

# DIVISION S-4—SOIL FERTILITY & PLANT NUTRITION

## Fates and Losses of Nitrogen from a Nitrogen-15-Labeled Cover Crop in an Intensively Managed Vegetable System

L. E. Jackson\*

### ABSTRACT

Cover crops are known to decrease leaching of  $\text{NO}_3^-$ -N during the winter fallow period in vegetable crop systems, but soil N dynamics following cover crop incorporation are not well understood. The ability of microbes and plants to assimilate and retain N from cover crop residue was studied in a sandy soil in a field under intensive vegetable production in California. The purpose was to describe changes in soil responses and  $^{15}\text{N}$  fates after adding a  $^{15}\text{N}$ -labeled cover crop under field management conditions. Fresh residue (478 g dry weight  $\text{m}^{-2}$ ) of  $^{15}\text{N}$ -labeled phacelia (*Phacelia tanacetifolia* Benth.) (C/N of 19) was added to miniplots contained within large cylinders. Microbial biomass and  $\text{NO}_3^-$ -N increased rapidly, then began to decline 2 wk later. Microbial biomass C declined faster than microbial biomass N. Only a small amount of  $^{15}\text{N}$  was ever found in microbial biomass, but  $\text{NO}_3^-$ -N was enriched with substantial  $^{15}\text{N}$ . Percentage recovery of the added  $^{15}\text{N}$  after 4 mo was 60.7% as soil organic N; 20.7% in plants; 1.4% as inorganic N; 1.4% in microbial biomass; 4.7% in ion exchange resin (IER) bags, leached below a depth of 60 cm; and 11.1% as unexplained loss. Losses of  $^{15}\text{N}$  during the first lettuce (*Lactuca sativa* L.) crop after the cover crop were relatively low, most likely due to low rainfall and appropriate scheduling of fertilizer and irrigation. Total soil  $^{15}\text{N}$  at 0- to 30-cm depth declined for the first 7 mo, and thereafter cover crop N was apparently no longer readily mineralizable. Microbes may have assimilated C from the plant residue, met their N demand mainly with soil-derived N, and released cover crop-derived N that was rapidly mineralized and nitrified. The resulting  $\text{NO}_3^-$ -N was either taken up by plants, leached, or denitrified. Proper management of water and fertilizer inputs after incorporation of low C/N plant material is important for avoiding N loss before plants are established, especially since  $\text{NO}_3^-$ -N is readily available, and microbes do not retain much of the cover crop N in this intensively managed soil.

**N**ITRATE LEVELS in the groundwater of intensively managed crop systems often exceed the public health drinking water standard due to leaching below crop root zones (Legg and Meisinger, 1982; Howarth et al., 1996; Zhang et al., 1998). Previous work in vegetable crop systems has shown that nonleguminous winter cover crops can assimilate up to  $\approx 100 \text{ kg N ha}^{-1}$ , thereby reducing the leaching of  $\text{NO}_3^-$ -N during winter rainfall periods (Shennan, 1992; Jackson et al., 1993; Creamer et al., 1997; Brandi-Dohrn et al., 1997). Incorporation of cover crop residue into soil temporarily increases

microbial activity and consequently alters the amount and seasonality of available inorganic N (Aulakh et al., 1991; Wyland et al., 1996; Kuo et al., 1997; Lundquist et al., 1999). A successful cover crop strategy is to synchronize the release of inorganic N from the cover crop with N demand by the subsequent cash crop so that cover crop-derived N is retained in the system, and N losses via leaching and denitrification of mineralized cover crop-derived N are minimized.

In most cropping systems, cover crops are typically incorporated at a low C/N ratio (i.e.,  $<20$ ) to ensure rapid decomposition and avoid prolonged net microbial immobilization of N that can be deleterious for uptake of N by the subsequent cash crop (Wyland et al., 1995; Ranells and Wagger, 1997a). Mineralization of N from cover crop residue can contribute either a small or a substantial fraction (e.g., 4–30%) of the N assimilated by a subsequent cash crop depending on the attributes of the cover crop, such as C/N ratio, soil type, and management practices (Varco et al., 1989; Harris and Hesterman, 1990; Jensen, 1992; Harris et al., 1994; Ranells and Wagger, 1997b). From a practical standpoint, release of cover crop N should be fast enough to match crop N demand, but not so rapid that  $\text{NO}_3^-$ -N losses via leaching and denitrification occur during periods of early season rainfall and preirrigation (Bremer and van Kessel, 1992). This can be difficult to achieve since microbial responses can be very rapid during the first 1 or 2 wk following incorporation of low C/N plant material, at least under nonlimiting moisture conditions, and activity can decline substantially thereafter (Wyland et al., 1996; Lundquist et al., 1999). In soils that are C-limited, microbes may rapidly use the readily available C and N from residue with low C/N ratios, creating a short-lived pulse of activity that cannot be sustained for a long period. By labeling plant material with the stable isotope,  $^{15}\text{N}$ , and following the fates of  $^{15}\text{N}$  through time to various soil and plant pools, a better understanding of the timing and magnitude of microbial responses, N availability, and N losses to the addition of fresh plant material can be developed.

In this study, such a time course was examined at a site that had been under long-term irrigated vegetable crop production in the Salinas Valley, California, where

Dep. of Vegetable Crops, One Shields Ave., Univ. of California, Davis, CA 95616. Received 11 Dec. 1998. \*Corresponding author (lejackson@ucdavis.edu).

**Abbreviations:** CEC, cation-exchange capacity; DAI, days after incorporation of cover crop residue; IER, ion exchange resin; MBC, microbial biomass C; MBN, microbial biomass N.

**Table 1. Soil characteristics at four depths at the study site on Chualar loamy sand soil in the Salinas Valley, California.**

Depth	Sand	Silt	Clay	-0.03 MPa	-0.1 MPa	-1.5 MPa	pH	CEC†	Organic N	Organic C	Bulk density
cm	g g <sup>-1</sup>			(g H <sub>2</sub> O · 100) g <sup>-1</sup> soil				cmol kg <sup>-1</sup>	g kg <sup>-1</sup>		Mg m <sup>-3</sup>
0-15	0.850	0.110	0.040	6.3	6.0	2.7	6.5	7.9	0.70	6.3	1.30
15-45	0.845	0.110	0.045	5.8	5.4	2.7	7.0	8.2	0.57	4.1	1.64
45-75	0.835	0.115	0.050	6.3	5.3	3.0	7.1	7.9	0.38	2.5	1.71
75-105	0.620	0.270	0.011	11.5	11.6	5.4	7.2	13.3	0.52	4.8	No data

† CEC is cation-exchange capacity.

NO<sub>3</sub><sup>-</sup>-N contamination of groundwater is a serious problem. The soil type, a Chualar loamy sand (fine-loamy, mixed, thermic Typic Argixeroll), has experienced intensive management with high fertilizer and irrigation inputs, frequent tillage, and little return of organic material to the soil; it now has low concentrations of soil organic C and N, as well as low microbial biomass C (MBC) and N (MBN) (Wyland et al., 1996; Table 1). This offered the opportunity to study cover crop decomposition in a situation where soil microbes undoubtedly experience low C availability during most of the year. The main objectives were to (i) describe the changes in soil responses and <sup>15</sup>N fates to addition of a <sup>15</sup>N-labeled low C/N cover crop under field management conditions, (ii) determine <sup>15</sup>N losses during the first year after cover crop addition, and (iii) assess management implications on the basis of information on the rates of release and availability of cover crop N.

## MATERIALS AND METHODS

The trial was located at the Rural Development Center in the Salinas Valley in the Central Coast region of California, on a field that had been cropped with drip-irrigated zucchini (*Cucurbita pepo* L.) in summer, and left bare through the fall and winter. The general plan of the experiment was to incorporate fresh residue of <sup>15</sup>N-labeled phacelia ('Phaci') in the spring into cylinders that had been previously driven into the soil and to measure subsequent accumulation of <sup>15</sup>N in various N pools through time. No control treatment without a cover crop was included due to time and cost constraints. Thus, this study tracks temporal changes in many variables after cover crop addition.

