydraulic and thermal soil properties, rooting depth, total C and N content, and C/N ratio were given values obtained from the field site at Rosemount. Monthly mean minimum and maximum temperatures and precipitation for the duration of the study were obtained from the Rosemount weather station. Parameters relevant to biologically driven soil transformation were kept as determined previously for NCSOIL, except for the half-life of pool III, which was calibrated against the experimental data. The root-to-shoot N concentration and exudates-to-root ratio were also calibrated.

Results and Discussions

Model Calibration

Model predictions of N uptake and corn yield were compared with measured values. We found that the model consistently overestimated N percentage in aboveground dry mass for the 2 g $^{15}N/m^2$ treatment, while a reasonable estimate was made for the 20 g

$^{15}N/m^2$ treatment. The initial value for root-to-shoot ratio N concentration was changed from 0.4 to 0.5 to account for this inconsistency. Nitrogen stress decreased shoot growth more than root growth, and root-to-shoot ratios of N concentration were higher in unfertilized crops (Hansson and others 1987, Paustian and others 1992). It also was reported that the highest C use efficiency would occur in the low fertility soil when expressed in units of C translocated belowground per unit of root C (Warembourg and Estelrich 2001). Therefore it is logical to change the root-to-shoot ratios at the low N application rate to account for the difference. The magnitude of simulated treatment difference approached the measured values with this minor change.

The model was more sensitive to the decay rate constant for the recalcitrant organic matter; pool III (CF-III), compared to the other parameters. Increasing CF-III values from the default value of 0.000025/day progressively gave better correspondence between measured and simulated output values. The best-fit value for initial CF-III was 0.0001/day (half-life ≈ 27 years). This increase in the decay rate corresponds to a stimulation of mineralization of soil N with the addition of N fertilizer. This is called a priming effect or added nitrogen interaction (Westerman and Kurtz 1973, Jenkinson and others 1985, Gregorich and others 1996). The proportion of active and slow SOM fractions relative to the passive pool will change because of more rapid turnover rates.

Measured and Simulated Aboveground Biomass

The model accurately predicted the measured cumulative aboveground dry mass over the 12 years for the high and low N rates (Figure 1A). There was no difference in dry matter yield between the two fertilizer rates for the first 5 years when the corn residues were returned (+R). For the first five years, the measured cumulative aboveground dry mass was 7.4 and 7.9 Mg/ha for the low and high fertilizer rates, when simulated it was 7.6 and 7.8 Mg/ha. This was due to the high soil fertility and previous field history of 20 years of pasture and alfalfa production on these plots. Previous management practices supported higher SOM and soil N levels. Crop residue management is known to influence N utilization from crop residue, SOM, and applied fertilizer N (Power and Doran 1988).

When residues were harvested (−R), differences in dry matter due to fertilizer rates were observed one year earlier (Figure 1B). For the first five years, the measured cumulative aboveground dry mass was 7.1 and 7.9 Mg/ha for the low and high fertilizer rates, while simulated values were 7.2 and 7.8 Mg/ha. This could be due to decreased SOM and depletion of N in the soil profile at the low N (20 kg N/ha) application rate. Larson and others (1972) estimated 6 Mg/ha/yr corn residue was required to increase or prevent loss of organic C and N from a conventionally (moldboard-plowed) tilled continuous corn on a silty clay loam.

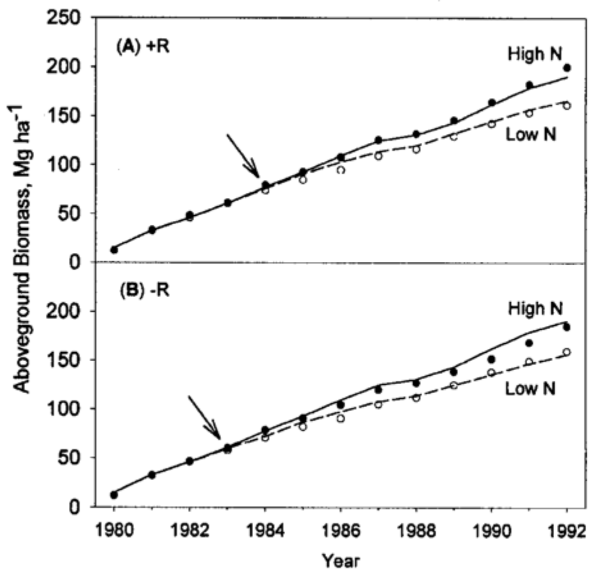

Figure 1. Measured (●, ○) and simulated (—, --) cumulative aboveground dry biomass for the high (200 kg N/ha) and low (20 kg N/ha) fertilizer application rates. The arrow indicates occurrence of differences in biomass related to N rate: (A) residue returned, +R; (B) residue harvested, −R.

