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Crop nitrogen utilization and soil nitrate loss in a lettuce field

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Abstract

Low N use efficiency and high nitrate (NO_3^-) pollution potentials are problems in intensive vegetable production systems. The purpose of this study was to quantify N utilization by lettuce (*Lactuca sativa* L. cv Salinas), and identify periods of NO_3^- loss in an on-farm study in the Salinas Valley in coastal California. During autumn and winter, surface moisture remained low, and NO_3^- concentrations increased, reflecting high net mineralizable N, as determined by anaerobic incubation, and nitrification potential, as determined by the chlorate inhibition method. At the onset of a large winter storm, tracer levels of $^{15}NO_3^-$ were injected in the top 5 mm of soil in 30 cm-deep cylinders. After two weeks, most of the ^{15}N was present as $^{15}NO_3^-$ at 10–30 cm depth. By difference, losses to denitrification accounted for $\sim$ 25% of the surface-applied ^{15}N. Leaching below 30 cm did not occur, since no ^{15}N enrichment of NO_3^--N was measured in anion-exchange resin membranes placed at the base of each cylinder. During the crop period, NO_3^- losses were most pronounced after irrigation events. Uptake of N by two crops of lettuce (above- and belowground material) was approximately equal to fertilizer inputs, yet simulation of N fates by the Erosion/Productivity Impact Calculator (EPIC) model indicated losses of 14.6 g-N m^{-2} by leaching and 2.5 g-N m^{-2} by denitrification during the 6-month crop period. The large NO_3^- losses can be attributed to accumulation of soil NO_3^- during winter that was leached or denitrified during the irrigated crop period.

Introduction

Leaching of NO_3^--N occurs in many cool-season vegetable (lettuce, celery and cole crops) production systems, because N application rates often exceed crop demand (Doerge *et al.*, 1991; Lund, 1979). The Salinas Valley in the central coast region of California experiences severe NO_3^- contamination of groundwater, presumably due to intensive vegetable production typically utilizing more than 150 kg-N ha^{-1} $crop^{-1}$ with two or three crops per year. Crisphead lettuce is the major crop grown in this region, accounting for about one-half of total USA production.

The period of maximum crop demand for N should coincide with periods of high N availability in surface soil to achieve high N use efficiency by shallow-rooted vegetable crops (Feigin *et al.*, 1982; Schenk *et al.*, 1991). Interruptions of nutrient supply to lettuce may result in lowered growth rate, from which plants do not fully recover upon restoration of nutrient supply (Burns, 1991). Fertilizer application should be directed towards optimizing utilization and turnover of soil-derived inorganic N and fertilizer N by plants and soil microbial biomass (Radke *et al.*, 1988), and avoiding high concentrations of inorganic N which lead to losses *via* volatilization of NH_4^+, and denitrification and leaching of NO_3^-.

Soil microbial activity and N turnover do vary seasonally, influencing N availability during cropped and non-cropped periods. In addition, frequent tillage promotes net mineralization of soil organic N and crop residue N (Addiscott *et al.*, 1991; House *et al.*, 1984). When net N mineralization causes an accumulation of soil NO_3^- during fallow periods, large NO_3^- leaching losses can occur with high precipitation (Martinez and Guiraud, 1990; Powlson, 1988).

In field studies, plant and soil N fates and losses *via* leaching and denitrification are difficult to measure, but can be simulated by soil-plant process models. In this study, the Erosion/Productivity Impact Calculator (EPIC) model (Sharpley and Williams 1990; Williams and Renard, 1985), that has been calibrated for crisphead lettuce (Warden *et al.*, 1992), was utilized to estimate partitioning of N within the cropping system. EPIC is a comprehensive model with component sub-models for crop growth, hydrology, weather, erosion, tillage, and N transformations. The nutrient component sub-model is based on the PAPRAN model (Seligman and Van Keulen, 1981) and recognizes two sources of mineralization: fresh organic N from crop residue, and stable organic N in the soil humus. Nitrate leaching is simulated by using an exponential function to describe the decrease in NO_3^- concentration caused by water flowing through a soil layer. The EPIC model permits, among others, detailed specification of tillage, irrigation, and fertilization operations, and is therefore well-suited to simulate crop production and soil processes in on-farm research.

The purpose of this study was to document seasonal changes in soil and plant N pools on a commercial vegetable production site, then use these data in the EPIC model to estimate rates of water percolation and associated NO_3^- leaching, and denitrification losses. In addition, to further address the potential for leaching and denitrification during the winter non-cropped period, fates of surface-applied $^{15}NO_3^-$ were examined in an *in-situ* cylinder experiment during a major rainfall event. The objectives of this study were to: 1) estimate the fraction of available N taken up by lettuce, a vegetable crop with high demand for water and N; 2) identify conditions of greatest potential NO_3^- losses during cropped and non-cropped periods of the year; and 3) evaluate whether high soil NO_3^- concentrations occur primarily due to over-fertilization and/or from net mineralization and nitrification of soil N.

