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Nitrogen leaching and soil nitrate, nitrite, and ammonium levels under irrigated wheat in Northern Mexico

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Abstract

Nitrate (NO_3^{-1}) leaching from agricultural soils can represent a substantial loss of fertilizer nitrogen (N), but a large variation in losses has been reported. We report N leaching losses under four N fertilizer treatments and two farmer's fields in the Yaqui Valley, Mexico. In these irrigated wheat systems, farmers typically apply 250 kg N ha^{-1} as anhydrous ammonia (knifed in) or urea (broadcast), with 75% applied directly before planting and 25% at the time of the first post-planting irrigation. Over two wheat seasons, we compared typical farmer's practices to alternatives that applied less N and more closely timed fertilizer application to plant demand. Field lysimeter measurements and predictions from a water transport simulation model (called NLOSS) were used to estimate the amount of N leached over the season. Approximately 5 and 2% of the applied N leached below the root zone with the typical farmer's practice in 1995–96 and 1997–98, respectively. The alternative treatments reduced N leaching losses by 60 to 95% while producing comparable economic returns to the farmer. Leaching losses from the two farmer's fields were substantially higher (about 14 and 26% of the applied N). Our results indicate that the typical farmer's practice leads to relatively high N leaching losses, and that alternative practices synchronizing fertilizer application with crop demand can substantially reduce these losses.

Nomenclature

b	slope of the water retention curve (9.5)
C_N	concentration at lysimeter depth (kg N m^{-3})
E	evaporation or root water withdrawal (kg water m^{-3} soil s^{-1})
e_a	saturation vapor pressure (kPa)
e_d	actual vapor pressure (kPa)
F_w	soil water flux (kg m^{-2} s^{-1})
G	ground heat flux (W m^{-2})
K	hydraulic conductivity (m s^{-1})
K_s	saturated hydraulic conductivity (2.5×10^{-6} m s^{-1})
k_c	reduction factor (−)
L	actual evapotranspiration (W m^{-2})
L_0	potential evapotranspiration (W m^{-2})
Q_N	NO_3^- leaching rate (kg N m^{-2} s^{-1})
Q_w	volumetric water flow rate at the lysimeter depth (m s^{-1})
R_n	net radiation (W m^{-2})
t	time (s)
U	wind speed at 2 m (m s^{-1})
z	depth into the soil (m)

Greek symbols

Δ slope of the saturation vapor pressure curve (kPa °C^{-1})
γ psychrometric constant (0.0656 kPa °C^{-1})
ρ_w water density (1000 kg m^{-3})
θ volumetric water content (m^3 water m^{-3} soil)
θ_s structural pore space (m^3 m^{-3} soil)
ψ soil moisture potential (m)
ψ_s saturated moisture potential (0.0616 m)
Note: (−) indicates a non-dimensional variable

Introduction

Nitrogen (N) fertilizer production and leguminous crops fix more N globally than do all natural terrestrial ecosystems (Vitousek et al. 1997; Vitousek and Matson 1993). Currently, global application of N fertilizer is about equally distributed between developed and developing countries. Galloway et al. (1995) estimate that global N fertilizer production will increase 60–90% by the year 2025, and two-thirds of the total will be applied in the developing world. If efficiency of fertilizer use is not increased, these N fertilizer applications will result in increased N losses as leachate to freshwater and marine systems and as trace gases important in tropospheric and stratospheric chemistry and global climate.

Understanding N leaching from fertilized agriculture is important for several reasons. First, the largest components of N leachate, nitrate (NO_3^-) and nitrite (NO_2^-), can impact human (Mansouri and Lurie 1993; NRC 1978) and ruminant (Lewis 1951) health. Second, enhanced N loading can alter nutrient balances and ecological processes in rivers, lakes, and estuaries, potentially leading to eutrophication (NRC 1978), net phytoplankton productivity, and increased bottom water hypoxy (Justic et al. 1995; Rabalais et al. 1996). Third, N leaching can represent a significant economic loss to the farmer. Finally, predicting other environmental impacts of agriculture (i.e., N trace-gas effluxes) requires an understanding of the factors which control soil N levels.

Fertilization is the largest direct cost in Yaqui Valley farm budgets (Matson et al. 1998). Thus, N leaching losses can represent significant costs to farmers. Several studies of alternative management strategies designed to maintain crop yield and return on investment while reducing N losses have been performed in temperate regions using developed-world agricultural practices (Martin et al. 1994; Moreno et al. 1996). Reviews addressing a range of N leaching issues have also been prepared for developed and temperate agricultural regions (Addiscott et al. 1991; Follett 1989; Ritter 1989). However, less information is available for tropical, subtropical, and developing world agricultural systems.

In this study, we report on seasonal inorganic N leaching losses in irrigated wheat systems in the Yaqui Valley of northwestern Mexico. Specifically, we estimate N leaching losses in four experimental treatments (two treatments in each of two seasons) and two farmer's fields (in one season) by combining lysimeter measurements with a simulation model of water transport. This work is part of a broader investigation of N trace-gas emissions, soil N cycling, N leaching losses, crop yield and grain quality, and the economic impacts of alternative management strategies in the region. In the broader context of this project, we hope to recommend alternative management practices that will reduce both N leaching losses and trace-gas emissions, while maintaining crop quality and yield.

Materials and methods

Experimental site

Our field experiments were conducted in the Yaqui Valley near Ciudad Obregon, Sonora, Mexico (27 °N 109′W, 40 masl). The soils in the valley are coarse sandy clay mixed with montmorillonitic clay, and are classified as Typic Calcicorthid (Table 1).

Four main crop rotations occur in the Yaqui Valley: cotton–wheat (16 month rotation), summer maize–

Table 1. Soil characteristics of the study area for FP9596 and ALT9596

Soil depth (cm)	0–15	15–30	30–60	60–90
Organic matter (g kg^{-1})	8.3	5.7	3.6	1.7
Total N (g kg^{-1})	0.52	0.40	0.27	0.18
pH 1:2 H_2O	8.3	8.3	7.9	7.9
Clay (%)	43.7	44.7	45.9	44.6
Silt (%)	22.5	22.7	25.3	27.0
Sand (%)	33.9	32.6	28.7	28.4

wheat (12 month rotation), fall maize–wheat (16 month rotation), and wheat–wheat (20 month rotation). Of these, wheat covers a large majority of the production land and is therefore the focus of this study. Currently, the average N fertilizer application rate is about 250 kg ha^{-1} per wheat crop cycle, with the most common practice being broadcast application of urea or injection of anhydrous ammonia, followed by irrigation. The first fertilization and irrigation occur about three weeks before planting, and the second fertilization and irrigation occur about five weeks after planting. Note that the high soil pH in these sites may contribute to relatively large losses of ammonia (not measured) from the applied fertilizer.