Measured and Simulated ^{15}N Concentration in Plant

Aboveground excess ^{15}N atom-% at the two N rates is illustrated in Figure 2. Measured ^{15}N concentration in the aboveground dry matter corresponded well with the predicted value for high N rate and residue returned treatments with maximum difference of 0.4 ^{15}N excess atom-% between measured and simulated in 1984 (Figure 2A). At the low fertilizer rate; however, the simulation underestimated the measured ^{15}N concentration in the corn for 1983, 1984, 1985, and 1991, with maximum difference of 1.2 ^{15}N excess atom-% between measured and simulated values in 1983 (Figure 2B). This could be attributed to the inability of the NCSWAP/NCSOIL model to fully address the potential contribution of previous field history and management practices to N supplying power of the soil and interaction with growing corn plants. Sanchez and others (2002) reported that living corn roots increased the N-supplying capacity of the soil by more than 50%. They suggested that the increased N-supplying capacity was caused by an increase in net mineralization.

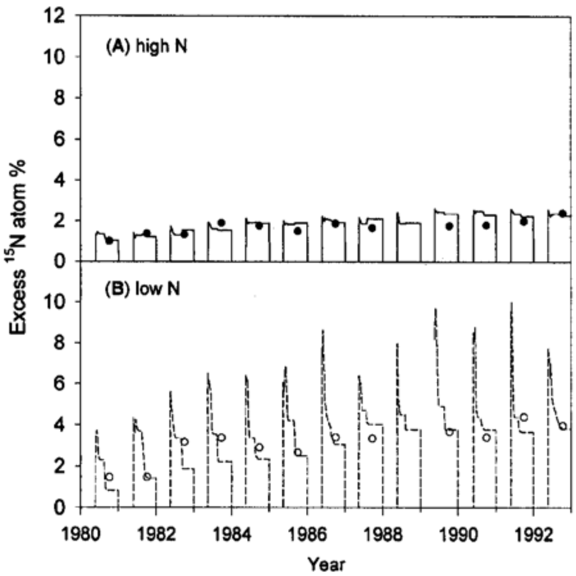

Figure 2. Measured (●, ○) and simulated (—, –) aboveground biomass ^{15}N concentration when residue was returned (+R): (A) high (200 kg N/ha), (B) low (20 kg N/ha) fertilizer application rate.

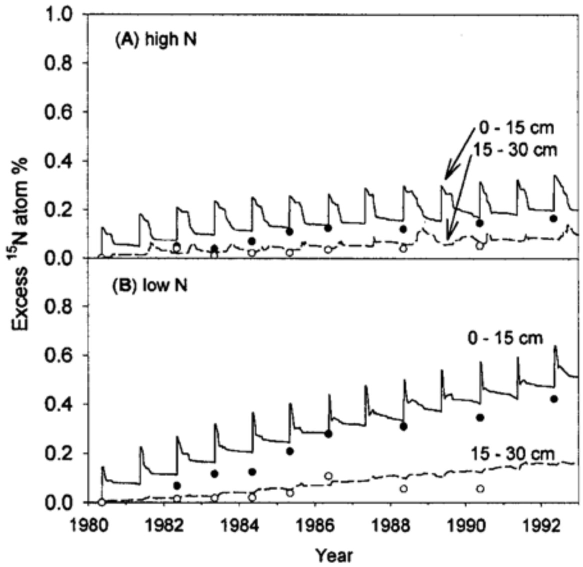

Figure 3. Measured (●, ○) and simulated (—, –) soil organic matter (pool I, pool II, pool III, with residues removed during sieving) ^{15}N concentration when residue was returned (+R) at two depths. (A) high (200 kg N/ha), (B) low (20 kg N/ha) fertilizer application rate.