Materials and methods

The central coast region of California (36° 37'lat 121° 32'long) has mild winters and cool, foggy, rainless summers. Winter temperatures rarely reach 0°C and maximum air temperatures usually exceed 15°. In summer, temperature maxima reach 21°C with minima at 12°C. The rainy season typically begins in late Sept. and lasts until late May. In 1989–90, precipitation in this eight-month period was 331 mm, 66% of normal (Nat. Ocean. Atmos. Adm., 1989–1990).

Field sampling was conducted in an 11 ha commercial vegetable field in the Salinas Valley, Monterey County, California, on a Mocho silt loam (Fine-loamy, mixed thermic Fluventic Haploxeroll). A 28 m × 45 m sampling site was divided into four blocks of 4.5 m × 7 m randomized plots. On each sampling date, data were collected from four plots. There were 11 sampling dates from Aug., 1989 to Oct., 1990. A celery crop was disked one month before the first sampling date, and beds were formed in early Nov. (Table 1). In 1990, lettuce (*Lactuca sativa* L. cv Salinas) was seeded in May, and harvested in Jul. A second crop was produced between Aug. and Oct. Fertilizer (16–6–8; N–P–K) application rates were 8.1 and 10.3 g-N m^{-2} for the two crops, and was band applied, except for the final fertigation. Total sprinkler/furrow irrigation was 490 mm of water from beginning to end of the two-crop peri-

Table 1. Chronology of field operations, irrigation, planting dates and harvest dates in 1989–1990. Rainfall during the cropped period is shown. Sampling dates are shown in Figure 1

Date	Field operation	Horticultural inputs
1 Aug 1989	Disked	
6 Nov	Beds listed	
23 April 1990	Beds shaped	
2 May	Lettuce direct-seeded	
5 May	Irrigation	30 mm (sprinkler)
11 May	Irrigation	25 mm (sprinkler)
15 May	Cultivation	
23 May-30 May	Rainfall	42 mm (rainfall)
5 Jun	Fertilization, cultivation, thinning	50.4 g m^{-2} (16-6-8)
7 Jun	Rainfall	2 mm (rainfall)
13 Jun-14 Jun	Irrigation	50 mm (furrow); 3 mm (rainfall)
26 Jun	Irrigation	50 mm (furrow); 2 mm (rainfall)
30 Jun	Rainfall	1 mm (rainfall)
8 Jul	Irrigation	50 mm (furrow)
16 Jul	Harvest	
22 Jul	Disked, beds listed	
23 July	Irrigation	60 mm (sprinkler); 2 mm (rainfall)
30 Jul	Lettuce direct-seeded, irrigation	30 mm (sprinkler)
6 Aug	Irrigation	25 mm (sprinkler)
18 Aug	Irrigation	20 mm (sprinkler)
24 Aug	Cultivation, thinning	
28 Aug	Fertilization	50.4 g m^{-2} (16-6-8)
31 Aug	Irrigation	50 mm (furrow)
18 Sept	Irrigation	50 mm (furrow)
5 Oct	Fertigation	50 mm (furrow); 2.2 g-N m^{-2} (NH_4NO_3)
10 Oct	Harvest	

od, and total rainfall amounted to 52 mm. During the entire two-crop growing season, only 0.4 g NO_3^--N m^{-2} was contained in the water used for irrigation.

Soil sampling and analysis

Soil cores (8 cm dia.) were taken to 105 cm depth, and partitioned into 0–15, 15–45, 45–75 and 75–105 cm depth increments. Before the field was formed into raised beds, one core was taken from one plot per block on each sampling date. Thereafter, cores were taken in the bed and in the furrow. The furrow space was equivalent to the 0–15 cm depth, so these cores were divided into 15–45, 45–75, and 75–105 cm increments.

Soil samples were mixed in the field, and subsamples were removed for moisture content, KC1-extractable inorganic N, anaerobic net mineralizable N (Waring and Bremner, 1964), and nitrification potential (Belser and Mays, 1980) following Jackson and Bloom (1990). Samples were stored on ice and all analyses were initiated within 24 h of sampling. Concentrations of NH_4^+ and NO_3^- were determined on a Wescan Ammonium Analyzer (Alltech Assoc., Inc., Deerfield, IL) with a reduction column for NO_3^- (Carlson, 1978; 1986). Soil water content was determined gravimetrically after 48 h at 105°C.

Organic matter, CEC, total N, bicarbonate-extractable P, particle size distribution, and soil moisture retention curves (water content at −0.03, −0.5, and −1.5 MPa on a pressure plate apparatus) were determined on air-dried samples collected for each soil profile layer (n = 4) on the first sampling date, using standard techniques (Klute, 1986; Page *et al.,* 1982). Bulk density was measured on four 8-cm dia. replicate cores. Saturated hydraulic conductivity was measured on one 8-cm dia. core per depth increment.