The experimental area was planted with bread wheat (Triticum aestivum L. cultivar ‘Rayon F89’) following a soybean rotation (Glycine max (L.) Merr) in the 1995–96 season, and after a rotation with unfertilized maize (Zea mays (L.)) in the 1997–98 season. Following the summer crop harvest, the field was plowed, disked twice, and then leveled. All plots received 20 kg P ha^{-1} as triple superphosphate, incorporated with the formation of 75 cm beds. The wheat was planted in two rows 20 cm apart on top of the bed at the rate of 100 kg ha^{-1}.

In 1995–96, treatments included 1) the typical farmer’s practice, hereafter referred to as FP9596 (250 kg N ha^{-1}, with 75% applied three weeks before planting and 25% five weeks following planting); 2) an alternative, referred to as ALT9596 (250 kg N ha^{-1}, with 33% applied at planting and 67% five weeks following planting); and 3) a second alternative and control treatments that were not used in this leaching study. Unfortunately, in the 1995–96 season, 125 kg N ha^{-1} was mistakenly applied in the second fertilization in FP9596, instead of the desired 62.5 kg N ha^{-1}. Lysimeters were installed in the first two treatments, so our leaching estimates for the 1995–96 season are from FP9596 and ALT9596.

In the 1997–98 season, FP9798 mimicked the typical farmer’s practice described above, and an alternative (ALT9798) applied 180 kg N ha^{-1}, with 33% applied at planting and 67% five weeks following planting.

The treatments were arranged in a randomized complete block design with four replications. Each experimental unit was 22×27 m. The experimental plots at the field station were furrow irrigated following the method and schedule used by most farmers in the area. Weeds were controlled by cultivation and thorough hand weeding to maintain the experimental area weed free. Rain is sparse during this season; a total of 6.1 and 20.1 mm fell in the 1995–96 and 1996–97 seasons, respectively.

We also installed and monitored lysimeters in two farmer’s fields during the 1995–96 season. Fields 810 and 910 were located approximately 75 m and 1.5 km from the experimental site described above, respectively. Soil conditions and properties (Table 2) at the two farmer’s fields were similar to those at the research station. The farmer’s fields differed from the experimental treatments primarily in irrigation and fertilizer management and distance from the lysimeters to the irrigation water entry point. Lysimeters were located 30, 150, and 75 m from the irrigation water entry point at the experimental site, field 810, and field 910, respectively.

The timing and amounts of fertilizer and irrigation water applied in the four experimental treatments (FP9596, ALT9596, FP9798, and ALT 9798) and the two farmer’s fields are shown in Table 3. Urea applied prior to planting was incorporated with bed formation; urea applied after planting was added with irrigation water. Anhydrous ammonia was combined with irrigation water entering the field. In the experimental treatments, there were six irrigations during the 1995–96 season, and five irrigations in 1997–98. All else being equal, a reduction in the soil water flux will reduce the amount of N leached. Radiation and ground heat flux measurements were collected at a

Table 2. Soil characteristics of the study area for the farmers' fields 810 and 910

	Farmer's field 810				Farmer's field 910			
Soil depth (cm)	0–15	15–30	30–60	60–90	0–15	15–30	30–60	60–90
Organic matter (g kg^{-1})	12.4	6.6	4.4	0.4	9.5	9.2	4.0	3.4
Total N (g kg^{-1})	0.77	0.57	0.34	0.26	0.68	0.63	0.40	0.32
pH 1:2 H_2O	8.0	7.8	8.0	8.1	8.3	8.4	7.8	8.0
Clay (%)	47.5	46.8	47.5	45	40.7	42.4	40.5	41.2
Silt (%)	22.5	16.9	25	28.7	17.2	20.1	23.2	17.5
Sand (%)	30	36.3	27.5	26.3	42.1	37.5	36.3	41.3

meteorological station managed by the ITSON (Instituto Tecnologico de Sonora), which was located less than 2 km from the experimental area.

Soil profile measurements

During the 1995–96 season, soil samples were collected, for each sampling date and replicate, at 0–15, 15–30, 30–60, and 60–90 cm depth intervals with a soil auger. Fresh soil samples were sieved and mixed. Ten g subsamples were placed in 100 ml 2N KCl, shaken for 1 min, and allowed to equilibrate for 18–24 h (Matson et al. 1996). Supernatant was removed and stored at 4 °C until analysis. NH_4^+-N and NO_3^--N

Table 3. Irrigation, fertilization, and planting information for the four experimental treatments and two farmer's fields in the 1995–96 and 1997–98 growing seasons

Description	Irrigation dates	Irrigation amount (m)	Fertilization dates	Fertilizer applied (kg N ha^{-1})	Planting date
FP9596:	11/6/95	0.10	11/3/95	187.5 Urea	11/23/95
Experimental	1/3/96	0.08	1/3/96	125 NH_3	
field–Typical	1/29/96	0.08			
farmer's	2/19/96	0.08			
practice	3/7/96	0.08			
	3/22/96	0.08			
ALT9596:	11/6/95	0.10	11/23/95	82.5 Urea	11/23/95
Experimental	1/2/96	0.08	1/2/96	167.5 Urea	
field–	1/29/96	0.08			
Alternative	2/19/96	0.08			
practice	3/7/96	0.08			
	3/22/96	0.08			
Farmer's field (810)	11/10/95	0.10	11/8/95	161 Urea	12/1/95
	1/4/96	0.08	1/4/96	52 NH_3	
	1/26/96	0.08			
	1/19/96	0.08			
	3/4/96	0.08			
	3/17/96	0.08			
Farmer's field (910)	11/30/95	0.10	11/13/95	191 Urea	12/18/95
	2/2/96	0.08			
	3/1/96	0.08			
	4/9/96	0.08			
	4/25/96	0.08			
FP9798:	11/19/97	0.10	11/18/97	187.5 Urea	12/10/97
Experimental	1/28/98	0.08	1/28/98	62.5 Urea	
field–Typical	2/25/98	0.08			
farmer's	3/19/98	0.08			
practice	4/4/98	0.08			
ALT9798:	11/19/97	0.10	12/10/97	60 Urea	12/10/97
Experimental	1/28/98	0.08	1/28/98	120 Urea	
field–	2/25/98	0.08			
Alternative	3/19/98	0.08			
practice	4/4/98	0.08			

in the supernatant was measured colorimetrically using a Lachat autoanalysis system (Zellweger Analytics, Milwaukee, WI). Unfortunately, the temporal resolution of the soil profile measurements is insufficient to estimate leaching losses. Therefore, soil water samples for the leaching calculations were collected from lysimeters, as described below.