Although the same amounts of ^{15}N (8 kg ^{15}N/ha) were added to both N treatments, the measured ^{15}N concentrations were higher in the plants with low N (ca. 4.0 excess ^{15}N atom-%) compared to the high N (ca. 2.0 excess ^{15}N atom-%) application rates, this difference was also simulated by the NCSWAP/NCSOIL model as shown by higher ^{15}N in the plants with low N. Greater dilution of the ^{15}N with nontracer fertilizer added at the higher fertilizer rate was responsible for differences in ^{15}N concentrations in the plant. There is a slight discrimination against ^{15}N relative to ^{14}N in biological transformation, which results in a slightly higher ^{15}N uptake and higher ^{15}N content of the organic matter (Broadbent and others 1980). Increased N uptake due to higher ^{14}N application would be expected to increase aboveground plant growth. Several ^{15}N studies have also shown a positive relationship between the amount of soil N uptake and rate of applied ^{15}N (Campbell and Paul 1978, Porter and others 1996).

Measured and Simulated ^{15}N Concentration in Soil

The NCSWAP/NCSOIL model very closely predicted ^{15}N concentration in SOM in the topsoil (0–15-cm) as well as at the 15- to 30-cm depth for the two fertilizer rates (Figure 3). Furthermore, the measured ^{15}N concentrations were higher in the soil with low N (ca. 0.4 excess ^{15}N atom-%) compared to the high N (ca. 0.2 excess ^{15}N atom-%) application rates, this difference was also simulated by the NCSWAP/NCSOIL model as shown by higher ^{15}N in the soil with low N. The data showed that inorganic N can be incorporated into organic forms in a short time period, provided that sufficient C is available. This is driven in the model by the low half-life of pool I, labile and resistant, and is consistent with the finding of Chichester and others (1975) that inorganic N can be converted to relatively stable organic forms in a very short time, if sufficient C is available. Jensen (1994) also found that two thirds of the biomass N increase was derived from the ^{15}N labeled residue in the first 10 days of a laboratory experiment. Since newly immobilized N constitutes a relatively labile pool of organic N, preferential mineralization of the recently immobilized N could have increased ^{15}N enrichment of the inorganic pool (Kelley and Stevenson 1987, Qian and others 1997).

We could not measure specific crop effects on N reaction, but growing crops perhaps accelerated tracer N incorporation into SOM (Broadbent and others 1980), a feature rendered in the model by the large amount of root exudation. Legg and others (1971) reported that the availability ratio of tracer N to total N declined from an initial value of 10.4 to about 2 after 11 years of continuous cropping. They also indicated that the incorporated ^{15}N in stable organic forms was consistently twice as bioavailable as the indigenous soil N,

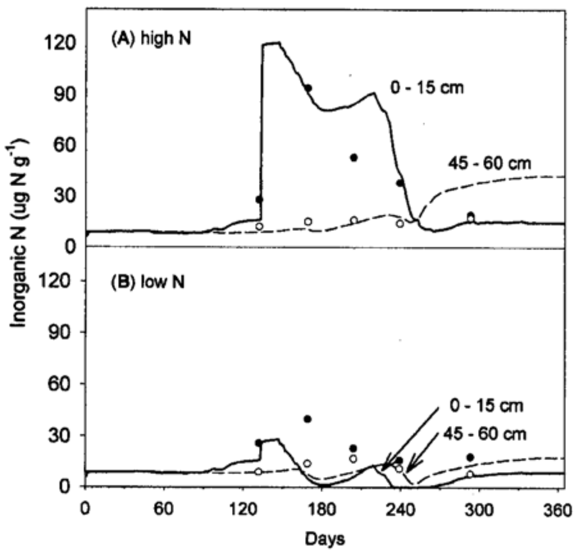

Figure 4. Measured (●, ○) and simulated (—, –) inorganic N concentration at two depths in 1980, when residue was harvested (−R): (A) high (200 kg N/ha), (B) low (20 kg N/ha) fertilizer application rate.

which is consistent with the hypothesis that about half of the indigenous N is biologically unavailable and inactive due to organomineral complexes in microaggregates that are inaccessible to microorganisms.