Nitrate leached during a large winter precipitation event was measured using tracer levels (~ 2 μg-N g^{-1} soil in the top 5 mm of surface soil) of $^{15}NO_3$- applied in steel containment cylinders which had been driven into the soil one day before the experiment. A 10 cm dia. anion exchange membrane (AG 1-X8; Bio-Rad Laboratories, Richmond, CA) was imbedded at the base of each cylinder by excavating a soil ledge from below and refilling soil into the ledge after placement. Cylinders were spaced 2 m apart. Initial soil concentrations of NH_4^+ and NO_3^- and ^{15}N enrichment were measured before the rainfall event. The tracer was injected into the top 5 mm of surface soil of 6 cylinders (20 cm dia. and 30 cm deep). Each cylinder received 450 μg $^{15}NO_3^-$-N. Tracer enrichment was 99.1 atom % ^{15}N. Using 19 injection points, 30.4 ml was applied per cylinder with a syringe. In a 16 day storm period (11 to 27 Jan.), rainfall was 40 mm and 18 mm of deionized water was applied with mist sprayers. On 27 Jan., the cylinders were removed, and three 10-cm soil layers were analyzed for ^{15}N content.

From each soil layer, 50 g subsamples of well-mixed soil were extracted in 125 ml of 2*N* KCl containing 25 μl of 3 mg phenylmercuric acetate l^{-1}. The anion-exchange membrane was shaken overnight in 200 ml of 1*M* KCl. Extracts were frozen, then aliquots were analyzed for NH_4^+ and NO_3^- as described above. A diffusion method was used to prepare samples for $^{15}NO_3^-$ and $^{15}NH_4^+$ analysis (Brooks *et al.,* 1989). In the latter, samples were spiked with internal standards of $(NH_4)_2SO_4$ to overcome detection limits. To determine whether ^{15}N had been incorporated into soil organic N during the experimental period, Kjeldahl digestions were conducted with salicylic acid and granular zinc to reduce NO_3^-, then inorganic ^{15}N was subtracted from the total $^{15}NH_4^+$-N in the digestion. Isotope Services (Los Alamos, New Mexico) performed the isotope analyses by mass spectroscopy. Calculations of ^{15}N concentrations in the three soil layers followed Hauck (1982).

Plant sampling and analysis

Plant samples were taken from each plot on Jun.1 (pre-thinning of first crop), Jul. 15 (harvest of first crop), Sept. 13 (heading of second crop), and Oct.10 (harvest of second crop). Plant samples were dried at 65°C, weighed, ground in a Tecator mill (Hogänas, Sweden), and total N was determined by Kjeldahl digestion to include NO_3^-. Plants were cut at surface level and cores for roots were taken over a single plant (taproot zone), midway between the two rows of plants on the bed (mid-bed zone), and in the center of the furrow. Cores were subsampled (500 g) except for the taproot zone. Roots were removed using a hydropneumatic root elutriator (Gillison's Fabrication, Benzonia, Michigan). Root length was determined on a Comair root scanner (Hawker de Haviland, Victoria, Australia). Roots in the 0–75 cm soil profile (m m^{-2} and g m^{-2}) were extrapolated from sampled cores, using relationships determined from measurements of root length density and dry weight (cm cm^{-3} and μg cm^{-3}) taken across the bed and furrows (Jackson and Stivers, 1993).

Data analysis

Statistical comparisons utilized General Linear Models procedures of SAS (Freund *et al.,* 1986). Comparisons of soil characteristics with ANOVA and Duncan's multiple-range tests were made within the autumn through winter period (5 sampling dates from Aug. through Mar.), and within the spring through summer period (7 sampling dates from Mar. through Oct.). This resulted in

> 100 different ANOVAs, and the multiple-range tests were too numerous to report in the text and figures. F-tests with $p < 0.05$ were considered significant.

The EPIC model was used to simulate soil N processes, after calibrating the crop growth submodel for crisphead lettuce using data from published literature (Frota and Tucker, 1972; Lorenz and Maynard, 1988; Richard *et al.,* 1985; Zink and Yamaguchi, 1962) and model validation with a nearby silty clay loam soil (Warden *et al.,* 1992). The trigger for onset of denitrification was modified in EPIC from the default water-filled porosity of 0.9 to 0.64 in accordance with model sensitivity analysis, and studies which suggest denitrification occurs at water-filled porosities of 0.6 to 0.7 (Linn and Doran, 1984). Model simulation began in Jan. rather than in the previous autumn because data on crop residues from the previous celery crop were not available. Mean values of soil NO_3^- and water content measured on 28 Jan., 1990 served as initial conditions, weighting bed and furrow data according to spatial distribution in the field (75% bed, 25% furrow).

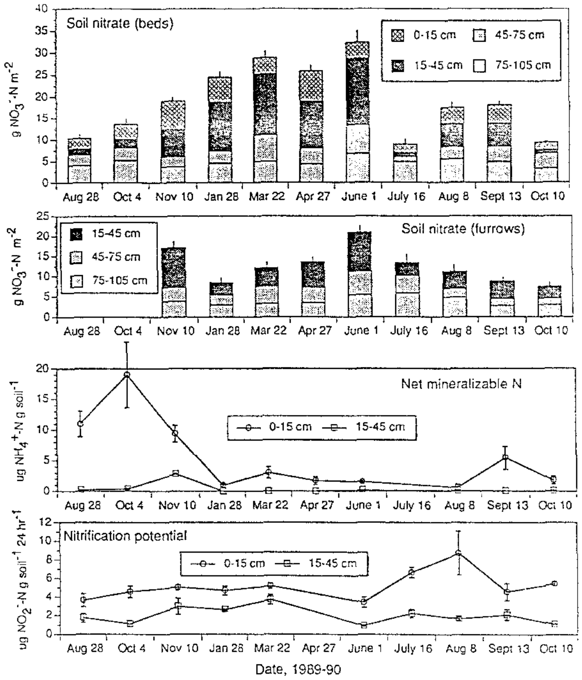

Fig. 1. Soil NO_3^--N in bed and furrow samples, and net mineralizable N and nitrification potential in bed samples during 1989–90 in the Salinas vegetable field (n = 4).