Moisture content was determined by weighing field moist samples before and after oven drying at 105 °C for 48 h. 100 cm^3 soil samples were collected at each depth and bulk density was determined (Blake and Hartge 1986; Vomocil 1965). Water-filled pore space (hereafter WFPS, calculated as the percent of pore volume occupied by water) was calculated using bulk density, gravimetric moisture, and particle density.

After the crop was harvested, soil samples were collected with a soil corer and the large roots were removed by hand from each of the soil cores. To remove the fine roots the soil samples were placed in a hydro-pneumatic elutriation device (Smucker et al. 1982). The coarse and fine roots were dried at 75 °C for 48 h and the weight was recorded. The relative root density profile was used to estimate the depth from which transpired water is removed from the soil.

Lysimeter N measurements

Soil water samples used for the leaching calculations were collected from lysimeters; in these experiments we used 21 mm O.D. Prenart Super Quartz (PSQ) samplers. In September, 1995, three PSQ's were installed in each experimental unit 5 m from the outer plot edge. A trench about 60 cm wide and 60 cm deep was dug in the shape of a cross, measuring 5 m long and 2 m wide. This geometry insured that sampling components of the PSQ lying within the plot were out of reach of the conventional tillage operations. The PSQ's were oriented to form the three top points of the cross. The three vertical walls of the trench where the PSQ's were installed were carefully leveled so that the faces were perpendicular to the soil surface. Using a soil auger, a hole 15 cm deep was made at a 45 ° angle at the vertices between the floor of the trench and the vertical wall. The soil removed from the hole was placed on a tarp and later replaced in the hole. A well-mixed slurry of 525 g of silica flour and 215 ml of distilled water was then prepared. The PSQ was preconditioned by dipping it into the slurry and applying a negative pressure of 38 mm-Hg for at least 30 s. Using a funnel, the hole was then filled with the slurry, and the PSQ was gently slid to the bottom of the hole with a stiff rod, resulting in a lysimeter depth of about 70 cm. The PSQ's were checked to insure they were maintaining vacuum before the trench was filled. In farmer's fields 810 and 910 the same procedure was followed except that the trenches were 100 cm wide and 90 cm deep, and the lysimeter depth was therefore about 100 cm.

A plastic container was installed outside the plot area to hold the Dionex 2 l plastic bottles used for soil water collection. The sampling bottles had three access points: one to connect to the PSQ through a polyethylene (Tygon) tubing; a second one to connect a B-D 30 cc plastic syringe with a three way valve; and the third to check and set the vacuum in the bottles. The vacuum system was closed by folding over the Tygon tubing upon itself and securing with a binder clip. Sampling bottles were initially set with a vacuum of 38 mm-Hg. The lysimeter water was withdrawn with the syringe and placed in a NASCO Whirl-pak 6 oz. plastic bag for transport to the laboratory; the volume of water collected was also recorded. In the laboratory the water samples were transferred to a plastic tube and stored at 4 °C until analysis. Soil water concentrations of NH_4^+, NO_3^-, and NO_2^- were measured colorimetrically on the Lachat autoanalysis system.

N leaching prediction

We combine measurements of lysimeter $NO_3^- + NO_2^-$ concentrations with numerical simulations of water flow through the soil column to predict the rate that N is leached below the root zone, Q_N (kg N m^{-2} s^{-1}):

$$Q_n = C_N Q_w$$

Here, C_N is the lysimeter $NO_3^- + NO_2^-$ concentration (kg N m^{-3} water) and Q_w is the modeled water flow rate at the lysimeter depth (m s^{-1}). We compute N leaching rates from the time of planting to preclude impacts of previous crop cycles on our estimates. The time required to hydrolyze the urea added in the first fertilization, nitrify the NH_4^+ to NO_3^-, and transport the NO_3^- to the lysimeter depth is much longer than the time over which the first irrigation water flux persists. Therefore, we assume that lysimeter mineral N levels associated with the first irrigation event are from the previous crop, and fluxes after planting result from the current season fertilization. We ran the model with a final irrigation at the end of the season to account for N losses associated with the subsequent crop's first irrigation.

Hydrologic model

We compute Q_w with the hydrology submodel of NLOSS (Nitrogen LOsses in Soil Systems), a model designed to simulate denitrification, nitrification, organic matter decomposition, N mineralization, trace-gas losses, and solute leaching in agricultural systems (Riley and Matson 2000). NLOSS assumes one-dimensional water flow in the soil, and allows for both micropore and crack flow. The micropore water transport is computed as

$$\rho_w \frac{\partial \theta}{\partial t} = \frac{\partial F_w}{\partial z} - E \tag{1}$$

where ρ_w is the density of water (1000 kg m^{-3}), θ is the volumetric water content (m^3 water m^{-3} soil), t is time (s), F is the (positive upward) flux of water in the soil (kg m^{-2} s^{-1}), z is the depth into the soil (m), and E is the rate of water removal via evaporation and root withdrawal (kg water m^{-3} soil s^{-1}). The water flux is calculated as

$$F_w = \rho_w K\left(\frac{\partial \psi}{\partial z} - 1\right) \tag{2}$$

where K is the soil hydraulic conductivity (m s^{-1}) and ψ is the soil moisture potential (m). Both the hydraulic conductivity and moisture potential depend on soil moisture (Clapp and Hornberger 1978):

$$K = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+3} \tag{3}$$

$$\psi = \psi_s\left(\frac{\theta}{\theta_s}\right)^{-b} \tag{4}$$

Here, K_s (2.5×10^{-6} m s^{-1}) is the saturated hydraulic conductivity, ψ_s (0.0616 m) is the saturated moisture potential, θ_s is the structural pore space (m^3 m^{-3} soil), and b (9.5) is the slope of the water retention curve. The boundary conditions for equation (2) are: $F_w(z = 0)$ = rain, irrigation, or standing pool flux; and $F_w(z = 2\ \text{m}) = -\rho_w K_s$.

For this study, with the crops planted in beds, the hydrology submodel averages the properties of the beds with the top 10 cm of the furrows. NLOSS solves the water flow equations iteratively with a fully explicit temporal discretization and a 100 s time step.

Estimating evapotranspiration

We apply the FAO Penman-Monteith technique to estimate the potential evapotranspiration, L_0 (W m^{-2}) (Allen et al. 1994):

$$L_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{37.}{T + 273.} U(e_a - e_d)}{\Delta + \gamma(1 + 0.34U)} \frac{3600.}{2.5 \times 10^6} \tag{5}$$

where R_n is the net radiation (W m^{-2}), G is the ground heat flux (W m^{-2}), Δ is the slope of the saturation vapor pressure curve (kPa °C^{-1}), γ is the psychrometric constant (0.0656 kPa °C^{-1}), U is the wind speed at 2 m (m s^{-1}), and e_a and e_d are the saturation and actual vapor pressures (kPa), respectively.