The soil type was a Chualar loamy sand (fine-loamy, mixed, thermic, Typic Argixeroll) with a high percentage of sand at 0 to 75 cm (Table 1), but with higher silt and clay content in the bottom depth below 75 cm. Water-holding capacity was low. It was higher in the surface (0-15 cm) than in the two middle depths (15-45 and 45-75 cm), but increased in the bottom-most layer. Soil organic C and N were low, even in the surface soil, and decreased with depth except for the lowest depth where clay content was higher. Soil pH and cation-exchange capacity (CEC) were slightly lower in the surface soil than at deeper depths. Soil bulk density was considerably lower in the surface than at the next two lower depths. Environmental data were obtained from a weather station ≈ 500 m from the study site (University of California Statewide Integrated Pest Management Project, 1994).

The experimental area was divided into four blocks running perpendicular to the beds, each 16 m long and 4 m wide. The zucchini plants were disked on 6 November 1993, and beds were listed and shaped on 19 November. On 28 February, polyvinyl chloride cylinders were inserted into the soil in two beds. Eight large cylinders per block were pushed into the soil using a backhoe, leaving 3 cm above the soil surface. The

cylinders were 25.4 cm in diameter and 60 cm deep, with a sharpened bottom edge that facilitated installation and helped to prevent soil compaction. Ion exchange resin bags (Wyland and Jackson, 1993), 23 cm<sup>2</sup> and containing ≈ 10 g of AG 1-X8 anion exchange resin, were inserted beneath three cylinders in each block to monitor NO<sub>3</sub><sup>-</sup>-N leaching. Based on previous studies (Wyland and Jackson, 1993), the maximum capacity of these IER bags to adsorb NO<sub>3</sub><sup>-</sup>-N was ≈ 16 g m<sup>-2</sup>. One cylinder in each block contained tensiometers at 15 and 45 cm, which were monitored weekly during the first 4 mo after incorporation.

Phacelia was planted in pots in a greenhouse in late December 1993 and watered with a dilute Hoagland's solution containing <sup>15</sup>(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> and K<sup>15</sup>NO<sub>3</sub> continuously from planting until harvest. The plants were removed from their pots on 18 March. The soil was washed from the roots, and the plant material was divided into shoots, clean roots, and roots slightly contaminated with organic matter fragments. The biomass was divided into equal portions, with each cylinder receiving an amount equivalent to 360.3 g dry shoots m<sup>-2</sup>, 97.6 g dry clean roots m<sup>-2</sup>, and 20.5 g dry contaminated roots m<sup>-2</sup>. Analysis of N, <sup>15</sup>N, and C in plant material was with a Europa Scientific ANCA-MS (Europa Scientific, Crewe, UK) at the Department of Soil Science, University of California at Berkeley. Shoots, clean roots, and contaminated roots contained 14.3, 11.5, and 8.2 atom % <sup>15</sup>N, respectively, so that each cylinder received a total of 77.6 mg <sup>15</sup>N (i.e., 1.53 g <sup>15</sup>N m<sup>-2</sup> or 11.37 g N m<sup>-2</sup>) from the cover crop residue. The C/N ratio of the cover crop material was 19:1.

A soil sample was collected from each block prior to residue incorporation, and background <sup>15</sup>N levels were determined at all depths. Actual mowing and disking practices were simulated while incorporating the residue. The residue was chopped into 4- to 8-cm pieces and mixed into the 0- to 15-cm soil layer in each cylinder on 20 March. Tillage was simulated with trowels and knives to incorporate the residue and again 22 d later. One week after residue incorporation, sprinkler irrigation delivered 32 mm of water. Two small rainfall events delivered 10 mm of precipitation shortly thereafter. Throughout the experiment, fertilizers were applied in a manner and rate equivalent to best management practices for commercially grown lettuce. An unlabeled, typical pre-plant fertilizer (356 kg ha<sup>-1</sup> of 5-17-17; i.e., 1.78 g N m<sup>-2</sup>) was banded at 10- to 12-cm depth in the planting line of the cylinder to simulate growers' practices at 32 d after residue incorporation (DAI). During the next 4 d, 25 mm of rainfall occurred. Crisphead lettuce ('Target') was planted in the cylinders at 45 DAI (3 May), and starter fertilizer was added at that time (381 kg ha<sup>-1</sup> of 5-20-3-1; i.e., 1.9 g N m<sup>-2</sup>). Seedlings were thinned to one plant per cylinder. One additional fertilizer application occurred at 85 DAI (238 kg ha<sup>-1</sup> of 20-0-0-5; i.e., 4.75 g N m<sup>-2</sup>). Thus, a total of 8.43 g N m<sup>-2</sup> was added as inorganic fertilizer to the crop. During the first crop, sprinklers were used to apply 150 mm of water from planting through the first 5 wk, and another 260 mm through harvest. Rainfall during the crop was only 9 mm, giving 419 mm of total water inputs.

The lettuce in the cylinders was harvested at 116 DAI on 14 July. A second crop was planted on 22 August and was managed with the same fertilizer and irrigation practices as the first crop. It was thinned on 15 September and harvested on 9 November. Irrigation input was 340 mm of water and rainfall was 15 mm, giving a total of 355 mm during the second crop. Harvest of the second crop occurred at 234 DAI and 79 d after planting.

Cylinder samples were taken 3, 14, and 28 DAI, at mid-crop and harvest of the first crop (72 and 116 DAI), at mid-crop and harvest of the second crop (179 and 234 DAI), and 1 yr after incorporation, on 27 March 1995. Samples taken on the first five sampling dates were analyzed for inorganic N ( $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N), moisture content, MBC and MBN, and  $^{15}\text{N}$  enrichment in  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N, and MBN. Resin bags were sampled at 28, 72, and 116 DAI. Total soil  $^{15}\text{N}$  including undecomposed residue was measured prior to cover crop incorporation and then at 14, 72, 116, 234, and 365 DAI.

One cylinder per block was excavated on each sampling date. The entire soil core was removed in layers (0–15, 15–30, 30–60 cm), and a soil core was obtained from beneath the cylinders (60–75 cm). Each soil layer was weighed, mixed thoroughly, and subsampled immediately for KCl-extractable  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N (100 g soil in 250 g 2 M KCl; three replicates per layer per cylinder), gravimetric soil moisture, and MBC and MBN (0–15 and 15–30 cm soil layers only, two replicates per layer). Only the upper two layers were sampled for microbial biomass, since previous work showed very low levels below 30 cm. The 0- to 15-cm layer was sieved (2-mm mesh) prior to subsampling for MBC, MBN, and inorganic N so that extraction of C and N from undecomposed plant material would not confound these measurements. Also, it was not initially possible to take subsamples of soil with representative amounts of plant material due to the large size of the residue pieces. Thus, these data represent pools in the soil, and do not include microbial and inorganic pools present on the decomposing residue. An unsieved subsample was retained for determination of total organic soil N and its  $^{15}\text{N}$  enrichment. Inorganic N was measured from the KCl extracts of soils and IER bags using a Wescan ammonia analyzer (Alltech Assoc., Inc., Deerfield, IL), with a reduction column for  $\text{NO}_3^-$ -N determination (Carlson, 1978, 1986). Microbial biomass was determined using the fumigation–extraction technique of Brookes et al. (1985), a modified Kjeldahl digestion for N content (Wyland et al., 1994), and a dichromate digestion for C content (Vance et al., 1987). The flush of C and N after fumigation was converted to MBC and MBN using the published values of 2.64 (Vance et al., 1987) and 1.86 (Shen et al., 1984), respectively.