Results

Soil properties

The Mocho silt loam soil had low clay, high silt, and low sand content (Table 2). Moisture retention at −0.03, −0.5, and −1.5 MPa decreased slightly at lower depths in the profile. Organic N and carbon (C) contents were low, particularly below 15 cm depth. Bulk density indicated an apparent plowpan layer at 15–45 cm depth. Saturated hydraulic conductivity decreased with depth, and showed pronounced restriction of water flow at depths between 15–75 cm.

Soil N availability during non-cropped period

Substantial soil NO_3^- was present in the soil profile (0–105 cm) following the summer celery harvest (Fig.1) and increased through autumn, winter, and spring. With the onset of winter rainfall, NO_3^- accumulated in the 15–45 cm layer of soil. Seasonal totals of precipitation on the Nov., Jan., and Mar. sampling dates were 70 mm, 168 mm and 276 mm, respectively. By late Mar., NO_3^- concentrations in the 45–75 cm layer were significantly higher than dates earlier in the season. In the Jan. and Mar. samplings, the uppermost 30 cm layer in the furrows contained less NO_3^- than the corresponding layer in the beds. At lower depths, no significant differences were observed between NO_3^- concentrations in bed and furrow samples. Soil NH_4^+ remained at ~ 1 g-N m^{-2} (0–105 cm depth) throughout the autumn and winter periods (data not shown).

Net mineralizable N reached its maximum during the autumn period of frequent tillage, following incorporation of celery crop residues (Fig. 1). It decreased in winter without a renewed pulse in early spring. Mineralization activity was greatest in the top 15 cm of soil. At lower depths, net mineralizable N was typically < 0.5 μg NH_4^--N g^{-1} soil. Nitrification potential, measured as accumulation of NO_2^- in the presence of excess NH_4^+,

Table 2. Soil properties at the Salinas field site (n = 4)

Soil characteristics	mean ± SE
Soil characteristics (0–105 cm depth)	
Clay (%)	17 ± 1.0
Silt (%)	64 ± 1.3
Sand (%)	19 ± 1.6
C.E.C. ($cmol_c$ kg^{-1})	23 ± 3.0
pH	7.4 ± 0.1
P (mg kg^{-1}; 0–15 cm depth)	26.2 ± 13.2
Soil characteristics by depth increment	
Organic N (g kg^{-1})	
0–15cm depth	0.97 ± 0.01
5–45cm depth	0.54 ± 0.10
45–75cm depth	0.41 ± 0.05
75–105cm depth	0.41 ± 0.05
Organic C (g kg^{-1})	
0–15cm depth	8.8 ± 0.03
15–45cm depth	6.2 ± 0.2
45–75cm depth	3.7 ± 0.6
75–105cm depth	4.3 ± 0.5
Saturated hydraulic conductivity (mm h^{-1})	
0–15cm depth	14.59
15–45cm depth	0.12
45–75cm depth	0.25
75–105cm depth	5.83
Moisture at −0.03 MPa (g g^{-1})	
0–15cm depth	0.252 ± 0.002
15–45cm depth	0.227 ± 0.002
45–75cm depth	0.178 ± 0.017
75–105cm depth	0.228 ± 0.049
Moisture at −0.5 MPa (g g^{-1})	
0–15cm depth	0.139 ± 0.005
15–45cm depth	0.118 ± 0.001
45–75cm depth	0.089 ± 0.008
75–105cm depth	0.122 ± 0.026
Moisture at −1.5 MPa (g g^{-1})	
0–15cm depth	0.118 ± 0.003
15–45cm depth	0.093 ± 0.002
45–75cm depth	0.074 ± 0.005
75–105cm depth	0.108 ± 0.033
Bulk density (g cm^{-3})	
0–15cm depth	1.4 ± 0.01
15–45cm depth	1.6 ± 0.03
45–75cm depth	1.5 ± 0.03
75–105cm depth	1.4 ± 0.03

Table 3. Recovery of $^{15}NO_3^-$-N at three depths from cylinders to which 450 μg $^{15}NO_3^-$-N (99.1 atom % ^{15}N) had been added to surface soil just prior to a winter rainfall event of 580 mm, and soil NO_3^--N before and after the rainfall event. Data are means ± SE (n = 6)

Soil depth	N recovery
^{15}N recovery by depth	μg $^{15}NO_3^-$-N recovered per cylinder mean ± SE
0–10 cm depth	34.6 ± 8.41
10–20 cm depth	177.6 ± 25.38
20–30 cm depth	56.3 ± 17.53
NO_3^--N in 0–30 cm profile	9NO_3^--N m^{-2} mean ± SE
At injection (11 Jan)	9.0 ± 0.68
At removal (27 Jan)	7.6 ± 0.82
Loss	-1.4 ± 0.61
Percent loss	-15.0 ± 6.2

remained high throughout the autumn and winter (Fig. 1). Below 15–45 cm depth, rates were less than 1 μg NO_2^--N g^{-1} soil d^{-1}.

