Journal of Agricultural Science, Cambridge (1993), **121**, 55–62.

Winter cover crops to minimize nitrate losses in intensive lettuce production

L. E. JACKSON, L. J. WYLAND* AND L. J. STIVERS

Department of Vegetable Crops, University of California, Davis, CA 95616, USA

(*Revised MS received 30 October 1992*)

SUMMARY

A 2-year study conducted in Salinas, California in 1989–91 showed that soil nitrate (NO_3–N) concentrations were reduced by cover crops during a short winter fallow period and that this practice can be compatible with year-round vegetable crop production schedules by planting and incorporating cover crops directly on the beds into which the lettuce crop will be direct seeded in the early spring. Cover crops grown the first year were oilseed radish (*Raphanus sativus* cv. Renova), white senf mustard (*Brassica hirta* cv. Martigena), white mustard (*Brassica alba*), phacelia (*Phacelia tanacetifolia* cv. Phaci), rye (*Secale cereale* cv. Merced) and annual ryegrass (*Lolium multiflorum*). Only phacelia and Merced rye were included in the second year. In both years, all of the cover crops depleted soil NO_3-N and soil moisture relative to the fallow control. Estimates of cover crop root length, based on core sampling to 60 cm soil depth, averaged 18800 m/m² after 17 weeks of growth the first year and 12500 m/m² after 13 weeks of growth the second year. Above-ground dry matter production averaged 449 g/m² (12·8 g N/m²) the first year and 161 g/m² (6·1 g N/m²) during a shorter growing period and under the more adverse growing conditions of the second year. Following cover crop incorporation with a rotary tiller, soil ammonium (NH_4-N), NO_3-N and net mineralizable N (anaerobic incubation) peaked after *c.* 1 week, then gradually declined for 1 month. Cover-cropped plots sustained higher net mineralizable N levels than the fallow control after incorporation. Nitrate concentrations after spring rains were lower in soils left fallow during winter. The subsequent lettuce crop was not affected by cover crop treatment.

INTRODUCTION

Groundwater contamination caused by leaching of soil nitrate (NO_3-N) during winter is an increasing problem in crop production, because excess soil NO_3-N can accumulate from both residual fertilizer nitrogen (N) and by mineralization of soil organic matter during a winter fallow. Cover crops grown during an otherwise fallow period can reduce NO_3-N leaching during winter (Muller *et al.* 1988; Powlson 1988; Radke *et al.* 1988). Cover crops can also improve soil structure and increase soil organic matter and microbial biomass following incorporation in the spring (Bolton *et al.* 1985; Roberson *et al.* 1991). Non-leguminous cover crops have been shown to immobilize as much as 70% of the available NO_3-N in the upper soil profile (Muller *et al.* 1988). Microbial activity increases after the incorporation of plant residues (Schnürer *et al.* 1985; Ocio *et al.* 1991). Increased microbial activity, in turn, has been shown to promote soil aggregate stability and thereby improve structure and water infiltration in agricultural soils (Williams 1966; Tisdall & Oades 1982; Roberson *et al.* 1991). Cover cropping may also reduce the potential for soil compaction caused by heavy machinery in the spring by lowering soil moisture content (Flocker *et al.* 1959).

To reduce NO_3-N leaching during winter, an effective cover crop must be capable of rapid winter growth, extensive root development and must tolerate the environmental stresses of winter without supplemental inputs (Meisinger *et al.* 1991). In vegetable production systems where planting occurs early in the spring, the desirable attributes of a cover crop are ease of incorporation and a minimum of residue present at planting. The inorganic N derived from the cover crops may be released more slowly than fertilizer N, depending upon rates of microbial cycling of both N and C (Smith *et al.* 1987), which may better coincide with the N demand of the subsequent crop.