To prepare KCl extracts and the Kjeldahl digests of the fumigated and control MBN extracts for  $^{15}\text{N}$  analysis, the diffusion technique of Brooks et al. (1989) was used. It was modified for diffusion of Kjeldahl digests by using 10 mL of 10 M NaOH rather than MgO to volatilize  $\text{NH}_3$ . When necessary, a  $^{14}\text{N}$  internal standard was added to spike samples that were low in N prior to diffusion. Lettuce shoots and roots harvested from the cylinders were oven-dried at 65°C, weighed, ground to a powder in a ball mill at 200 rpm for 4 h, then subsamples were weighed into tin disks for combustion in a mass spectrometer. Soil samples were prepared for  $^{15}\text{N}$  of total soil N (0–30 cm depth) analysis by grinding with a mortar and pestle, sieving (2 mm mesh), then grinding any sieved-out plant residue, and returning it to the sample and mixing well. A 40-g subsample was then ground in a ball mill at 200 rpm for 4 h before subsamples were weighed and wrapped in tin disks for combustion in the mass spectrometer. The  $^{15}\text{N}$  analysis was conducted at the University of California, Berkeley, on a mass spectrometer (Automated Nitrogen and Carbon Analyzer, Europa Scientific, Crewe, UK). Percentage recovery of  $^{15}\text{N}$  in

each N pool of the added  $^{15}\text{N}$  in the cover crop was calculated as described in Hauck (1982) and Wyland et al. (1995), using the basic equation:

Percentage recovery of  $^{15}\text{N}$  =

$$\left( \frac{[\text{N}(A_o/100)] - [\text{N}(A_i/100)]}{^{15}\text{N}_a} \right) 100 \quad [1]$$

where N is grams  $^{14+15}\text{N}$  per square meter of sample (KCl extract, Kjeldahl digest, soil combustion for organic N, lettuce, or flush of N in MBN extracts),  $A_o$  is the atom percent  $^{15}\text{N}$  of sample,  $A_i$  is the atom percent  $^{15}\text{N}$  prior to addition of  $^{15}\text{N}$ -labeled cover crop residue, and  $^{15}\text{N}_a$  is grams  $^{15}\text{N}$  per square meter of cover crop N added to the soil. The portion of each N pool that was derived from cover crop N was calculated as:

$$\text{Portion derived from cover crop N} = \left( \frac{N_o / ^{15}\text{N}_a}{^{14+15}\text{N}_a} \right) 100 \quad [2]$$

where  $N_o$  is the grams  $^{15}\text{N}$  per square meter of sample, and  $^{14+15}\text{N}_a$  is the grams  $^{14+15}\text{N}$  per square meter of cover crop N added to the soil.

Statistical analyses were performed in SAS (SAS Institute, 1985), using analysis of variance and GLM procedures. Differences between means were assessed with the REGW Multiple Range Test. In Table 1, mean comparisons are not shown due to the large numbers of comparisons. For these data, any significant changes noted in the text are at  $P < 0.05$ .

## RESULTS

### Fates of Cover Crop Nitrogen During the First Four Months

#### Soil Moisture and Temperature

This loamy sand soil remained consistently moist throughout the first 4 mo after residue incorporation. In late March, cover crop residue was incorporated into moist soil, which averaged 0.065 g  $\text{H}_2\text{O}$  g $^{-1}$  soil in the 0- to 15-cm, 0.086 g  $\text{H}_2\text{O}$  g $^{-1}$  soil in the 15- to 30-cm, and 0.085 g  $\text{H}_2\text{O}$  g $^{-1}$  soil in the 30- to 60-cm layer. Thus, matric potential was above  $-0.03$  MPa at all depths (Table 1). At subsequent samplings, moisture was fairly constant at similar values because water availability was maintained with typical management practices to prevent moisture stress in this shallow-rooted crop (data not shown). Tensiometer readings at the 15- and 45-cm depths remained above  $-10$  kPa until mid June, but thereafter decreased to approximately  $-25$  and  $-15$  kPa at the two depths, respectively, before irrigation was applied.

Air temperatures gradually increased during the post-incorporation period, with mean daily air temperatures of 12, 13, 14, 16, and 16°C in March, April, May, June, and July, respectively (University of California Statewide Integrated Pest Management Project, 1994). Corresponding mean soil temperatures at the 15-cm depth were 13, 18, 19, 22, and 21°C. The 4 mo following incorporation of the plant residue were generally free of clouds and fog.

#### Soil Microbial Biomass

Microbial biomass was initially very low, but increased markedly in the first 2 wk after cover crop incorporation, followed by a sharp decline (Fig. 1c and 2). At the onset of the experiment prior to incorporation

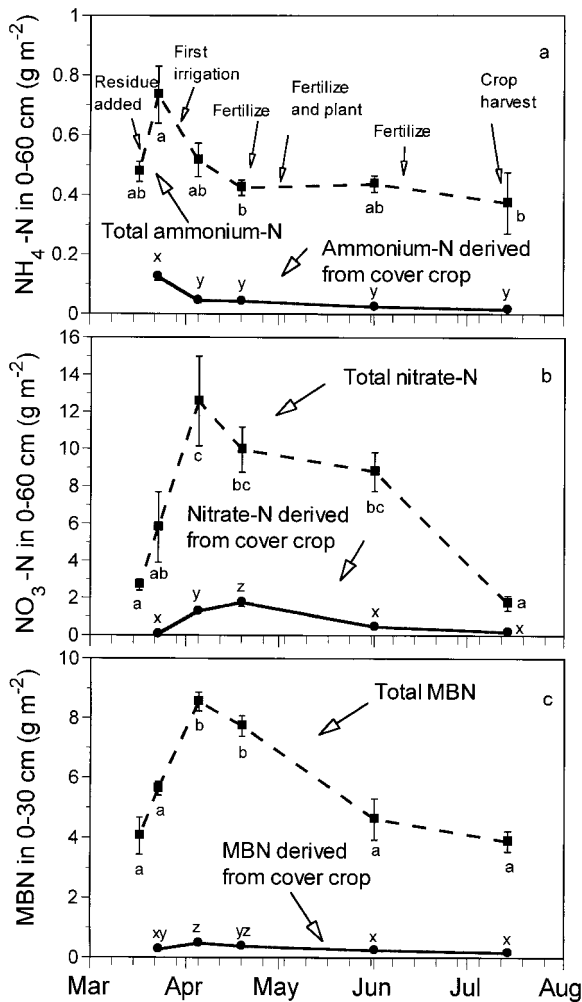


Fig. 1. Temporal changes in N pools ( $\text{g N m}^{-2}$  at  $0\text{-}60\text{ cm}$  depth) and the amount of N derived from the fresh residue of *Phacelia tanacetifolia*, based on  $^{15}\text{N}$  accumulation in the soil pools. (a)  $\text{NH}_4^+\text{-N}$ , (b)  $\text{NO}_3^-\text{-N}$ , and (c) Microbial biomass N (MBN). Data are shown from prior to addition of cover crop residue until harvest of lettuce 4 mo later. Means  $\pm$  SE. Lowercase letters indicate mean separations. Note the difference in the magnitude of the y axis among graphs.

of cover crop residue, MBN was  $15\text{ mg N kg}^{-1}$  soil (Table 2) and MBC was  $300\text{ mg C kg}^{-1}$  soil (data not shown) in the  $0\text{-}$  to  $15\text{-cm}$  layer of soil. At this time, there were  $4\text{ g N m}^{-2}$  (Fig. 1c) and  $85\text{ g C m}^{-2}$  (Fig. 2) as microbial biomass at the  $0\text{-}$  to  $30\text{-cm}$  depth. Immediately after incorporation, a rapid and significant increase in MBN occurred in the first 3 d in the surface ( $0\text{-}15\text{ cm}$ ) layer (Table 2). A slight decrease in MBN also occurred at  $15\text{-}$  to  $30\text{-cm}$  depth at this time. Since its  $^{15}\text{N}$  enrichment was above ambient levels, some residue was probably incorporated deeper than the intended  $15\text{-cm}$  depth. During the subsequent week, MBN continued to increase (Table 2 and Fig. 1c). For the next 2 wk, no significant change occurred in MBN. During the subsequent 6 wk ( $28\text{-}72\text{ DAI}$ ), MBN declined to the same level before the incorporation of cover crop residue, and remained at this level until lettuce harvest ( $116\text{ DAI}$ ).