Measured and Simulated Inorganic N Concentration

In 1980, soil NO_3-N movement was monitored at several depths throughout the growing season. The simulated soil NO_3-N corresponded well with the measured values for the high N application rate except for an overestimation in the middle of July (about 200 days) in the topsoil and deeper in the profile at the end of the growing season (Figure 4A). More leaching than the model predicted must have occurred farther down in the profile. Jensen (1994) reported finding significant amounts of both organic and inorganic ^{15}N in the 10- to 45-cm depth as well as below the 45-cm depth.

Measured soil NO_3-N was higher than the simulated value in the topsoil for the low N application rate (Figure 4B), which is consistent with the Campbell and Paul (1978) finding that at low N rates (82 kg/ha) most of the applied N was in the top 30 cm of the soil, while at higher rates 50% of residual N had leached to the 30- to 60-cm depth. Underestimation of the actual value could be explained by inability of the NCSWAP/NCSOIL to integrate potential contribution of previous crop (alfalfa) to soil N level and high mineralization rate due to previous field history. Correction for this deficiency would require estimation of and introduction into the model of the amount of residual crop material in the soil profile at the time zero of simulation.

Simulated Daily Inorganic N Losses

On a daily basis, simulated N losses due to leaching and denitrification for the high N rate were higher than for the low N application rate (Figure 5). A lower denitrification rate at the low N level than at high N level treatments is expected due to a limited supply of NH_4^+ and NO_3^-, especially when residue is harvested. The return of residue decreased NO_3^- leaching, but increased denitrification, especially in the high N treatment. The smaller supply of available C limits denitrification in treatments with residue harvested, which is consistent with findings of Myrold and Tiedje (1985) and Richards and Webster (1999). Burgess and others (1996) have reported that N availability decreased with addition of crop residues due to increased immobilization. Residue with high C content increases microbial population and N fertilizer immobilization, but new microbial growth utilizes some crop residue N and contributes to the mineralizable N pool (Fribourg and Bartholomew 1956, Power and others 1986).

The model predicted less leaching and more denitrification when residue was returned to these plots compared to when residue was removed (Figure 5). This is comparable to reported research (Power and Doran 1988, Aulakh and others 1991). Power and Doran (1988) indicated that the amount and location of C substrates in the soil are of major importance in providing energy for microorganisms and consequent nitrification and denitrification. The cool and more moist soil environment created by residue return (Power and others 1986) can promote N losses through both leaching and denitrification (Aulakh and others 1991). Burgess and others (1996) also found significantly less NO_3^- in the 10- to 20-cm depth when residues were returned. Leaching of N decreased 30% with pea and 40% with barley when residue was returned (Ambus and others 2001). Furthermore, these authors indicated that N_2O emission increased 1.6 and 6.5 times when alfalfa and wheat residues mixed into the soil, respectively, compared with residue placed in a layer.

Simulated Cumulative Inorganic N Dynamics

Changes in daily rates of leaching and denitrification may be small, but these differences are more obvious if shown as cumulative effects over the 12 years. The dynamics of cumulative inorganic N added, lost, immobilized, or mineralized is illustrated in Figure 6. Most of the added N fertilizer (2400 kg N/ha) was lost through leaching in the first six years at the high fer-