Soil moisture was < 11%, i.e. < −1.5 MPa (Table 2), in the top 15 cm in the autumn samples (data not shown), but rose in late Jan. and Mar. to ~ 20% (> −0.5 MPa). Soil moisture at 15–45 cm was generally > −0.5 MPa. At lower depths, soil water potential occasionally exceeded −0.03 MPa.

During the first major rainfall event (580 mm during 16 days), NO_3^--N decreased 1.4 g-N m^{-2} from the top 30 cm of soil cylinders (Table 3). At the onset of the storm, mean soil moisture was 13.9% (~ −0.5 MPa) in the top 10 cm, but was 19.4% (~ −0.1 MPa) at lower layers. After the storm, 59.7% of the applied ^{15}N was recovered as $^{15}NO_3^-$-N. Most of the $^{15}NO_3^-$ was transported from the surface into the 10–20 cm layer, and some $^{15}NO_3^-$ was recovered in the 20–30 cm layer. Concentrations of NH_4^+ were low (1-1.5 μg NH_4^+-N g^{-1} soil) and no ^{15}N enrichment of NH_4^+ was observed. Of the applied ^{15}N, 16.4% (73.8 ± 21.0 μg-N per cylinder) was recovered as soil organic N. The NO_3^- adsorbed by anion exchange membranes showed no ^{15}N enrichment, implying that the remaining 23.9% of surface-applied $^{15}NO_3^-$ was lost by denitrification rather than leaching below 30 cm depth.

Soil N availability during cropped period

During each of the two crops of lettuce, NO_3^- in the soil profile (0–105 cm depth) generally declined through the growth period (Fig. 1). At crop harvest (Jul. and Oct.), soil NO_3^- was significantly lower than earlier in the crop cycle. In the three weeks between crops, NO_3^- in the soil profile increased by ~ 5 g-N m^{-2}, even though no additional fertilizer was added at this time. During the second crop of lettuce, there was less NO_3^- in the soil profile than during the first crop. Approximately 1 g NH_4^+-N m^{-2} (0–105 cm) was present throughout the summer (data not shown).

Concentrations of NO_3^- in the top layer of soil (0–15 cm depth) were generally higher than deeper layers (Fig. 1). Surface NO_3^-, however, decreased during periods of highest irrigation, even though fertilizer was also applied during these periods. Nitrate in the furrows was similar to the same layers in the beds, except for the 15–45 cm zone, which was significantly higher in the furrows. Contribution of net mineralizable N during the spring and summer to the inorganic N pools appears to have been relatively low, since typical values were < 1.0 g NH_4^+-N m^{-2} (0–105 cm). In the top layer of soil, net mineralizable N was generally 1–2 μg NH_4^+-N g^{-1} soil during both crops of lettuce (Fig. 1). Nitrification potential in the presence of excess NH_4^+ remained high through the summer, indicating that available NH_4^+ was being readily nitrified.

During the summer, soil moisture in the two lower depths (45–75 cm and 75–105 cm) exceeded 21 and 28%, respectively, on all sampling dates following planting of lettuce (data not shown). Soil water potential was thus greater than −0.03 MPa (Table 1). In samples from the upper layer of soil, soil moisture typically corresponded to water potentials of −0.1 to −0.3 MPa.

Table 4. Shoot and estimated root dry weights and N accumulation of lettuce during two summer crops (n = 4). Estimates of root dry weight and N content were determined by extrapolation from sampled cores

Date	Shoot dry weight ($g\ dw\ m^{-2}$) mean ± SE	Shoot nitrogen ($g\text{-}N\ m^{-2}$) mean ± SE	Estimated root dry weight (0–75 cm depth) ($g\ dw\ m^{-2}$) mean ±SE	Estimated root nitrogen (0–75 cm depth) ($g\text{-}N\ m^{-2}$) mean ± SE	Estimated total dry weight ($g\ dw\ m^{-2}$) mean ± SE	Estimated total nitrogen ($g\text{-}N\ m^{-2}$) mean ± SE
June 1 (thinning)	6.4 ± 1.5	0.26 ± 0.06	0.63 ± 0.13	0.02 ± 0.003	7.1± 1.3	0.27 ± 0.06
July 16 (harvest)	321.8 ± 54.6	8.51 ± 2.02	45.90 ± 2.76	1.00 ± 0.07	367.7 ± 54.0	9.51 ± 2.00
Sept. 13 (heading)	39.4 ± 6.0	1.54 ± 0.23	20.35 ± 1.29	0.59 ± 0.04	59.7 ± 6.4	2.13 ± 0.24
Oct. 10 (harvest)	261.5 ± 25.5	6.76 ± 0.41	34.11 ± 4.85	0.94 ± 0.14	295.6 ± 26.4	7.71 ± 0.48