The fraction of potential evapotranspiration that actually occurs depends on the plant's developmental stage. This effect is often modeled with a reduction factor called the crop coefficient, k_c (−); for the applications described here we use the crop coefficients developed for wheat in the Yaqui Valley (Fischer et al. 1977). Thus, we estimate the actual evapotranspiration, L (W m^{-2}), as

$$L = k_c L_0 \tag{6}$$

We apply the method of Meyer and Green (1981) to reduce the evapotranspiration rate for very dry soils. The resulting evapotranspiration is partitioned into soil evaporation and transpiration by the methods described by Ritchie and Burnett (1971) and Hanks and Ritchie (1991). Finally, transpired water is removed from the soil profile as a function of the measured relative plant rooting density.

Uncertainty analysis

We performed Monte Carlo simulations to estimate the uncertainty in our N leaching predictions resulting from parameter and lysimeter measurement uncertainties. For this analysis we assumed lognormal distributions for, and ignored any covariation between, the hydrologic parameters. A geometric standard deviation of 1.5 was used for the distributions of the saturated hydraulic conductivity, saturated matric potential, and slope of the water retention curve. A normal distribution, based on the standard error of the measurements, was assumed for the lysimeter concentrations. Each Monte Carlo result was computed from 100 individual model simulations. We report predictions of N leached over the season as the mean and standard deviation of these simulation results.

Results and discussion

Hydrologic model

NLOSS accurately predicted the water content in the top soil layer over the course of the 1995–96 wheat season (Figure 1). The WFPS predictions are identical for the FP9596 and ALT9596 treatments, since they were irrigated at the same time and with the same amount of water. Comparable data for comparison to model predictions during the 1997–98 season were unavailable. For figure clarity, the Monte Carlo uncertainty bands are not shown; however, uncertainty in the predicted WFPS resulting from parameter uncertainty ranged between 5 and 15% WFPS. After several weeks following the first irrigation NLOSS predicted the mean WFPS about 7% lower than measured values for the deeper soil layers. This error is relatively small given the spatial heterogeneity of the system, and the fact that the model has not been tuned to the site.

Soil profile mineral N concentrations

Soil NH_4^+ concentrations reflected the fertilizer additions, and the highest concentrations of NH_4^+ occurred with the preplant fertilizer applications (FP9596 and the 810 and 910 farmer's fields). NH_4^+ concentrations during the 1995–96 season in FP9596, ALT9596, and the 810 and 910 farmer's fields are shown in Figure 2.

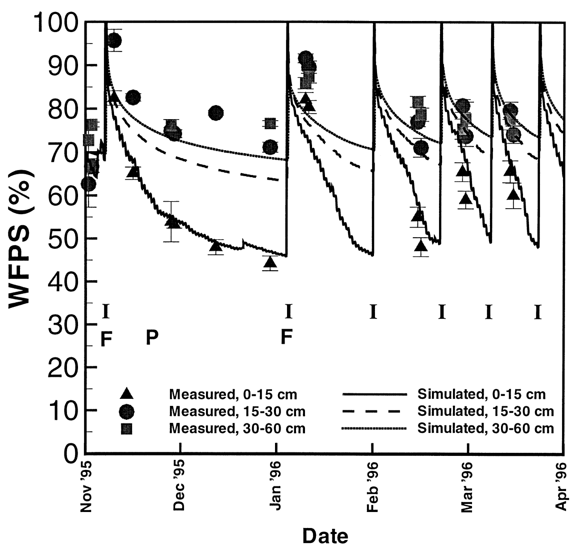

Figure 1. Measured and simulated water-filled pore space (WFPS) at three soil depths over the 1995–96 wheat season. F, I, and P refer to fertilization, irrigation, and planting dates, respectively.

NH_4^+ was rapidly converted to NO_3^- at all sites (Figures 3, 4). Near-surface NO_3^- concentrations remained higher in FP9596 than in ALT9596 for the whole season (Figures 3a, 3b). By the end of the growing season, near-surface soil NO_3^- concentrations were an order of magnitude higher in FP9596 than in ALT9596. Figures 2, 3 and 4 do not include data for the 60–90 cm depth since the mineral N concentrations at this depth were very low.

In FP9596, NO_2^- concentrations in the top 30 cm of soil were comparable to NO_3^- concentrations following the initial fertilization and irrigation (Figure 3). Inhibition of *Nitrobacter* bacteria activity at high pH and ammonia levels probably led to NO_2^- accumulation in the soil profile (Bezdicek et al. 1971; Venterea and Rolston 2000). In contrast, NO_2^- is a very small fraction of $NO_3^- + NO_2^-$ levels in most soils. $NO_3^- + NO_2^-$ concentrations in the 810 and 910 farmer's field are shown in Figure 4.

Lysimeter N solution concentrations

Over the course of the season, FP9596 lysimeter $NO_3^- + NO_2^-$ concentrations increased by an order of magnitude, while lysimeter concentrations in ALT9596 fell by about an order of magnitude (Figure 5). The standard errors of the concentrations in these figures ranged from 10 to 80% of the mean.

N lysimeter concentrations in the 810 and 910 fields were an order of magnitude higher than in the experimental plots; the temporal dynamics also differed from the experimental treatments. In the 810 field, a pulse in lysimeter N concentration occurred about a week after the first fertilization and irrigation, apparently reflecting high N levels at depth as a result of residual N from the previous crop. In the latter half of the season, concentrations in the 810 field were similar to those in the 910 field (Figure 5).

$NO_3^- + NO_2^-$ lysimeter data for FP9798 and ALT9798 during the 1997–98 wheat season are shown in Figure 6. The relatively higher levels of soil N in FP9596 and ALT9596 as compared to FP9798 and ALT9798 probably result from higher residual soil N, as indicated by the crop yield of plots that did not receive N fertilizer (data not included). FP9798 shows a sharp increase in $NO_3^- + NO_2^-$ concentration