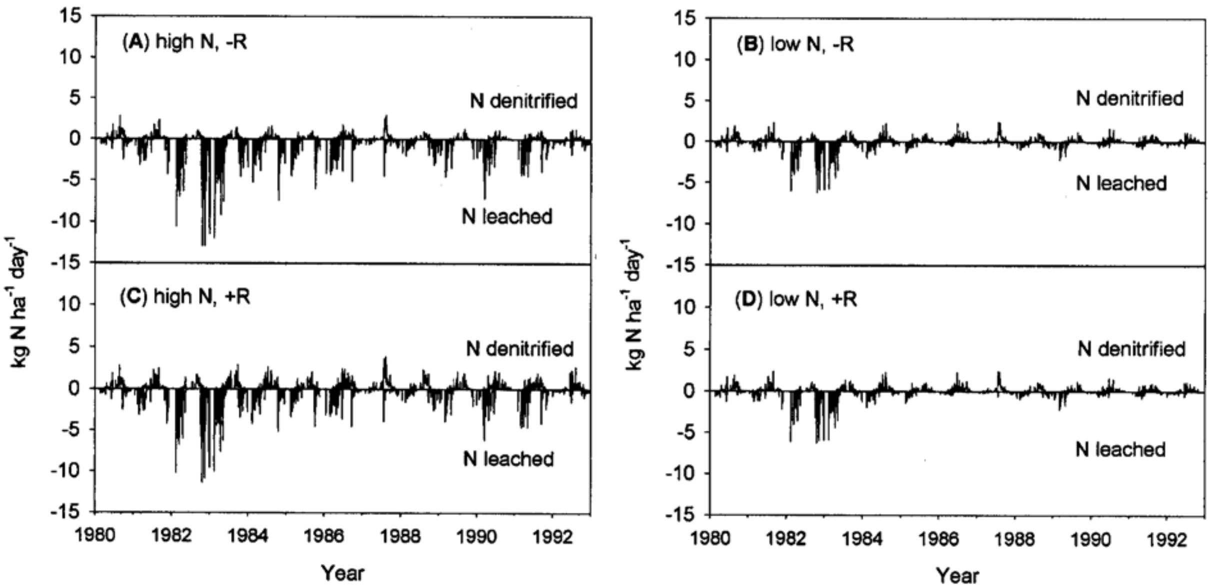

Figure 5. Daily simulated inorganic N leaching and denitrification with either residue harvested (−R) or residue returned (+R) for the (A, C) high (200 kg N/ha) and (B, D) low (20 kg N/ha) fertilizer application rates.

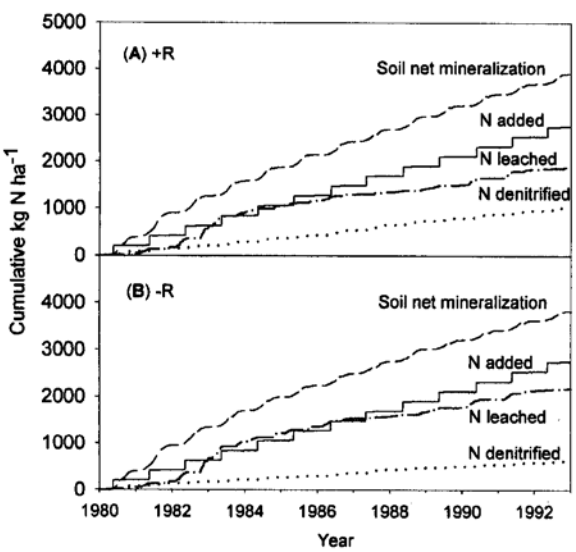

Figure 6. Simulated cumulative inorganic N added, leached, denitrified, or mineralized for the high N (200 kg N/ha) fertilizer application rates: (A) residue returned, +R; (B) residue harvested, −R.

tilizer rate when the residues were returned (Figure 6A). The same pattern was observed for the treatments with residue harvested, but the loss is extended from six to nine years (Figure 6B). Mineralization and immobilization rates increased with increased fertilizer addition, indicating that the higher fertilizer rate contributed to release of soil N and increased N losses in both residue management treatments.

The N dynamics could be explained by a high N mineralization rate in this soil of about 400 kg N/ha at the beginning of the experiment, due to the high fertility of this site and the alfalfa–grass mix plowed under, as discussed earlier this may be a priming effect. It has been observed that the addition of N fertilizer can stimulate mineralization of soil N due to the priming effect (Westerman and Kurtz 1973, Jenkinson and others 1985, Gregorich and others 1996). Power and others (1986) found that mineralization and uptake of indigenous soil N by corn increased from 73 to 124 kg/ha with increased residue rate.

Sensitivity Analysis

Additional simulations were carried out to look at long-term N dynamics under several conditions. A series of simulation runs were carried out at each fertilizer rate and with various amounts of residue returned to examine N dynamics. The amount of residue returned ranged from 0 to 100% (Table 1). Simulated losses indicated less leaching and denitrification at low N than at high N application rates. If the simulated N losses are assumed to be indirectly validated by the ^{15}N kinetics and crop yield, then N balances can be calculated and N losses for 30 years can be estimated.