Little of the increase in MBN was derived from the cover crop (Table 2 and Fig. 1c). During the initial increase of MBN that was sampled 3 d after incorporation, only 5% of the MBN was derived from the residue.

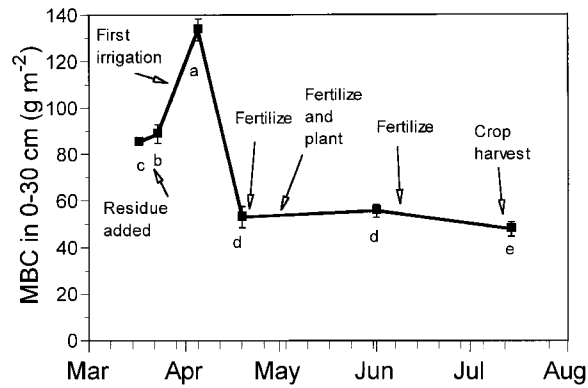


Fig. 2. Changes in soil microbial biomass C (MBC,  $\text{g C m}^{-2}$  at  $0\text{-}30\text{ cm}$  depth) during the first 4 mo after incorporation of fresh cover crop residue. Means  $\pm$  SE. Lowercase letters indicate mean separations.

Likewise, in later samples only 5 to 7% of the MBN was derived from the residue, despite increasing amounts of MBN in the soil. The amount of MBN derived from cover crop N was highest from 14 to 28 DAI and never exceeded  $0.5\text{ g N m}^{-2}$  ( $0\text{-}30\text{ cm}$ ) during the 4 mo after incorporation of plant residue. The proportion of the MBN pool that was derived from cover crop N remained fairly constant during the first 4 mo after incorporation, indicating that cover crop-derived N was still available to any fraction of the MBN that was turning over.

Microbial biomass C increased following incorporation (Fig. 2), with a pronounced increase between 3 and 14 DAI, but 2 wk later, MBC had decreased to below its pre-incorporation levels and remained constant during the subsequent 3 mo. The C/N ratio of the microbial biomass decreased during this period, starting initially at 20:1, then declining to 16:1 between 1 and 2 wk after incorporation of residue and to 7:1 at 4 wk after incorporation, and thereafter remaining at  $\approx 12:1$  (Fig. 1c and 2).

### Soil Nitrogen

In the surface layer ( $0\text{-}15\text{ cm}$ ),  $\text{NO}_3^-\text{-N}$  concentration responded fairly quickly to the simulated tillage and the addition of residue, and  $\approx 30\%$  was derived from cover crop N during the first 2 to 4 wk (Table 2). At 3 DAI,  $\text{NO}_3^-\text{-N}$  concentrations had doubled compared with initial values. Only a small but significant fraction was derived from cover crop N at this time, indicating that a pulse of  $\text{NO}_3^-\text{-N}$  production occurred in the  $0\text{-}$  to  $15\text{-cm}$  layer initially in response to the soil disturbance rather than the addition of residue. Thereafter, at 14 DAI, the  $\text{NO}_3^-\text{-N}$  concentration in the surface soil remained high, and one-third of it was derived from cover crop N. During the next week, the concentration of  $\text{NO}_3^-\text{-N}$  increased, and a high percentage was still derived from residue. By the middle of the crop period ( $72\text{ DAI}$ ),  $\text{NO}_3^-\text{-N}$  in the surface soil had decreased significantly, and this decline continued through harvest ( $116\text{ DAI}$ ), as did the percentage of  $\text{NO}_3^-\text{-N}$  derived from the residue.

Nitrate from the surface soil moved to lower depths by 2 wk after incorporation of residue, as indicated by the significant increase between 3 and 14 DAI (Table 2). A small amount was derived from cover crop residue.

**Table 2. Concentrations of NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, and microbial biomass N (MBN) in the soil after cover crop incorporation, and the percentage derived from the N in the cover crop residue, as calculated from <sup>15</sup>N concentrations.**

	Prior to incorporation	Days after incorporation				
		3	14	28 (before planting)	72 (mid-crop)	116 (harvest)
<b>N concentrations†</b>						
— mg kg dry soil <sup>-1</sup> —						
<b>Depth 1 (0–15 cm)</b>						
MBN	14.9 ± 1.51	23.1 ± 1.2	30.5 ± 1.2	27.6 ± 1.4	17.3 ± 1.8	13.1 ± 1.1
NH <sub>4</sub> <sup>+</sup> -N	0.9 ± 0.08	1.2 ± 0.1	0.6 ± 0.03	0.7 ± 0.02	0.5 ± 0.04	1.3 ± 0.2
NO <sub>3</sub> <sup>-</sup> -N	6.3 ± 0.44	12.8 ± 0.7	15.8 ± 2.0	22.0 ± 0.9	12.2 ± 0.7	6.3 ± 1.4
<b>Depth 2 (15–30 cm)</b>						
MBN	5.5 ± 0.9	4.5 ± 0.6	8.7 ± 0.4	8.5 ± 1.3	5.0 ± 0.9	5.0 ± 0.2
NH <sub>4</sub> <sup>+</sup> -N	0.5 ± 0.04	0.5 ± 0.05	0.6 ± 0.06	0.4 ± 0.02	0.4 ± 0.03	0.1 ± 0.01
NO <sub>3</sub> <sup>-</sup> -N	1.5 ± 0.2	1.7 ± 0.5	8.4 ± 1.5	11.2 ± 0.5	8.1 ± 0.4	0.7 ± 0.2
<b>Depth 3 (30–60 cm)</b>						
NH <sub>4</sub> <sup>+</sup> -N	0.3 ± 0.02	0.6 ± 0.1	0.4 ± 0.03	0.3 ± 0.01	0.4 ± 0.2	0.1 ± 0.02
NO <sub>3</sub> <sup>-</sup> -N	2.1 ± 0.3	5.5 ± 1.7	13.0 ± 2.3	5.0 ± 0.8	8.0 ± 0.5	0.5 ± 0.1
<b>Depth 4 (60–75 cm)</b>						
NH <sub>4</sub> <sup>+</sup> -N	0.2 ± 0.08	0.4 ± 0.2	0.4 ± 0.02	0.3 ± 0.05	0.4 ± 0.03	0.2 ± 0.03
NO <sub>3</sub> <sup>-</sup> -N	24.4 ± 9.08	12.0 ± 6.1	13.0 ± 1.8	10.5 ± 2.5	6.5 ± 1.0	1.0 ± 0.2
<b>Derived from residue†</b>						
— % —						
<b>Depth 1 (0–15 cm)</b>						
MBN	—	5.1 ± 0.4	6.9 ± 0.7	6.0 ± 0.3	6.9 ± 0.5	5.2 ± 0.5
NH <sub>4</sub> <sup>+</sup> -N	—	55.5 ± 4.1	31.2 ± 2.9	24.4 ± 1.2	11.7 ± 2.6	7.3 ± 2.4
NO <sub>3</sub> <sup>-</sup> -N	—	2.0 ± 0.1	31.5 ± 0.7	29.9 ± 1.8	11.4 ± 2.6	6.1 ± 0.5
<b>Depth 2 (15–30 cm)</b>						
NH <sub>4</sub> <sup>+</sup> -N	—	0.5 ± 0.1	1.3 ± 0.2	1.5 ± 1.8	4.3 ± 0.9	9.5 ± 1.1
NO <sub>3</sub> <sup>-</sup> -N	—	0	8.9 ± 2.7	12.3 ± 1.5	3.9 ± 0.9	7.4 ± 1.7
MBN	—	3.1 ± 1.5	2.0 ± 0.04	1.4 ± 0.04	2.1 ± 0.2	2.1 ± 0.1
<b>Depth 3 (30–60 cm)</b>						
NH <sub>4</sub> <sup>+</sup> -N	—	0.5 ± 0.05	0.7 ± 0.1	1.6 ± 0.2	3.1 ± 1.4	2.3 ± 0.5
NO <sub>3</sub> <sup>-</sup> -N	—	0	0	2.2 ± 0.7	2.8 ± 1.4	27.9 ± 5.8
<b>Depth 4 (60–75 cm)</b>						
NH <sub>4</sub> <sup>+</sup> -N	—	0.9 ± 0.5	2.9 ± 2.8	0.7 ± 0.2	0.3 ± 0.5	1.1 ± 0.3
NO <sub>3</sub> <sup>-</sup> -N	—	0	0	0	0	6.3 ± 3.3

† Mean ± standard error.