In many agricultural systems, the fallow period is brief (2–5 months) and the time between incorporation of a cover crop and planting of the subsequent cash crop must be minimized. Irrigated vegetable pro-

* To whom correspondence should be addressed.

duction in California is done primarily on raised beds in a system designed for furrow irrigation and precision cultivation. One way to integrate cover cropping into the crop production schedules of this region may be to plant and incorporate cover crops directly on established beds rather than planting on the flat, disking and reshaping the beds prior to crop seeding. This would permit the use of lighter equipment in preparing the field in the spring, which would minimize soil compaction under high soil moisture conditions. Cover crops grown on pre-formed beds during late autumn and winter have been shown to reduce soil erosion and compaction (Estler 1991; Roberts & Cartwright 1991). Techniques for incorporating cover crops on pre-formed beds will apply to subsurface drip irrigation systems which use semi-permanent beds, because the shallow cultivation will not damage the drip lines buried at *c.* 15–20 cm.

Control of NO_3-N leaching during the period of winter rainfall is of critical importance in the high-input, intensive vegetable production systems of the central coast region of California, where the ground is typically prepared in the autumn for planting in late winter or early spring. Nitrate contamination of groundwater is a serious problem in this area (MCFCWCD 1988). The objective of the present study was to evaluate the ability of six non-leguminous cover crops to reduce NO_3-N leaching and improve N cycling. Selected taxa were again considered more critically in the second year of the study. Growth rate, root development and soil N and water uptake during winter were evaluated. Soil N dynamics following incorporation of the cover crops on the beds and their effect on the subsequent lettuce crop were also investigated.

MATERIALS AND METHODS

In 1989 an experiment comparing six non-leguminous winter cover crops was established in Salinas, California on an Antioch loam (fine-loamy, mixed, thermic Typic Argixeroll) with pH 6·7, CEC 18·8 cmol/kg, and 12 600 mg/kg organic carbon. The design was a randomized complete block with three replicate blocks. The cover crop species and seeding rates were: oilseed radish (*Raphanus sativus* cv. Renova), 8·0 kg/ha; white senf mustard (*Brassica hirta* cv. Martigena), 6·3 kg/ha; white mustard (*Brassica alba*), 5·2 kg/ha; phacelia (*Phacelia tanacetifolia* cv. Phaci), 3·9 kg/ha; rye (*Secale cereale* cv. Merced), 17·5 kg/ha; and annual ryegrass (*Lolium multiflorum*), 8·7 kg/ha. A bare fallow plot, treated with paraquat (1,1′-dimethyl-4,4′-bipyridinium, applied at 56 kg/ha) to eliminate weeds and subsequently hand cultivated, was included in each block as a control. Cover crops were planted on 15 November 1989, in two 12 m rows (42 cm apart) on beds 1 m from furrow centre to centre. The field was sprinkler irrigated with 1·2 cm of water once after seeding.

Soil samples were taken on 15 November 1989, 7 January and 8 March 1990, at 0–15, 15–30 and 30–60 cm depths (two 4 cm diameter cores per plot, mixed and subsampled). Cores were taken from the centre of the beds to avoid edge effects. The field-moist soil was immediately extracted in 2N KCl (5–10 g soil in 25 ml KCl), and the supernatant was frozen until analysis for NH_4-N and NO_3-N content with a Wescan ammonium analyser (Alltech Assoc Inc, Deerfield, IL), using a reduction process to measure NO_3-N (Carlson 1978, 1986). Gravimetric soil moisture content was determined for each sample. In March, a separate set of 4 cm diameter soil cores was taken at 0–30 and 30–60 cm depths directly within the cover crop plant row and midway between the plant rows in the centre of the beds. Roots were washed free of soil and root length was measured on a Comair root scanner (Hawker de Haviland, Victoria, Australia). Above-ground plant material was collected from a 0·5 m^2 area on one bed in each plot in January and March. Above-ground plant and root samples were oven dried at 65 °C, weighed and analysed for total N by the Kjeldahl method. Root length (m/m^2) and root weight (g/m^2) in the beds only were estimated by extrapolation of root length (cm/cm^3) and root weight ($\mu g/cm^3$) densities in sample cores to densities in the entire bed using a model that assigned weightings of measured values perpendicular to the plant rows as follows: I = $(a/2)$; II, IV, V = $(a+c/2)$; III = (a) and VI = (c) where a = root length density (cm/cm^3) in mid-row cores and c = root length density (cm/cm^3) in mid-bed cores. Roman numerals I–VI refer to one-sixth wide segments of the distance from mid-furrow to mid-bed, beginning with the furrow segment. Root length and weight at the 30–60 cm depths were calculated in the same manner.