Crop N utilization

Growth rate and N accumulation in the two summer crops of lettuce showed the typical pattern for crisphead lettuce with slow early season growth followed by rapid growth toward the end of the crop period (Table 4). At thinning, ~ 25 days after germination, only 2% of aboveground plant dry weight and 4% of aboveground plant N had accumulated. Data from the second crop showed that over 70% of aboveground dry weight and N accumulated during the last three weeks of the crop cycle. Total N in above- and belowground plant material at harvest of the two crops of lettuce was 9.5 and 7.7 g-N m^{-2}, respectively. This approximately equals the amount of fertilizer N applied (8.1 and 10.3 g-N m^{-2} for the two crops, respectively).

Root allocation was 11% and 12% of total plant dry weight on the two harvest dates (Table 4). Roots grew slowly during the first month, but root length density and dry weight increased rapidly after thinning, especially in the top 0–15 cm of soil (Table 5). Between heading and harvest, increases in root length density occurred more slowly than root dry weight. Root length density in the furrows was similar to corresponding layers in the beds. Most of the roots (> 40% of root dry weight and 20% of the root length) were in the top 0–15 cm of soil of the beds at harvest.

EPIC simulations

Results of model simulation for soil NO_3^- fell within 10–35% of mean measured values, indicating that NO_3^- dynamics were satisfactorily predicted (Fig. 2). One notable exception was in Jun., when the predicted NO_3^- underestimated the observed value. Plant biomass was successfully simulated at crop harvest, yet EPIC produced slight overestimates earlier in the growing season. According to EPIC, crop growth was never constrained by N stress, and water stress limited crop growth on 3 d.

The EPIC simulation showed that more NO_3^- was leached below 105 cm depth during the cropped period (14.6 g-N m^{-2} from May through Oct.) than during the period from late Jan. through Apr. (2.8 g-N m^{-2}). In the two-week interval between crops, percolation or root zone drainage was 13 mm and leaching was 1.3 g-N m^{-2} (Table 6). Similar amounts of water were applied to both crops of lettuce, but EPIC indicated that more NO_3^- was leached during the second crop and that greater percolation also occurred. Higher soil moisture at the onset of the second crop contributed to greater percolation and leached NO_3^-; soil moisture in the lower two depths was ≤ -0.03 MPa in Apr. samples, but rose to > -0.01 MPa in Aug. samples (data not shown). Maximum daily rates of NO_3^- leaching coincided with sprinkler irrigation to germinate the second crop.

Table 5. Root length density and root dry weight per cm^{-3} in sampled cores from three soil zones on four sampling dates during two lettuce crops (n = 4)

Depth	Taproot zone		Mid-bed zone		Furrow zone	
	$cm\ cm^{-3}$ mean ± SE	$\mu g\ cm^{-3}$ mean ± SE	$cm\ cm^{-3}$ mean ± SE	$\mu g\ cm^{-3}$ mean ± SE	$cm\ cm^{-3}$ mean ± SE	$\mu g\ cm^{-3}$ mean ± SE
June 1 (thinning, first crop)						
0–20 cm	1.1 ± 0.07	33.0 ± 4.18	0.03 ± 0.02	0.8 ± 0.4	—	—
July 16 (harvest, first crop)						
0–15 cm	7.9 ± 1.14	2537 ± 267.5	3.3 ± 0.41	96 ± 13.9	—	—
15–45 cm	2.9 ±0.04	210 ± 94.2	2.4 ± 0.54	57 ± 14.3	1.5 ± 0.33	49 ± 8.5
45–75 cm	0.8 ± 0.34	24 ± 9.1	0.6 ±0.30	14 ± 4.9	0.5 ± 0.09	14 ± 2.4
September 13 (heading, second crop)						
0–15 cm	2.7 ± 0.33	371 ± 56.7	2.3 ± 0.25	71 ± 10.0	—	—
15–45 cm	1.5 ± 0.27	40 ± 7.8	1.6 ± 0.09	31 ± 2.7	1.6 ± 0.03	49 ± 5.2
45–75 cm	0.2 ± 0.04	5 ± 1.4	0.1 ± 0.04	2 ± 0.8	0.6 ± 0.09	8 ± 3.1
October 10 (harvest, second crop)						
0–15 cm	7.3 ± 0.60	2012 ± 328.7	3.5 ± 0.12	100 ± 4.2	—	—
15–45 cm	2.8 ± 0.39	121 ± 29.9	1.7 ± 0.36	30 ± 12.2	2.4 ± 0.21	59 ± 6.4
45–75 cm	0.6 ± 0.32	17 ± 7.7	0.2 ± 0.03	3 ± 0.3	0.4 ± 0.09	7 ± 1.6

Denitrification losses accounted for 3.2 g-N m^{-2} in the 8-month EPIC simulation. Losses were 2.5 g-N m^{-2} during the cropped period from May through Oct. After fertilization in Jun. and Sept., EPIC indicated that daily denitrification rates reached as high as 0.035 g-N m^{-2} d^{-1}, but rates were usually $\leq$0.01 g-N m^{-2} d^{-1}.