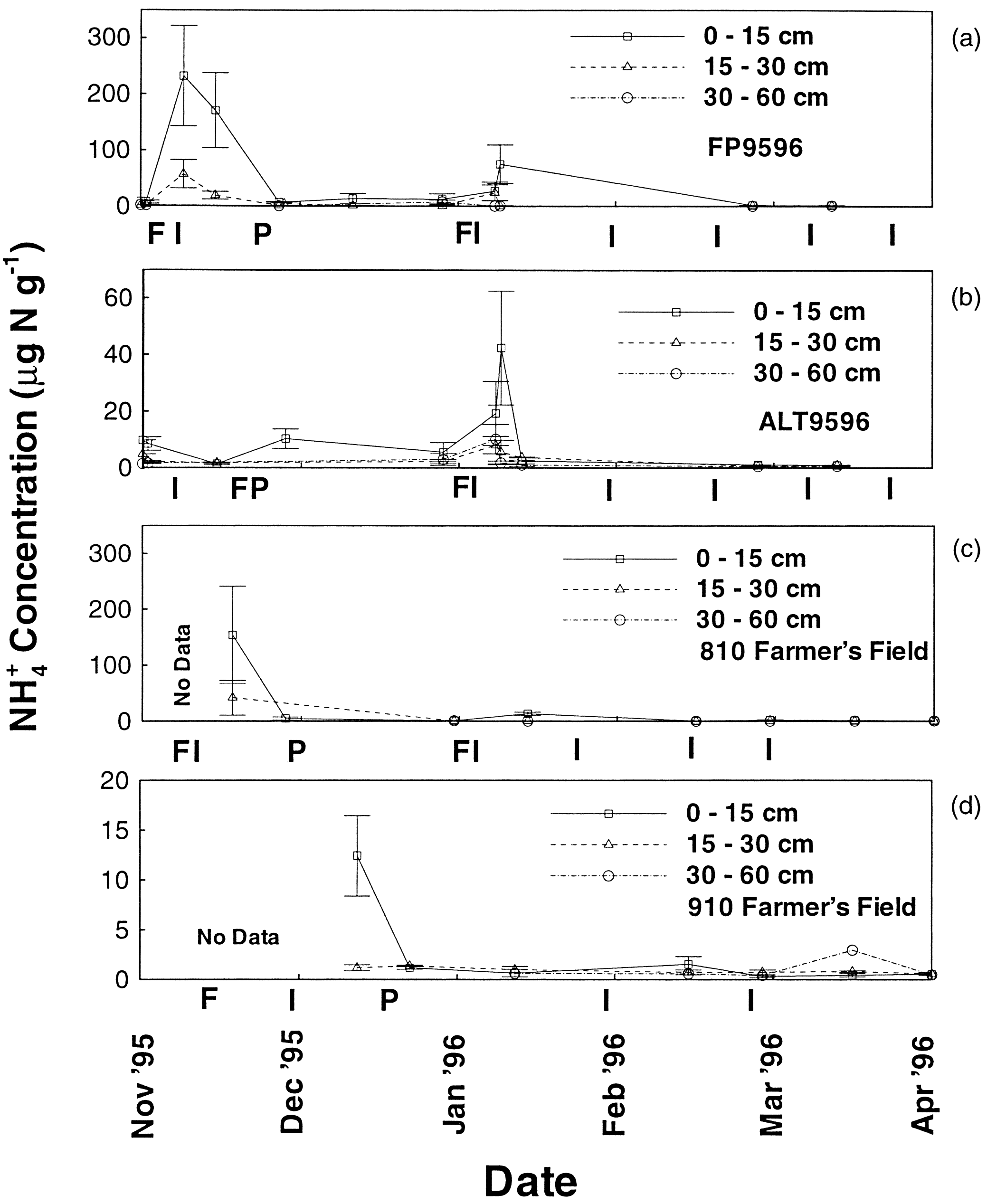

Figure 2. 1995–96 wheat season soil concentrations at 0–15, 15–30, and 30–60 cm depth intervals for the (a) typical farmer's practice (FP9596), (b) alternative practice (ALT9596), and (c) 810 and (d) 910 farmers' fields. F, I, and P refer to fertilization, irrigation, and planting dates, respectively.

towards the end of the season, while concentrations in ALT9798 rose slightly after the fertilization and irrigation events in January, 1998, but then returned to low levels. Over the course of the season, FP9798 $NO_3^- + NO_2^-$ concentrations increased by an order of magnitude and ALT9798 concentrations decreased by an order of magnitude. This relationship existed in the 1995–96 season also, although the intermediate pattern of N concentrations differed between the two seasons.