Cover crops were incorporated into the beds to a depth of 15–20 cm with a rotary tiller (Marvin 'Rowmaster' bedshaper/incorporator, Landplane Co, Woodland, CA) on 20 March 1990. Ammonium sulphate fertilizer was applied at a rate of 85 kg N/ha, and 'Salinas' lettuce was direct-seeded on 10 April. Soil samples (0–15 cm depth) were taken weekly from 20 March (just prior to incorporation) until the end of June, and analysed for NH_4-N and NO_3-N. Net mineralizable N was measured in 100 g subsamples using a 7-day anaerobic incubation procedure (Waring & Bremner 1964). Data are expressed as net change in NH_4-N concentration over the incubation period.

In the second year of the study, a different section of the field was disked and bedded on 9 November 1990, and was seeded with phacelia and Merced rye on 13 November. A randomized complete block design was used and plots were seeded in two 8 m rows on bed tops (0·75 m wide). A fallow plot was

included in each block as a control and the treatments were replicated six times. Preplanting soil samples at 0–15, 15–30 and 30–60 cm depths were taken on 12 November and inorganic and net mineralizable N were measured as previously described. The field was sprinkler irrigated with 1·2 cm of water once after seeding. Tensiometers (2725 series, SoilMoisture Corp, Santa Barbara, CA) were installed at 20 and 40 cm depths in each treatment in three of the blocks, and readings were obtained weekly until cover crop incorporation in February.

Soil samples were taken on 2 January and 12 February 1991, from the same depths and using the same extraction and analytical techniques as previously described. Above-ground plant samples and root samples from 0–30 and 30–60 cm depths, from within and between plant rows, were also collected on these dates. Root length and total N content of above- and below-ground plant material were determined as described for the first year.

Cover crops were incorporated into the beds with a rotary tiller on 12 February 1991. Soil samples (0–15 cm depth) were collected with a 8·5 cm diameter soil corer every 2 or 3 days for the first 2·5 weeks following incorporation and then weekly until the end of March. These samples were coarse-sieved (2 mm mesh) and 100 g of sieved soil was extracted in 250 ml 2N KCl and analysed for NH_4-N and NO_3-N using the procedures described above. Net mineralizable N was measured on separate 100 g subsamples.

The field was rototilled and direct seeded with 'Salinas' lettuce on 26 April, after 56 kg N/ha ammonium sulphate had been broadcast on the previous day. Soil samples were taken from the middle of the bed on 5 April prior to planting and during the lettuce cropping period at thinning (6 June) and harvest (11 July). These samples, taken at depths of 0–15, 15–30 and 30–60 cm, were analysed for NH_4-N, NO_3-N and net mineralizable N. Above-ground lettuce samples were collected at harvest (ten heads/plot), dried, weighed and analysed for total N by the Kjeldahl method.

Statistical analyses were conducted with the SAS program (SAS Institute 1985), using ANOVA and GLM procedures.

RESULTS

Uptake of nitrogen by cover crops and depletion of soil nitrate

All the winter cover crops grown in 1989/90 significantly depleted soil NO_3-N relative to the bare soil control by the time of incorporation (Fig. 1). Soil NO_3-N concentrations averaged 82·5 μg NO_3-N/g dry soil (0–15 cm depth) and 66·8 μg NO_3-N/g dry soil (15–30 cm depth) at the time of planting. By March, mean values in the cover-cropped plots were 1·7 and 6·3 μg NO_3-N/g dry soil at the two soil depths, respectively. In contrast, NO_3-N concentrations in the bare soil control were 17·5 and 20·8 μg NO_3-N/g dry soil at the two depths in March. Soil NO_3-N concentrations decreased from the early growth stages of the cover crops (January) to the time of incorporation (March) compared with bare soil.