The simulated cumulative effects of N rates and residue management over the 30 years predicted that

Table 1. Cumulative simulated N leaching and denitrification in the soil profile (100 cm deep) over 30 years

Fertilizer rate	Residue (Mg/ha)	N (kg/ha) Leaching	Denitrification
High (200 kg N/ha)	0	2906	1333
	4.4	2554	2194
	6.7	2456	2574
Low (20 kg N/ha)	0	1035	1320
	4.4	981	1539
	6.7	948	1705

[1] Mention of a specific proprietary product does not constitute a recommendation by the US Department of Agriculture and does not imply approval to the exclusion of other suitable products.

about 2900 kg N/ha (of a total of 6000 kg N/ha added) would be lost due to leaching, if the same management practices were continued, for this high fertility site at the high N rate and residue harvested. The simulated cumulative N losses due to denitrification would be 1333 kg N/ha. The predicted N leaching decreased from about 2900 kg N/ha to 2550 kg N/ha when 66% (ca. 4.4 Mg/ha) of the residue is returned. The corresponding predicted denitrification loss increased from 1333 to 2194 kg N/ha with an annual loss of about 29 kg N/ha at the high N application rate, which exceeds N loss due to leaching.

The predicted N losses due to leaching and denitrification were about 2450 and 2570 kg N/ha, respectively, at 100% (ca. 6.7 Mg/ha) residue returned and high N rate. Residue return decreased leaching but increased denitrification. This is consistent with the finding of other researchers that NO_3^- leaching decreased when residues were returned (Burgess and others 1996, Ambus and others 2001). Residue return created a cool and moist soil environment that promoted N losses through denitrification.

Over the 30 years of the low N application rate, the simulated cumulative effects of a total of 600 kg N/ha added indicate that some of the soil N will be mineralized due to plant uptake demand. When the residue was harvested, the predicted N leaching was about 1000 kg N/ha. This is about 400 kg N/ha above the total N added during the 30 years (20 kg N/ha/yr). Additional processes leading to increased N mineralization due to N fertilization are suggested. Contribution to the mineralizable N pool can occur as a result of the priming effect of indigenous soil N (Fribourg and Bartholomew 1956, Power and others 1986). The NCSWAP/NCSOIL model addressed the positive effects of N supply on N mineralization by higher level of SOM synthesized from increased level of root exudates.

Summary and Conclusions

Measured and simulated data were compared for ^{15}N uptake, ^{15}N in SOM, corn yield, and NO_3-N in soil. Differences due to treatments (residue and N rate) were found in yield, tracer N uptake, and in SOM. There was no difference in dry matter yield between the two fertilizer rates for the first five years when the corn residues were returned. This was due to high soil fertility and previous field history. When residues were harvested, differences in dry matter due to fertilizer rates were observed one year earlier. Measured ^{15}N concentration in the aboveground dry matter corresponded very well with predicted values for high N rate and residue returned treatments. At the low fertilizer rate, however, the simulation underestimated the measured ^{15}N concentration in the corn. The lower simulated N uptake compared to measured values was attributed to the inability of the NCSWAP/NCSOIL model to fully address the potential contribution of previous field history and management practices that supported higher SOM and N levels. To account for the site's history of high N and earlier management practices, the root-to-shoot ratio N concentration of the model was changed from 0.4 to 0.5, and the decomposition rate constant for organic matter (pool III) was optimized to 0.0001/day. The magnitude of simulated treatment difference became closer to the measured values with the changes. All other parameters in the NCSWAP/NCSOIL model were left unchanged.

The model closely predicted ^{15}N in the SOM at the 0- to 15-cm and 15- to 30-cm depth for both fertilizer rate and residue management. The simulation model provided a powerful tool for more specific evaluation of measured data. Mineralization, immobilization, and N leaching were simulated for the two fertilizer rates at several rates of residue returned. The predicted cumulative N loss during the 30-year simulation indicates more NO_3^- leaching to below 1 m depth for residue harvested than residue returned treatments, while higher denitrification rates were predicted for the residue returned than residue removed. The results from this simulation should not be extrapolated to the field with different management history or under different climatic condition. Nevertheless, the simulation emphasizes the importance of N fertilizer application rates and residue management on N losses.

Reduction in terrestrial greenhouse gases requires close examination of the amount of residue returned to maintain the SOM level and reduce nitrate leaching and denitrification. The increased potential for immobilization and denitrification of surface applied fertilizer with corn residue returned is a challenge to more efficient N fertilizer and indigenous N utilization. This study suggests that better synchronization of N release from the residue and addition of N fertilizer with plant N uptake can minimize leaching and denitrification.

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