Discussion

Lettuce crops of high yield and N content were produced in this on-farm study. Above- and belowground uptake of N by the lettuce crops approximately equalled fertilizer input. Fertilizer application rates, however, did not consider soil NO_3^- present in the profile at planting, so that substantial NO_3^- was lost from the root zone due to leaching and denitrification. Net mineralization of N during winter led to the accumulation of soil NO_3^- in the spring, which became susceptible to loss with the onset of spring irrigation. Slow development of the shallow root system in lettuce contributed to low recovery of NO_3^- by the crop.

Winter N dynamics

Winter N dynamics play an important role in the fate of N during the irrigated cropping period in this production system. Nitrate accumulated in autumn and winter because there were high potentials for N mineralization and nitrification. Net mineralization of N peaked in early autumn, after incorporation of celery residues, and declined during winter and spring. The soil N dynamics in this cropping system indicated net mineralization of N during most of the year. Periods of net immobilization of N may be short-lived due to frequent tillage with little addition of organic matter (Follett and Schimel, 1989). Vegetable crops produce aboveground material with low C:N ratio (e.g. ~ 13 for celery crop residues). Little crop residue is left in the field because the harvest index is high (70–90%) and root systems are sparse. Despite

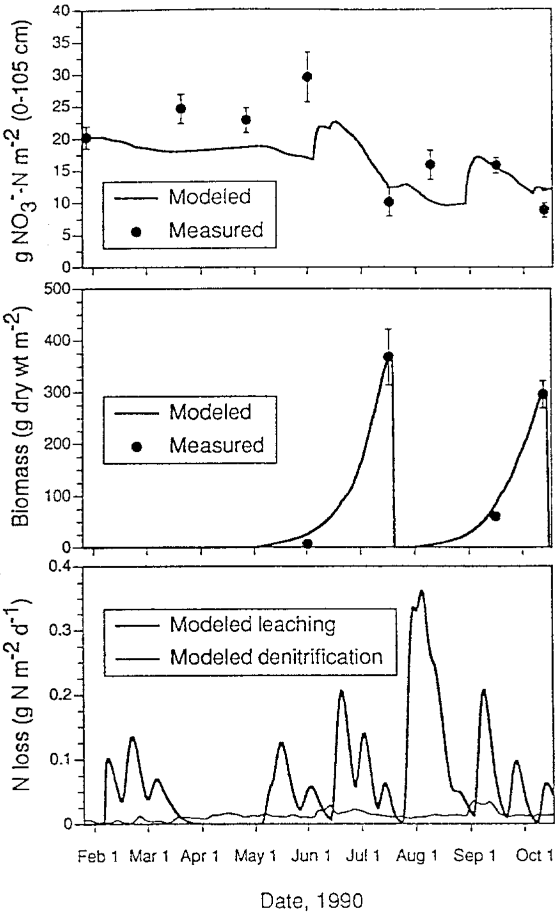

Fig. 2. EPIC simulations of actual management practices from late January through mid-October, 1990. Measured (means ± SE) and modeled values are shown for soil NO_3^--N and crop biomass

evidence for a pulse of high mineralization activity in winter, NH_4^+ never accumulated in the soil and must have been immobilized or readily oxidized to NO_3^-. The chlorate-inhibition assay showed high potential nitrification even after net mineralizable N declined in early spring, suggesting that capacity to oxidize NH_4^+ was sustained even though supply declined.

Winter leaching of NO_3^- is undoubtedly important in some years, but this year's data suggest that periods of heavy rainfall must coincide with soil already near saturation for substantial winter leaching below the rootzone to occur. Low surface moisture prevailed in listed beds during most of the fallow period, and single large rainfall events did not deliver enough water to promote extensive drainage. Few important leaching events occurred during this year with lower than normal precipitation. To test the effect of normal spring precipitation on N loss, an EPIC simulation used average rainfall in Jan., Feb., Mar. and Apr. Four storms were added to increase rainfall from 145 to 224 mm. EPIC indicated that percolation and leached NO_3^- from late Jan. until planting in May was 78 mm and 6.1 g-N m^{-2}, an approximate doubling compared to actual 1990 conditions. The model showed however, that crop yields were not affected by the increase in spring rainfall.

The ^{15}N experiment suggested that NO_3^- is gradually displaced downwards in the soil profile in periodic small leaching events, and denitrification also appears to contribute to surface N losses in major storms. Surface-applied $^{15}NO_3^-$ was mainly recovered within the upper 20 cm of the profile, and was not leached below 30 cm. Surface soil moisture was low at the onset of the storm, and only 5.5 mm of rainfall occurred during the first two days. These conditions would increase moisture in the top few mm near the surface, and could explain high losses of ^{15}N by denitrification, without promoting drainage and NO_3^- leaching at lower depths. The plowpan layer below 15 cm, created by use of heavy machinery in wet soil, undoubtedly contributes to high potential denitrification by restricting water drainage.