N leaching rates

As described earlier, NLOSS estimates N leaching

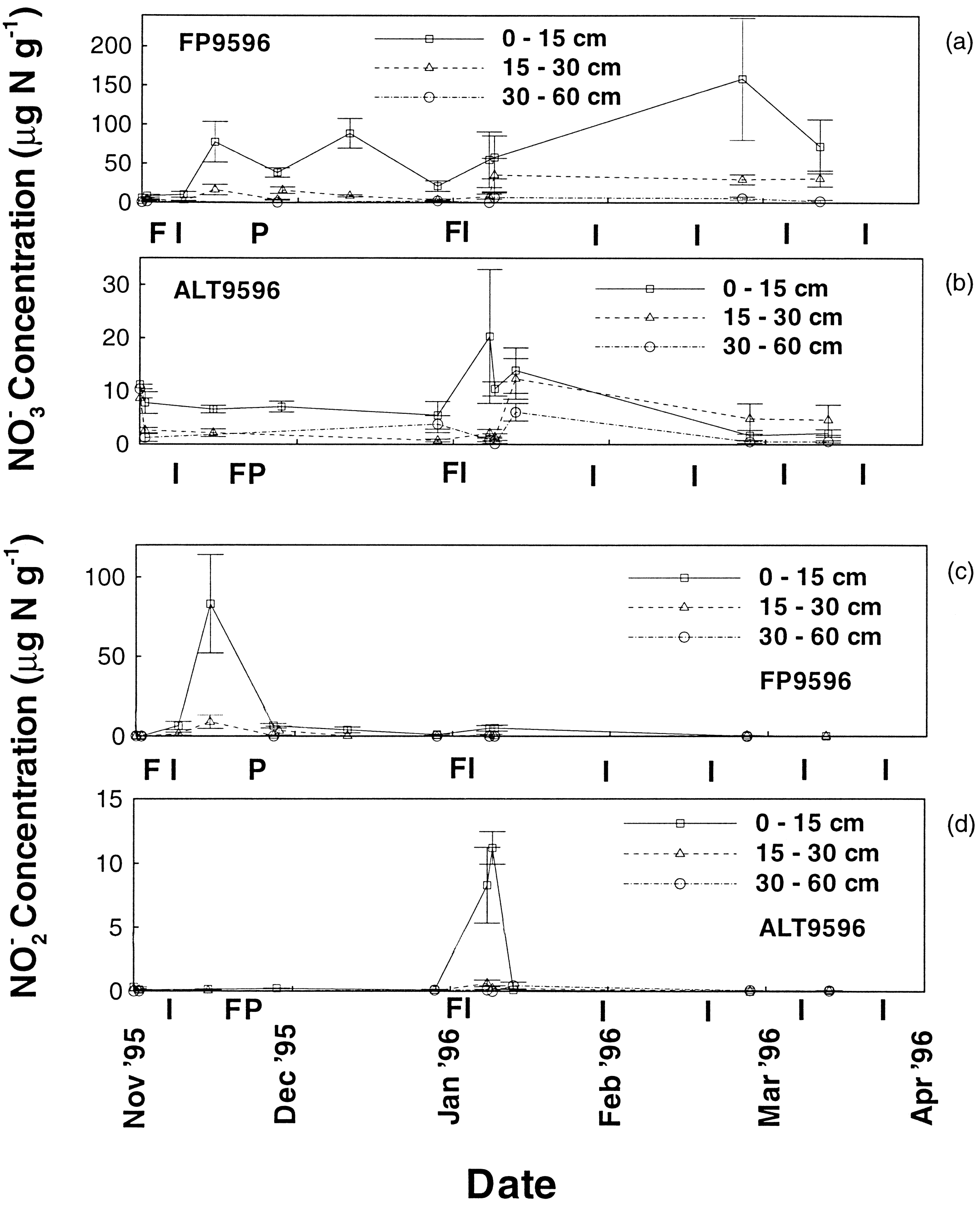

Figure 3. 1995–96 wheat season soil concentrations at 0–15, 15–30, and 30–60 cm depth intervals for the (a) typical farmer's practice (FP9596) and (b) alternative practice (ALT9596), respectively, and concentrations at 0–15 cm and 15–30 cm depths for (c) FP9596 and (d) ALT9596, respectively. F, I, and P refer to fertilization, irrigation, and planting dates, respectively

rates by combining N lysimeter concentrations and predicted soil water fluxes; predictions for the 1995–96 season are shown in Figure 7. Not shown are analogous predictions for FP9798 and ALT9798. The water flux through the profile is identical in FP9596 and ALT9596, so the difference in N leaching rates reflects the difference in lysimeter N concentrations. As described earlier, the fluxes were computed after

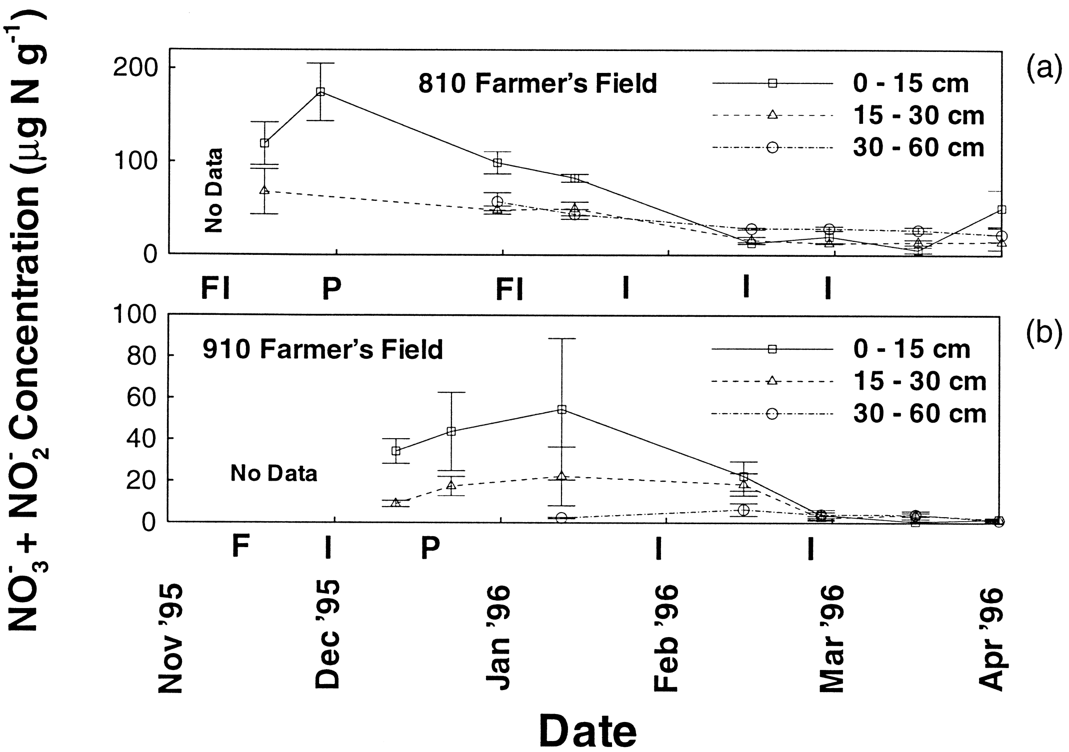

Figure 4. 1995–96 wheat season soil NO_3^- + NO_2^- concentrations at 0–15, 15–30, and 30–60 cm depth intervals for the (a) 810 and (b) 910 farmers' fields, respectively. F, I, and P refer to fertilization, irrigation, and planting dates, respectively.

planting in all four cases. Notice that the majority of leaching occurs within a few days of each irrigation event.

NLOSS predicted that, during the 1995–96 season, 15 ± 3.8 and 6.0 ± 1.6 kg N ha^{-1} (representing about 5 and 2% of the applied N) leached below the root zone in FP9596 and ALT9596, respectively. Thus, ALT9596 reduced the N leaching loss by about 60% compared to FP9596. During the 1997–98 season, 5.2 ± 1.9 and 0.21 ± 0.11 kg N ha^{-1} (representing about 2 and 0.1% of the applied N) leached out of the root zone in FP9798 and ALT9798, respectively. In this season, the alternative treatment reduced N leaching losses by about 95% compared to the typical farmer's practice. For comparison, Moreno et al. (1996), in an irrigated maize crop in Spain, reported seasonal N leaching losses ranging from 0.2 to 10% of the applied N fertilizer. Timmons and Dylla (1981) found seasonal N leaching losses in a corn crop ranging from 0.5 to 33% of the applied N. Summer N leaching losses were between 3 and 8% of the applied N in a sugarcane system in Louisiana (Southwick et al. 1995).

The high initial N levels in the farmer's fields confounds the calculation of leached N for a particular season. These elevated N levels led to significantly higher predicted leaching losses compared to the two experimental treatments. NLOSS predicted that 60 ± 19 and 34 ± 8.5 kg N ha^{-1} (representing about 28 and 17% of the applied N) leached from the 810 and 910 fields, respectively, during the 1995–96 season. These high losses relative to the experimental sites may be attributed to the higher residual N in the farmers' fields. Unmeasured differences in hydrologic characteristics may also have contributed to the differences between the experimental treatments and the farmers' fields.

Summary and conclusions

NLOSS accurately predicted the soil water content over the growing season. Accurate estimates of WFPS are critical because WFPS strongly influences microbial processes, such as nitrification and denitrification, responsible for the conversion of NH_4^+ to NO_3^- and for the production of the trace gases NO and N_2O.