The first irrigation event of 32 mm occurred at 7 DAI. Concentrations and <sup>15</sup>N enrichment of NO<sub>3</sub><sup>-</sup>-N continued to increase at lower depths through the middle of the lettuce crop period. The proportion of NO<sub>3</sub><sup>-</sup>-N derived from residue at the second depth (15–30 cm) increased significantly by the time of planting, and there was a slight but significant enrichment of NO<sub>3</sub><sup>-</sup>-N in depth 3 (30–60 cm) at this time. By harvest, NO<sub>3</sub><sup>-</sup>-N concentrations had decreased at all depths, and <sup>15</sup>N enrichment was present at all depths from 0 to 75 cm.

In terms of the total NO<sub>3</sub><sup>-</sup>-N pool in the profile (g N m<sup>-2</sup> at 0–60 cm depth), a rapid rise occurred during the first 2 wk after incorporation of plant residue, and remained high from before planting through the middle

of the crop period, during which time N fertilizer was applied twice (Fig. 1b). A large decrease occurred in the last month of the crop period when lettuce had the highest N uptake (Table 3). The amount of NO<sub>3</sub><sup>-</sup>-N derived from cover crop N was highest from 14 to 28 DAI and never exceeded 2.0 g N m<sup>-2</sup> (0–60 cm) during the 4-mo period after incorporation of plant residue.

The IER bags at the 60-cm depth give an estimate of cumulative NO<sub>3</sub><sup>-</sup>-N leached throughout the 4-mo period (Fig. 3). Just before lettuce planting, some leaching had occurred (2.2 g m<sup>-2</sup>), but none of the leachate was residue-derived. By the middle of the crop, there was a trend toward higher accumulation of NO<sub>3</sub><sup>-</sup>-N in the IER bags (4.3 g m<sup>-2</sup>), but differences were not significant.

**Table 3. Nitrogen in the two lettuce crops after cover crop incorporation and the percentage derived from the N in the cover crop residue, as calculated from <sup>15</sup>N concentrations.**

	Nitrogen in lettuce			
	Days after incorporation			
	72 (Mid-crop, first crop)	116 (Harvest, first crop)	179 (Mid-crop, second crop)	234 (Harvest, second crop)
<b>N pools†</b>				
— g m <sup>-2</sup> —				
<b>Shoots</b>	0.625 ± 0.123	23.35 ± 3.333	0.060 ± 0.020	11.16 ± 1.755
<b>Roots</b>	0.168 ± 0.024	2.48 ± 0.254	0.005 ± 0.001	1.52 ± 0.629
<b>Derived from residue†</b>				
<b>Shoots</b>	9.70 ± 0.605	9.20 ± 0.768	3.69 ± 0.807	4.63 ± 0.978
<b>Roots</b>	9.19 ± 0.601	8.25 ± 0.599	2.90 ± 0.166	3.84 ± 0.708

† Mean ± standard error.

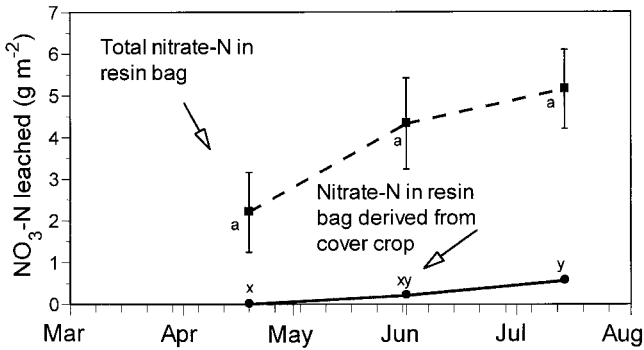


Fig. 3. Leaching of NO<sub>3</sub>-N as indicated by accumulation of NO<sub>3</sub>-N in ion exchange resin bags at the 60-cm depth in the soil profile during the first 4 mo after incorporation of fresh cover crop residue. The percentage of N derived from *Phacelia tanacetifolia* residue is also shown. Means ± SE. Lowercase letters indicate mean separations. See Fig. 1a for the dates of agricultural management practices.

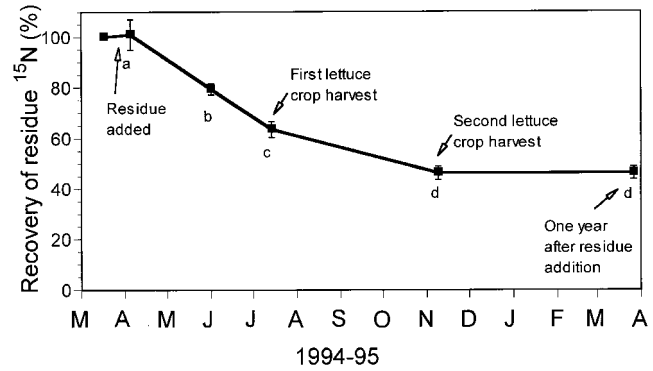


Fig. 4. Recovery of <sup>15</sup>N in total soil N (including NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, microbial biomass N, soil organic N, and residue fragments) from the <sup>15</sup>N-labeled residue of *Phacelia tanacetifolia* in the 0- to 30-cm soil depth during 1 yr after incorporation of fresh cover crop residue. Means ± SE. Lowercase letters indicate mean separations.

At this time, a greater proportion (4.8%) was derived from the residue. Despite the large decrease in the NO<sub>3</sub><sup>-</sup>-N pool during the last month of the crop period (Fig. 1b), the rate of accumulation of NO<sub>3</sub><sup>-</sup>-N in the resin bag was low but a higher proportion was derived from the residue (Fig. 3). At lettuce harvest, 5.1 g NO<sub>3</sub><sup>-</sup>-N m<sup>-2</sup> had accumulated in the IER bag at the 60-cm depth, 11% of which was residue-derived. Since the capacity of the bags was not exceeded (see above), most of the loss of soil NO<sub>3</sub><sup>-</sup>-N during the last month (Fig. 1b) is best attributed to plant uptake, and possibly to denitrification (see below), but not to substantial leaching.

Throughout the entire period, NH<sub>4</sub><sup>+</sup>-N concentrations were <2 mg N kg<sup>-1</sup> soil in the surface soil (0–15 cm depth), and the total NH<sub>4</sub><sup>+</sup>-N pool in the profile never exceeded 0.8 g N m<sup>-2</sup> at the 0- to 60-cm depth, with very little contribution from cover crop-derived N (Table 2 and Fig. 1a). However, 3 d after incorporation, one-half of the NH<sub>4</sub><sup>+</sup>-N in the surface layer was derived from cover crop residue, even though the total concentration was still only ≈1 mg kg<sup>-1</sup> soil. The NH<sub>4</sub><sup>+</sup>-N concentration and its percentage derived from the residue had declined by 14 DAI, and contribution from cover crop N declined thereafter. Slight <sup>15</sup>N enrichment of NH<sub>4</sub><sup>+</sup>-N was measured sporadically in the lower depths through the post-incorporation period (Table 2), but it is difficult to interpret these results.

The recovery of <sup>15</sup>N in the total soil N pool (0–30 cm), which included inorganic N and MBN as well as other organic N and any remaining undecomposed residue, declined steadily at successive sampling dates after incorporation (Fig. 4). By harvest of the first crop, only 63.5 ± 3.1% of the added <sup>15</sup>N was recovered in the total soil N.