Some $^{15}NO_3^-$ was incorporated into the organic N fraction, suggesting some microbial immobilization of NO_3^-. Ammonium would presumably be a preferred source of inorganic N, due to lower energy expenditures for reduction and metabolism (Rice and Tiedje, 1989), but immobilization of NO_3^- may occur under conditions of low concentrations and low flux of NH_4^+-N, as suggested by low net mineralizable N.

Alternate management scenarios

Greatest NO_3^- losses occurred during the crop season when frequent irrigation increased percolation below the root zone, particularly during the second crop of lettuce. Irrigation in this study (490 mm from May through Oct.) was lower than is normally applied, and further reduction could

Table 6. EPIC simulations of N fates under actual and alternative management scenarios for two successive crops of lettuce. See Table 1 for actual management practices. Actual fertilizer application was 18.4 g-N m^{-2} for the two-crop period, compared to typical application of 35.6 g-N m^{-2} in Scenario II

Processes	Scenario I	Scenario II	Scenario III
	Actual management practices in this study	Typical fertilizer application (17.8 g-N m^{-2} crop $^{-1}$)	No irrigation between crops
Crop 1 (May 1–July 16)			
Percolation (mm)	60	60	60
Leached NO_3^--N (g-N m^{-2})	5.19	5.21	5.19
Denitrification (g-N m^{-2})	1.17	1.38	1.17
Crop yield (g-dw m^{-2})	371.1	371.1	371.1
Between Crops (July 17–July 29)			
Percolation (mm)	13	13	1
Leached NO_3^--N (g-N m^{-2})	1.27	1.29	0.07
Denitrification (g-N m^{-2})	0.13	0.18	0.13
Crop 2 (July 30–October 10)			
Percolation (mm)	96	96	58
Leached NO_3^--N (g-N m^{-2})	8.18	9.54	5.63
Denitrification (g-N m^{-2})	1.22	1.39	1.48
Crop yield (g-dw m^{-2})	300.5	300.5	300.5

risk water deficits in this drought-sensitive crop. Typical irrigation per crop is 450 mm of water, and average measured irrigation efficiencies are 60% (Schulbach, 1988, 1992). One possibility to decrease irrigation with minimum potential for plant water deficit would be to eliminate water application between crops. An EPIC simulation not including pre-plant irrigation before seeding the second crop was run to test this hypothesis; water percolation and leached NO_3^- decreased to 58 mm and 5.6 g-N m^{-2}, respectively, representing an ~ 40% decrease compared to actual management practices from mid-Jul. through mid-Oct. (Table 6). Crop biomass was not affected by the treatment.

In vegetable production systems, fertilizer application often exceeds recommended amounts, (Doerge *et al.*, 1991; Lorenz and Maynard, 1988), and it is usually applied according to routine schedules, rather than using soil and plant testing to time application to maximize crop yields and minimize N losses. In this study, applied fertilizer was lower than for general recommendations for lettuce or than typically used in this region which is approximately 17.8 g-N m^{-2} per crop (Lorenz and Maynard, 1988; Schulbach, 1992). An EPIC simulation was made with 17.8 g-N m^{-2} for both crops of lettuce using typical scheduling (1, 12, and 4.8 g-N m^{-2}, and 1, 12, and 2.6 g-N m^{-2}, respectively, at planting, thinning, and heading, for the two crops, and for the second crop, 2.2 g-N m^{-2} was also applied as a pre-harvest fertigation). The model predicted that the additional fertilizer would not change crop growth compared to actual management practices, but leaching and denitrification would increase ~ 20%, mainly due to increased N losses in the latter part of the season (Table 6). Growers may over-apply water and fertilizer to avoid perceived risk of low yield and quality of this high cash value crop.

The EPIC model provided a useful tool to evaluate the impacts of management practices on crop yield and N losses to the environment. It is a comprehensive model which described soil and plant N pools satisfactorily. Further data will be collected for lettuce production to advance improvements on calibrating the model for these intensively managed systems. For example, simulation of net mineralization of N may have been underestimated during the winter and spring, accounting for higher measured values of inorganic N compared to modeled values. Modeled denitrification may also be lower than actually occurred in the field despite the lower soil moisture trigger in the modified EPIC. Direct measurement of denitrification in similar irrigated vegetable crop systems showed peak fluxes of 0.14 to 0.19 g-N m^{-2} d^{-1}, and denitrification losses of 9.5 to 17.2 g-N m^{-2} yr^{-1} on lettuce, broccoli, and celery fields receiving fertilizer at 47.5 to 66.5 g-N m^{-2} y^{-1} (Ryden and Lund, 1980).

In summary, accumulation of soil NO_3^- during the mild winters in this coastal Mediterranean-type climate leads to high potential for N loss *via* leaching and denitrification, either during winter rainfall events, or more likely, during the subsequent second irrigated crop period. The results of this study are directly pertinent to actual schedules and management practices, since the data were collected on-farm. This study suggests that N losses could be minimized by 1) basing fertilizer application on plant demand, as determined by soil and plant N tests; 2) reducing irrigation between crops; and 3) retrieving soil NO_3^- *via* year-round crop production, or if feasible, planting winter cover crops during the otherwise fallow period (Jackson *et al.*, 1993).

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