Rapid cover crop growth during winter was demonstrated by the increase in above-ground biomass from January to March (Table 1). Above-ground dry matter (DM) in January ranged from 5·0 to 54·6 g/m²; the most rapid early growth occurred with

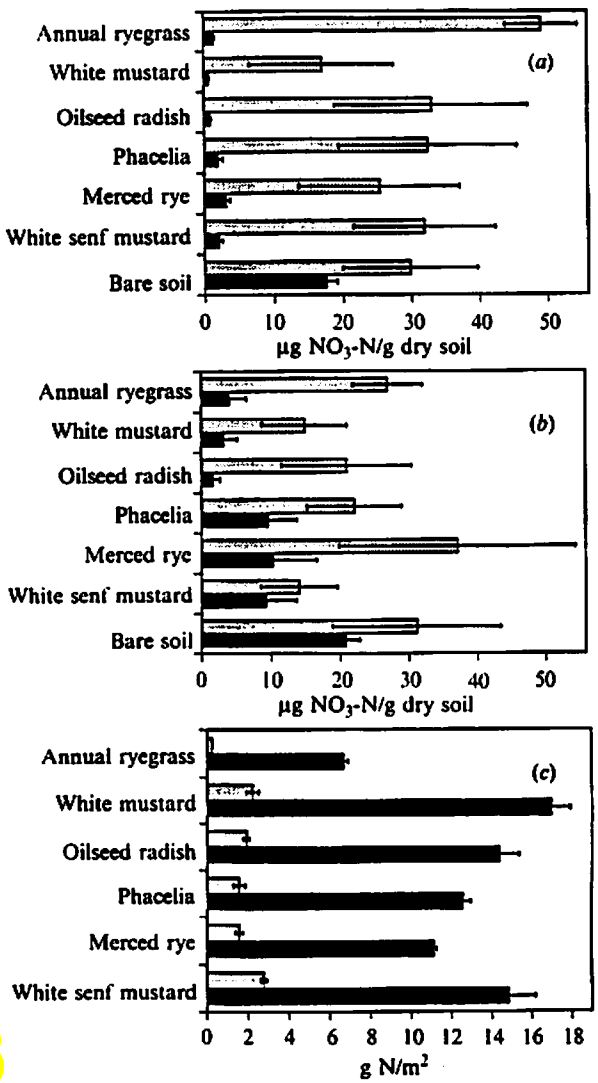

Fig. 1. Mean nitrate concentration at (*a*) 0–15 cm and (*b*) 15–30 cm soil depth and (*c*) N content of above-ground cover crop biomass (g/m²) at midseason in January (□) and at incorporation in March 1990 (■). Horizontal lines represent S.E. (D.F. error = 12 for soil nitrate samples and 10 for biomass samples).

Table 1. *Mean biomass (g/m²), root length (m/m²) and total N content (g/m²) of six cover crops grown in 1989/90. Cover crops were planted 15 November 1989, sampled on 7 January and 8 March 1990 and were incorporated on 20 March 1990. Root length and biomass are estimates, based on extrapolations from sampled cores*

Cover crop	Above-ground biomass (g/m²) Jan 1990	Above-ground biomass (g/m²) Mar 1990	Root biomass (g/m²) Mar 1990	Root length (m/m²) Mar 1990	Total plant N (g/m²) Mar 1990
Oilseed radish	43·3	412·8	286·7	15300	20·0
White mustard	43·8	591·3	227·3	22200	20·5
White senf mustard	54·6	589·3	59·2	13100	16·1
Phacelia	32·7	455·2	150·2	19800	18·2
Merced rye	28·7	441·0	95·0	19600	12·9
Annual ryegrass	5·0	207·0	88·3	22700	8·5
S.E. (D.F. = 10)	4·23	20·13	68·08	2818·8	2·02

the brassicas and the slowest with annual ryegrass. In March, above-ground DM ranged from 207 to 591·3 g/m². Total above- and below-ground (as estimated from the root cores) plant N content at incorporation ranged from 8·5 g N/m² in annual ryegrass, to 20·5 g N/m² in white mustard.

Root length and biomass at incorporation similarly indicate extensive root development under these non-irrigated winter conditions (Table 1). Specific root length (m root/g DM), which provides a measure of root thickness, was lowest (*c.* 50–100 m/g) for oilseed radish and white mustard, which develop a thicker tap root, and highest for the grasses and white senf mustard (20–26 m/g) which have a more fibrous root system. The specific root length of phacelia was intermediate (13 m/g).

Phacelia and Merced rye were the two cover crops chosen for the second year of the study. The winter of 1990/91 differed from the previous year by having below normal precipitation (63·8 mm of rainfall from planting to incorporation; which is 151 mm below average and 157·2 mm less than the previous year), freezing temperatures in December (minimum < 0 °C for 11 consecutive days) and above normal temperatures in February (mean = 11·9 °C).