Using NLOSS, we estimate that, during the 1995–

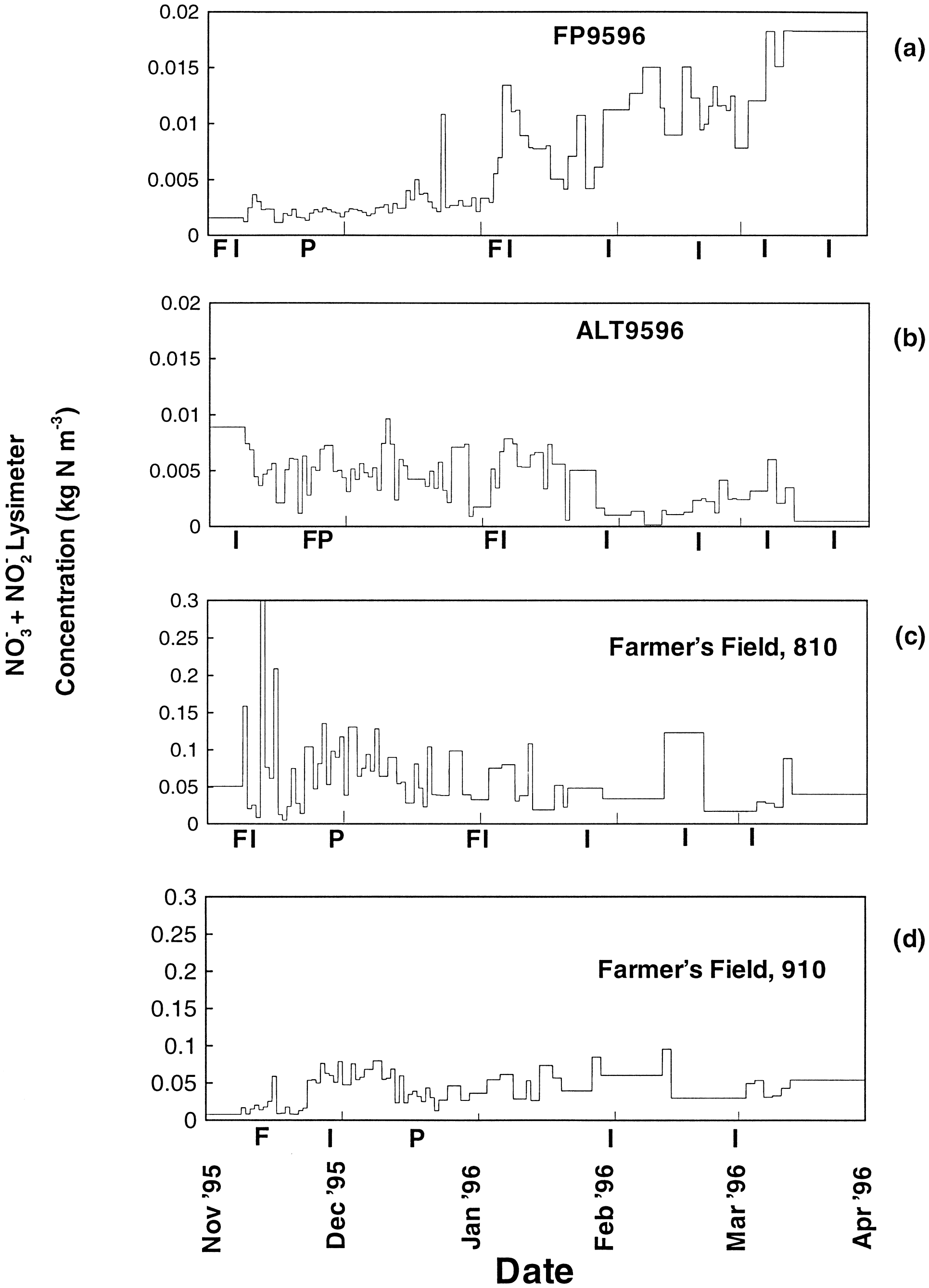

Figure 5. 1995–96 wheat season lysimeter $NO_3^- + NO_2^-$ concentrations for the (a) typical farmer's practice (FP9596), (b) alternative practice (ALT9596), and (c) 810 and (d) 910 farmers' fields. F, I, and P refer to fertilization, irrigation, and planting dates, respectively. The data are shown continuously to indicate the value NLOSS applies at each time step to compute leaching rates.

96 season, about 5 and 2% of the applied fertilizer N leached from the system between planting and the beginning of the subsequent growing season in FP9596 and ALT9596, respectively. Thus, the alternative practice resulted in approximately a 60% reduction in total N leached compared to the typical farmer's practice. During the 1997–98 season, the alternative (ALT9798) reduced N leaching losses by

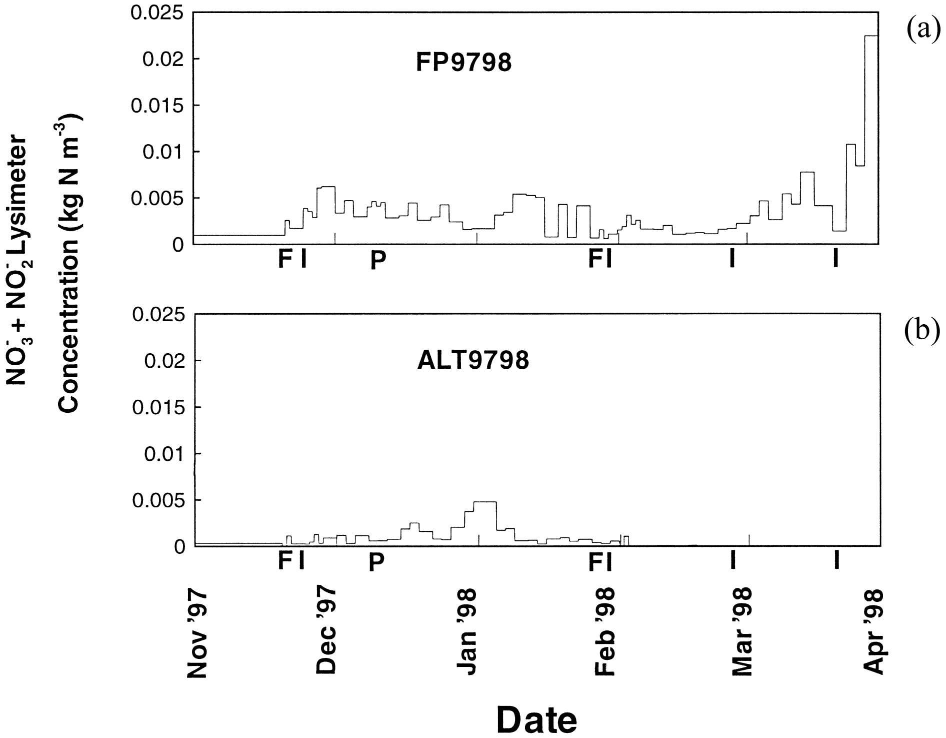

Figure 6. 1997–98 wheat season lysimeter $NO_3^- + NO_2^-$ concentrations for the (a) typical farmer's practice (FP9798) and (b) alternative practice (ALT9798). F, I, and P refer to fertilization, irrigation, and planting dates, respectively. The data are shown continuously to indicate the value NLOSS applies at each time step to compute leaching rates.

about 95% compared to the typical farmer's practice (FP9798). Significantly, the farmer's economic returns were comparable in the typical farmer's and alternative practices during both seasons (unpublished data).