**Crop Nitrogen Uptake**

As is typical for direct-seeded lettuce, N in shoots and roots accumulated slowly for the first 6 wk after planting, then rapidly increased during the last month before harvest (Table 3). Lettuce head formation and size was normal, as evidenced by mean plant dry weight

in the cylinders, which was 44 g plant<sup>-1</sup>, a typical value for crisphead lettuce (Jackson et al., 1994).

Lettuce plants assimilated 20.7% of the N from the cover crop residue N by harvest at 116 DAI (Fig. 5 and Table 3). Similar <sup>15</sup>N enrichment was measured in the roots and the shoots. Cover crop N contributed 9.1% of the lettuce N.

**Fates of Nitrogen-15 at Harvest of the First Lettuce Crop**

At the harvest of the first lettuce crop, 4 mo after incorporation of cover crop residue, the total recovery of <sup>15</sup>N in various plant and soil pools (0–60 cm depth) was 88.9% of the added amount in the residue (Fig. 5). Most of the <sup>15</sup>N remained in the soil organic N pool, yet a substantial fraction was in the lettuce crop. Only 1.4% of the <sup>15</sup>N was retained in the MBN by crop harvest. Similarly, little <sup>15</sup>N was present as inorganic N. As an indication of leaching below the 60-cm depth, the IER bag accumulated 4.7% of the <sup>15</sup>N from the cover crop. Another 11.1% of the <sup>15</sup>N from the cover crop could not be accounted for.

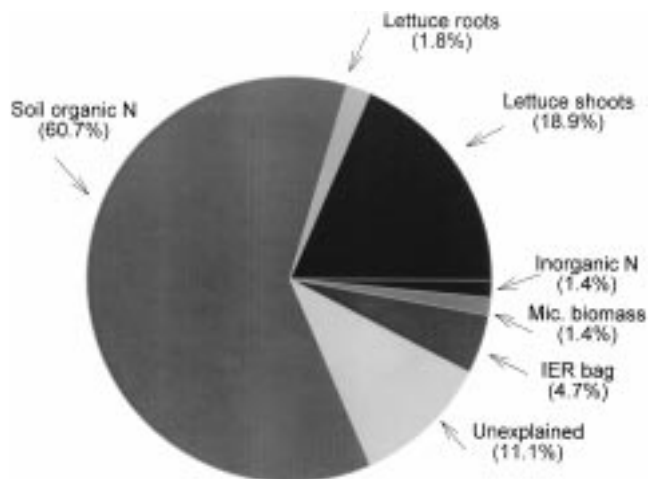


Fig. 5. Proportion of the added <sup>15</sup>N in *Phacelia tanacetifolia* residue that was recovered in different plant and soil components at harvest of the first lettuce crop, which was 4 mo after residue incorporation. Means ± SE.

### Nitrogen-15 Fates in Subsequent Seasons

The second crop of lettuce used much less cover crop-derived N than did the first crop (Table 3). Only  $5.1 \pm 0.6\%$  of the cover crop N was present in this lettuce crop at harvest maturity. This accounted for 4.5% of the N in this lettuce crop. Total growth and N accumulation were lower due to cooler temperatures.

Recovery of  $^{15}\text{N}$  derived from the cover crop as total soil N continued to decline during the period between July and November, but at a slower rate than during the initial 4 mo (Fig. 4). However, there was no change between November 1994 and the sample at 1 yr after cover crop incorporation in March 1995; both samples contained  $46.1 \pm 2.1\%$  of the added  $^{15}\text{N}$ . At this time, following the winter fallow, MBC was at the same pre-incorporation values as in the previous year (data not shown).

## DISCUSSION

Incorporation of phacelia residue resulted in active decomposition, but little assimilation of residue-derived N by the microbial biomass. Despite the marked increase in MBN, little MBN was derived from the residue. Part of the increase in  $\text{NO}_3^-$ -N and MBN during the first 2 wk after incorporation of the plant material may have been a response to soil disturbance and soil rewetting rather than simply a release of N from the decomposing residue. The plant residue may have supplied a temporary source of available C for microbes, who then met their own N demand mainly with soil-derived N rather than cover crop-derived N, but were instrumental in releasing cover crop-derived N that was readily mineralized and nitrified (see below). During the next few months, plants used a fairly high proportion of cover crop-derived N ( $\approx 20\%$ ) with relatively low soil N loss. Soil organic  $^{15}\text{N}$  continued to decline for the next 3 mo, but was of minor importance as a source of N for the second lettuce crop. The sandy soil texture probably offered little protection for decomposing material, and this may have hastened the decomposition rate (Ladd et al., 1995). Dilution from a larger pool of exogenous soil N would have further reduced the recovery of  $^{15}\text{N}$  by the second crop (Crozier et al., 1998). Thereafter, no change occurred in soil organic  $^{15}\text{N}$ , suggesting that the N remaining from the cover crop residue was no longer readily available for net mineralization.

### Microbial Biomass and Nitrogen Mineralization of Plant Residue

Despite the twofold increase in MBC and MBN following cover crop incorporation, the  $^{15}\text{N}$  enrichment of the MBN remained very low and relatively constant throughout the postincorporation and subsequent cropping periods. Soil microbial biomass appears to have been relying primarily upon soil or microbially derived N, rather than cover crop-derived N. Microorganisms in soil have been found to prefer microbial cell material over straw as a N substrate, even when the straw had a low C/N ratio of 14:1 (Jawson et al., 1989). Amato and

Ladd (1980) found that isotopically labeled microbial biomass was a more labile N pool than plant residue. Dead microbial biomass has been identified as a primary component of native soil available N (Marumoto et al., 1982).

In another study on the Chualar soil, soil mixing and disruption of aggregates caused a sudden decline in MBN, as determined by fumigation–extraction, and in most microbial groups, as determined by phospholipid fatty acid analysis (Calderón et al., in press). In our study, soil disturbance during incorporation of cover crop residue into the soil may have killed a portion of the microbial biomass, thereby possibly producing a preferred N source to other microbes whose growth was stimulated by cover crop-derived C. This could partially account for the much lower  $^{15}\text{N}$  enrichment of the MBN compared with high enrichment of  $^{15}\text{N}$  in the  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$ -N pools. This explanation is consistent with the idea that the microbial biomass that is newly formed from the decomposition of plant residue is partly associated with the residue and partly located within the soil matrix (Ladd et al., 1995), giving it close proximity to available N in the soil. Another source of soil-derived N may have been  $\text{NO}_3^-$ -N. Microbial immobilization of the large pool of unlabeled  $\text{NO}_3^-$ -N may have been stimulated by the temporary availability of cover crop-derived C (Jackson et al., 1989; Azam et al., 1993). In either of these scenarios, soil microbes would be relying on different substrates for C vs. N assimilation.

The microbes that were decomposing the fresh phacelia residue experienced conditions of relatively high moisture content. The soil was kept consistently moist. Phacelia leaves and stems are slightly succulent, and the added residue had a high water content. Shoot material contained 86% moisture. Water availability may have been important for the movement of organisms between the surfaces of soil particles and decomposing plant residue. Water films may have also promoted the transport and diffusion of water soluble carbohydrates and  $\text{NO}_3^-$ -N back and forth between phacelia residue and soil particles. The mixing of these compounds could have been facilitated by the sandy soil texture. Thus, one factor that might partially explain the microbial utilization of C and N substrates from different sources could be enhanced movement of organisms and decomposition products in water films.