We also compared treatments by examining, over time, the fraction of cumulative N lost from each site. A larger fraction of the N leached earlier in the season in ALT9596 than in FP9596. Adding fertilizer closer to the time of maximum plant demand, as in ALT9596 and ALT9798, lowered soil NO_3^- concentrations substantially, suggesting that later applications during periods of high plant demand lead to better fertilizer utilization. Between planting and harvest, lysimeter N concentrations decreased an order of magnitude in the alternative practices, and increased an order of magnitude in the typical farmer's practice.

Near-surface NO_2^- concentrations were significant in the week following the first simultaneous irrigation and fertilization in FP9596 and ALT9596. *Nitrobacter* activity was probably inhibited during these periods, leading to an accumulation of NO_2^- in the soil profile.

In the farmer's fields (plots 810 and 910), the total N leached over the season accounted for 28 and 17% of the applied N, respectively. Lysimeter NO_3^- + NO_2^- levels in these fields were about an order of magnitude higher than in the experimental treatments. Also, the time history of soil N concentrations differed between FP9596 and ALT9596.

The results of this study indicate that fertilizer management can substantially influence N leaching losses. In particular, management practices that apply N early in the crop cycle are likely to lead to significant losses while practices that more closely tie fertilizer application to plant demand can substantially reduce N leaching losses. In our sites, pre-fertilization conditions in the soil were also responsible for variations in seasonal N leaching losses. In particular, the high N levels in the two farmers' fields led to high N leaching rates, even though fertilizer management was comparable to the experimental sites. Thus, al-

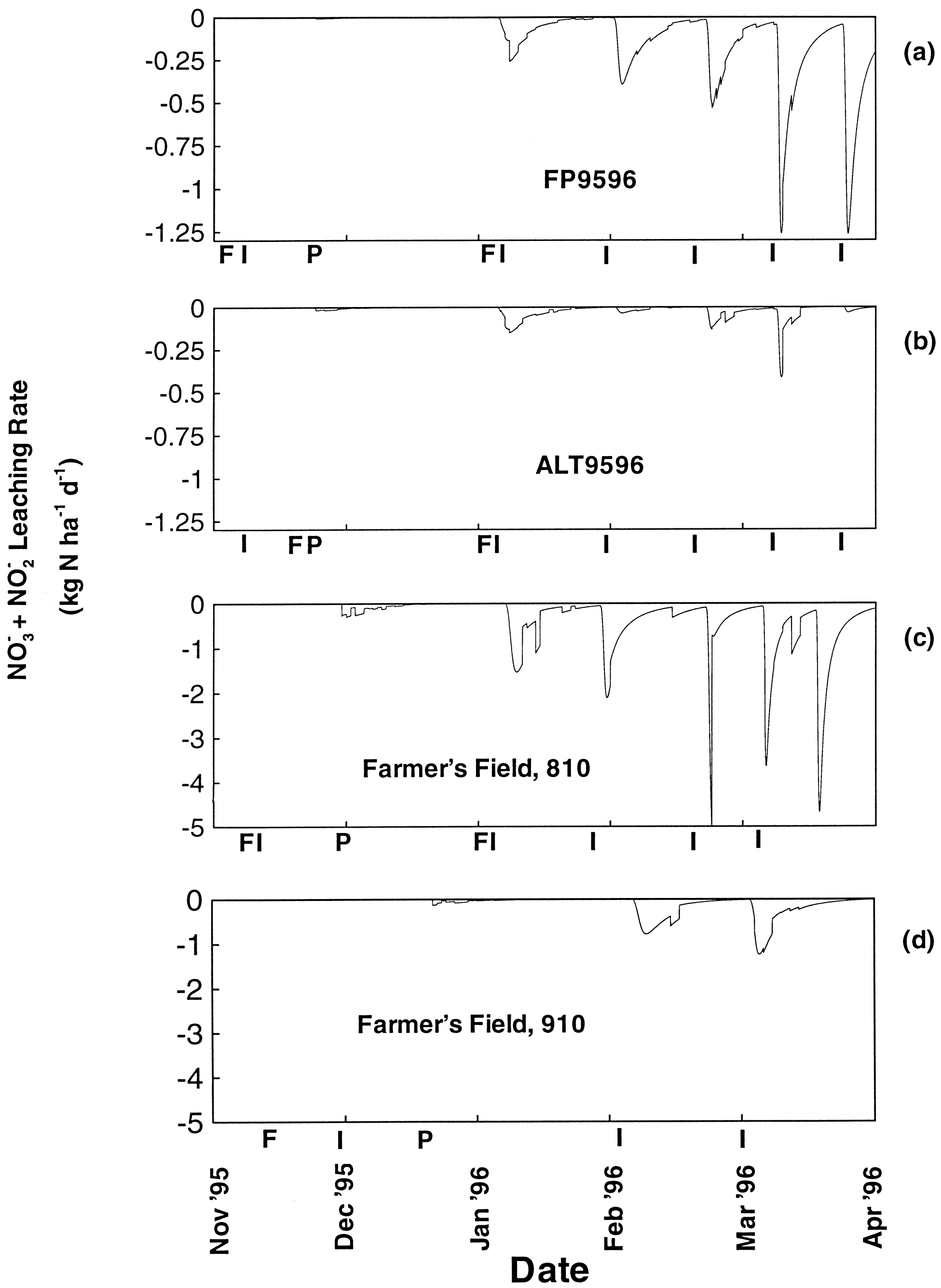

Figure 7. Predicted $NO_3^- + NO_2^-$ leaching rates for the (a) typical farmer's practice (FP9596), (b) alternative practice (ALT9596), and the (c) 810 and (d) 910 farmers' fields. F, I, and P refer to fertilization, irrigation, and planting dates, respectively.

though fertilizer management strongly impacted leaching losses in this system, variability in pre-fertilization conditions and possibly soil hydrologic properties also affected the predicted N leaching losses.

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