Rapid mineralization of C and N is to be expected in sandy soils, where there is little clay and silt to protect microbial biomass and microbial decay products (van Veen et al., 1987; Ladd et al., 1995). Similar rates of net N mineralization of residue to this study were found in response to incorporation of  $^{15}\text{N}$ -labeled white mustard (*Sinapis alba* L.) catch-crop material (C/N of 15:1) in an agricultural field on a sandy loam soil (Jensen, 1992). More rapid rates (44% mineralized in only 18 d) were observed when crimson clover (*Trifolium incarnatum* L.) shoots were incorporated into a gravelly loam soil (Crozier et al., 1998). However,  $^{15}\text{N}$ -labeled leguminous material (C/N of 15:1) in a medic pasture mineralized N more slowly, and  $^{15}\text{N}$  in the MBN accounted for a higher proportion of added  $^{15}\text{N}$  than in our study (Ladd

et al., 1981a). Their soil (Roseworthy) had fairly similar particle-size distribution (82, 4, and 12% sand, silt, and clay, respectively) and organic C ( $7.3 \text{ g kg}^{-1}$ ) as the Chualar soil (Ladd et al., 1981a), but microbial biomass was approximately two times higher (Amato and Ladd, 1980). After 1 yr of decomposition, Ladd et al. (1981a) recovered 52% of the legume residue in the topsoil of the medic pasture, but 39% of the white mustard (Jensen, 1992) and 45% of the phacelia residue (this study) were recovered from agricultural soils. These are not large differences, but they tend to confirm that tilled soils, especially sandy soils, have less ability to retain N, possibly due to C limitation, compared with undisturbed agricultural or grassland soils where N retention is generally higher (Follett and Schimel, 1989; Biederbeck et al., 1994).

### Nitrogen Fates and Losses

By the end of the first lettuce crop at 4 mo after cover crop incorporation,  $\approx 40\%$  of the  $^{15}\text{N}$  in the cover crop had been mineralized (Fig. 5). A substantial fraction was present in the lettuce crop, and a relatively low proportion was leached. The small percentage of the  $^{15}\text{N}$  that was not accounted for could have been lost by denitrification, or possibly may represent experimental error. Given the small amount of microbial immobilization of cover crop N and the propensity for leaching in this sandy soil, retention of  $^{15}\text{N}$  within the soil-plant system (0–60 cm) was quite high ( $>80\%$ ) during the first 4 mo after incorporation. Low rainfall in the spring contributed to the high recovery of  $^{15}\text{N}$ . In regions with higher spring rainfall, greater proportions of cover crop-derived N can be lost (Bremer and van Kessel, 1992; Harris et al., 1994). Although most of the cover crop-derived  $\text{NO}_3^- \text{-N}$  was retained within the rooting zone, nearly  $5 \text{ g NO}_3^- \text{-N m}^{-2}$  derived from soil and fertilizer were leached during the first crop of lettuce (Fig. 3). Most of this leaching occurred within a month of seeding, when lettuce plants had low N demand. Nearly  $3 \text{ g NO}_3^- \text{-N m}^{-2}$  were present in the soil column just before plant residues were incorporated; this would presumably have been lower if the cover crop had actually been grown in situ. In this study, fertilizer applications were split so that more N was available in the last wk prior to harvest in this slow-growing crop. Also, irrigation was applied to match crop demand (Gallardo et al., 1996). Appropriate scheduling of fertilizer and irrigation also undoubtedly contributed to the lower leaching rate later in the crop growth period.

Uptake of cover crop-derived N by the first lettuce crop was fairly high considering that it was harvested only 10 wk after planting. In several other studies using  $^{15}\text{N}$ -labeled leguminous residue with C/N ratios of  $\approx 10:1$  to  $20:1$ , subsequent corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.) crops recovered 8 to 28% of the added  $^{15}\text{N}$  (Ladd et al., 1981b; Varco et al., 1989; Harris and Hesterman, 1990; Crozier et al., 1998). These cereal crops were grown for periods of 4 to 7 mo, providing a longer period for plant uptake of mineralized  $^{15}\text{N}$  than occurs with lettuce. The second lettuce crop recovered

a smaller fraction of cover crop-derived N than the first crop, and total  $^{15}\text{N}$  recovery in plants during the 7-mo period between cover crop incorporation and second crop harvest was 25% of the applied  $^{15}\text{N}$ .

The first crop of lettuce utilized  $26 \text{ g N m}^{-2}$ , of which  $23 \text{ g N m}^{-2}$  was derived from non-cover crop sources. Fertilizer N can account for at most one-third of the lettuce N uptake. Mineralized N derived from sources of soil organic matter other than the cover crop must have been the major source of crop N. In fact, the importance of net mineralization and nitrification is demonstrated by the substantial  $\text{NO}_3^- \text{-N}$  produced during the subsequent 2 wk after cover crop incorporation. An increase of  $\approx 8 \text{ g NO}_3^- \text{-N m}^{-2}$  (0–60 cm depth) from non-cover crop sources occurred at this time, and may be partially attributed to N mineralization in response to soil disturbance and irrigation. Later studies have confirmed that soil mixing and aeration immediately stimulate  $\text{NO}_3^- \text{-N}$  production in this soil, even when plant residue is not simultaneously incorporated (Calderón et al., in press). Rewetting can also initiate a large burst of  $\text{NO}_3^- \text{-N}$  production (Davidson et al., 1993).

In summary, this study has shown that cover crop N became readily available in the sandy soil of this vegetable crop system. Although microbes mediate this process, little N from the plant residue was retained in the microbial biomass. Instead, much of the N that was released from the cover crop was rapidly nitrified, leading to  $\text{NO}_3^- \text{-N}$  accumulation in the soil. Irrigation and fertilizer management of the subsequent crop are consequently very important for maximizing plant uptake and minimizing the loss of  $\text{NO}_3^- \text{-N}$  derived from mineralization of N in the cover crop material.

### ACKNOWLEDGMENTS

I thank Lisa Wyland for help with data collection and sample preparation. I am grateful to Greg Lazzarini, Bill Tarp, and the Rural Development Center for their help with field operations. Funding for this research was provided by the USDA-EPA Agriculture in Concert with the Environment Program Project 91-COOP-1-6590, USDA-SARE Project SW96-016, and the California Iceberg Lettuce Advisory Board.

### REFERENCES

- Aulakh, M.S., J.W. Doran, D.T. Walters, A.R. Moier, and D.D. Francis. 1991. Crop residue type and placement effects on denitrification and mineralization. *Soil Sci. Soc. Am. J.* 55:1020–1025.
- Amato, M., and J.N. Ladd. 1980. Studies of nitrogen immobilization and mineralization in calcareous soils. V. Formation and distribution of isotope-labeled biomass during decomposition of  $^{14}\text{C}$  and  $^{15}\text{N}$ -labeled plant material. *Soil Biol. Biochem.* 12:405–411.
- Azam, F., F.W. Simmons, and R.L. Mulvaney. 1993. Immobilization of ammonium and nitrate and their interaction with native N in three Illinois Mollisols. *Biol. Fertil. Soils* 15:50–54.
- Biederbeck, V.O., H.H. Janzen, C.A. Campbell, and R.P. Zentner. 1994. Labile soil organic matter as influenced by cropping practices in an arid environment. *Soil Biol. Biochem.* 26:1647–1656.
- Brandi-Dohrn, F.M., R.P. Dick, M. Hess, S.M. Kauffman, D.D. Hemphill, Jr., and J.S. Selker. 1997. Nitrate leaching under a cereal rye cover crop. *J. Environ. Qual.* 26:181–188.
- Bremer, E., and C. van Kessel. 1992. Plant-available nitrogen from lentil and wheat residues during a subsequent growing season. *Soil Sci. Soc. Am. J.* 56:1155–1160.

- Brookes, P.C., A. Landman, G. Pruden, and D.S. Jenkinson. 1985. Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biol. Biochem.* 17:837–842.
- Brooks, P.D., J.M. Stark, B.B. McInteer, and T. Preston. 1989. Diffusion method to prepare soil extracts for automated nitrogen-15 analysis. *Soil Sci. Soc. Am. J.* 53:1707–1711.
- Calderón, F.J., L.E. Jackson, K.M. Scow, and D.E. Rolston. 2000. Microbial responses to simulated tillage in cultivated and uncultivated soils. *Soil Biol. Biochem.* (In press).
- Carlson, R.M. 1978. Automated separation and conductimetric determination of ammonia and dissolved carbon dioxide. *Anal. Chem.* 50:1528–1532.
- Carlson, R.M. 1986. Continuous flow reduction of nitrate to ammonium with granular zinc. *Anal. Chem.* 58:1590–1591.
- Creamer, N.G., M.A. Bennett, and B.R. Stinner. 1997. Evaluation of cover crop mixtures for use in vegetable production systems. *HortScience* 32:866–870.
- Crozier, C.R., L.D. King, and R.J. Volk. 1998. Tracing nitrogen movement in corn production systems in the North Carolina Piedmont: A nitrogen-15 study. *Agron. J.* 90:171–177.
- Davidson, E.A., P.A. Matson, P.M. Vitousek, R. Riley, K. Dunkin, G. Garcia-Mendez, and J.M. Maass. 1993. Processes regulating soil emissions of NO and N<sub>2</sub>O in a seasonally dry tropical forest. *Ecology* 74:130–139.
- Follett, R.F., and D.S. Schimel. 1989. Effect of tillage practices on microbial biomass dynamics. *Soil Sci. Soc. Am. J.* 53:1091–1096.
- Gallardo, M., L.E. Jackson, K. Schulbach, R.L. Snyder, R.B. Thompson, and L.J. Wyland. 1996. Production and water use in lettuces under variable water supply. *Irrig. Sci.* 16:125–137.
- Harris, G.H., and O.B. Hesterman. 1990. Quantifying the nitrogen contribution from alfalfa to soil and two succeeding crops using nitrogen-15. *Agron. J.* 82:129–134.
- Harris, G.H., O.B. Hesterman, E.A. Paul, S.E. Peters, and R.R. Jahnke. 1994. Fate of legume and fertilizer nitrogen-15 in a long-term cropping systems experiment. *Agron. J.* 86:910–915.
- Hauck, R.D. 1982. Nitrogen-isotope ratio analysis. p. 735–779. In A.L. Page et al. (ed.) *Methods of soil analysis*. Part 2. 2nd ed. ASA, CSSA, and SSSA, Madison, WI.
- Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jaworski, K. Lajtha, J.A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kudeyarov, P. Murdoch and Z. Zhao-Liang. 1996. Regional nitrogen budgets and riverine N and P fluxes for the drainages to the North Atlantic Ocean: Natural and human influences. *Biogeochemistry* 35:75–139.
- Jackson, L.E., J.P. Schimel, and M.K. Firestone. 1989. Short-term partitioning of ammonium and nitrate between plants and microbes in an annual grassland. *Soil Biol. Biochem.* 21:409–415.
- Jackson, L.E., L.J. Wyland, and L.J. Stivers. 1993. Winter cover crops to minimize nitrate losses in intensive lettuce production. *J. Agric. Sci. (Cambridge)* 121:55–62.
- Jackson, L.E., L.J. Stivers, B.T. Warden, and K.K. Tanji. 1994. Crop nitrogen utilization and soil nitrate loss in a lettuce field. *Fert. Res.* 37:93–105.
- Jawson, M.D., L.F. Elliott, R.I. Papendick, and G.S. Campbell. 1989. The decomposition of <sup>14</sup>C-labeled wheat straw and <sup>15</sup>N-labelled microbial material. *Soil Biol. Biochem.* 21:417–422.
- Jensen, E.S. 1992. The release and fate of nitrogen from catch-crop materials decomposing under field conditions. *J. Soil Sci.* 43: 335–345.
- Kuo, S., U.M. Sainju, and E. Jellum. 1997. Winter cover cropping influence on nitrogen in soil. *Soil Sci. Soc. Am. J.* 61:1392–1399.
- Ladd, J.N., M. Amato, P.R. Grace, and J.A. van Veen. 1995. Simulation of <sup>14</sup>C turnover through the microbial biomass in soils incubated with <sup>14</sup>C-labelled plant residues. *Soil Biol. Biochem.* 27:777–783.
- Ladd, J.N., J.M. Oades, and M. Amato. 1981a. Microbial biomass formed from <sup>14</sup>C, <sup>15</sup>N-labelled plant material decomposing in soils in the field. *Soil Biol. Biochem.* 13:119–126.
- Ladd, J.N., J.M. Oades, and M. Amato. 1981b. Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. *Soil Biol. Biochem.* 13:251–256.
- Legg, J.O., and J.J. Meisinger. 1982. Soil nitrogen budgets. p. 503–566. In F.J. Stevenson (ed.) *Nitrogen in agricultural soils*. Agron. Monogr. 22. ASA, CSSA, and SSSA, Madison, WI.
- Lundquist, E.J., L.E. Jackson, K.M. Scow, and C. Hsu. 1999. Changes in microbial biomass and community structure, and soil carbon and nitrogen pools after incorporation of rye into three California agricultural soils. *Soil Biol. Biochem.* 31:221–236.
- Marumoto, T., J.P.E. Anderson, and K.H. Domsch. 1982. Decomposition of <sup>14</sup>C and <sup>15</sup>N-labelled microbial cells in soil. *Soil Biol. Biochem.* 14:461–467.
- Ranells, N., and M.G. Wagger. 1997a. Grass-legume bicultures as winter annual cover crops. *Agron. J.* 89:659–665.
- Ranells, N., and M.G. Wagger. 1997b. Nitrogen-15 recovery and release by rye and crimson clover cover crops. *Soil Sci. Soc. Am. J.* 61:943–948.
- SAS Institute. 1985. *SAS user's guide: Statistics*. 5th ed. SAS Inst., Cary, NC.
- Shen, S.M., G. Pruden, and D.S. Jenkinson. 1984. Mineralization and immobilization of nitrogen in fumigated soil and the measurement of microbial biomass nitrogen. *Soil Biol. Biochem.* 16:437–444.
- Shennan, C. 1992. Cover crops, nitrogen cycling, and soil properties in semi-irrigated vegetable production systems. *HortScience* 27: 749–754.
- University of California Statewide Integrated Pest Management Project. 1994. Division of Agriculture and Natural Resources, Univ. of California. Available at <http://www.ipm.ucdavis.edu>. (verified 30 Mar. 2000).
- Vance, E.D., P.C. Brookes, and D.S. Jenkinson. 1987. An extraction method for measuring soil microbial biomass C. *Soil Biol. Biochem.* 19:703–707.
- van Veen, J.A., J.N. Ladd, J.K. Martin, and M. Amato. 1987. Turnover of carbon, nitrogen and phosphorus through the microbial biomass in soils incubated with <sup>14</sup>C-, <sup>15</sup>N- and <sup>32</sup>P-labelled bacterial cells. *Soil Biol. Biochem.* 19:559–565.
- Varco, J.J., W.W. Frye, M.S. Smith, and C.T. MacKown. 1989. Tillage effects on nitrogen recovery by corn from a nitrogen-15 labeled legume cover crop. *Soil Sci. Soc. Am. J.* 53:822–827.
- Wyland, L.J., and L.E. Jackson. 1993. Evaluating nitrate recovery by ion-exchange resin bags. *Soil Sci. Soc. Am. J.* 57:1208–1211.
- Wyland, L.J., L.E. Jackson, and P.D. Brooks. 1994. Eliminating nitrate interference during Kjeldahl digestion of soil extracts for microbial biomass determination. *Soil Sci. Soc. Am. J.* 58:357–360.
- Wyland, L.J., L.E. Jackson, and K.F. Schulbach. 1995. Soil–plant nitrogen dynamics following incorporation of a mature rye cover crop in a lettuce production system. *J. Agric. Sci. (Cambridge)* 124:17–25.
- Wyland, L.J., L.E. Jackson, W.E. Chaney, K. Klonsky, S.T. Koike, and B. Kimple. 1996. Altering surface soil dynamics with cover crops in a vegetable cropping system: Impacts on yield, nitrate leaching, pests and management costs. *Agric. Ecosyst. Environ.* 59:1–17.
- Zhang, M.H., S. Geng, and K.S. Smallwood. 1998. Assessing groundwater nitrate contamination for resource and landscape management. *Ambio* 27:170–174.