Soil NO_3-N concentrations increased during winter in all treatments during this unusually dry period (Table 2). Variation in soil NO_3-N concentration was high at the beginning of the growing season (Table 2), but no significant differences among treatments existed. At the time of incorporation, the NO_3-N concentrations in the rye cover-cropped treatments (0–60 cm depth) were significantly lower than the bare soil (Table 2). Similar trends were observed between phacelia and bare plots, but variation between plots may account for the lack of significant differences. Soil moisture in the upper soil profile in the cover-cropped treatments (0–15 cm) was also significantly lower than the control by the time of incorporation (Table 2). Tensiometer readings indicated that by week 9 after planting, soil water potential averaged −0·06 MPa in the cover-cropped plots and −0·025 MPa in the bare plots. By the end of January

Table 2. *Mean gravimetric soil moisture content (%) and mean soil nitrate concentration (μg/g dry soil) at different soil depths at intervals (weeks after planting) during the growth of cover crops in the winter of 1990/91*

Soil depth (cm)	Sampling time… Cover crop	Planting	Week 7	Week 12
	Gravimetric soil moisture (%)			
0–15	Phacelia	9·3	13·0	9·0
	Merced rye	8·4	13·0	9·9
	Bare soil	9·2	13·6	12·6
	S.E. (10 D.F.)	0·53	0·31	0·37
15–30	Phacelia	11·9	13·4	10·5
	Merced rye	12·0	13·2	11·4
	Bare soil	11·4	13·5	13·1
	S.E. (10 D.F.)	0·45	0·34	0·39
30–60	Phacelia	15·0	15·5	15·0
	Merced rye	14·3	15·7	13·0
	Bare soil	14·2	15·7	15·9
	S.E. (10 D.F.)	0·31	0·39	0·84
	Soil nitrate concentration (μg NO_3-N/g dry soil)			
0–15	Phacelia	49	29	98
	Merced rye	29	32	79
	Bare soil	42	26	112
	S.E. (10 D.F.)	11·6	8·3	16·3
15–30	Phacelia	8	23	72
	Merced rye	6	27	66
	Bare soil	10	17	94
	S.E. (10 D.F.)	2·7	7·5	9·5
30–60	Phacelia	8	10	81
	Merced rye	9	7	72
	Bare soil	5	5	85
	S.E. (10 D.F.)	2·9	2·6	9·8

(week 11), soil water potential had dropped below the range of the tensiometers in the cover-cropped plots, while it remained at or above −0·03 MPa in the bare soil plots.

Above-ground DM was 10·4 g/m² for phacelia and 6·8 g/m² for Merced rye in January 1991, and increased to 159·0 and 162·1 g/m² for phacelia and Merced rye, respectively, by incorporation on 12 February 1991. There were no significant differences between the two species. Total plant N content at incorporation averaged 7·5 g N/m² for phacelia and Merced rye.

Root DM (0–60 cm depth) at incorporation in 1991 was estimated to be 47·5 and 50·0 g/m² for phacelia and Merced rye respectively. Estimated root length at incorporation in 1991 was 12500 m/m² for both phacelia and Merced rye. Allocation to shoots and roots was approximately the same: 77 and 23% for phacelia and 76 and 24% for Merced rye. Slightly higher specific root lengths were measured in 1991 (26·3 m/g for phacelia and 25 m/g for Merced rye).

Soil N following incorporation

Soil NO_3-N, NH_4-N and net mineralizable N underwent rapid changes following cultivation with a rotary tiller to incorporate cover crops (Fig. 2*a*, *b* and *c*). A large pulse of NO_3-N occurred in all treatments immediately following incorporation (Fig. 2*a*). Nitrate concentrations were significantly higher in the bare treatment compared to the cover-cropped treatments 2 days after incorporation and remained higher until after the first rain in March. Soil NO_3-N concentration in the bare soil was significantly lower than in the cover-cropped plots by day 37 of the post-incorporation time series measurements. Ammonium concentrations in the cover-cropped soils were significantly higher than the bare soil 4 days after incorporation (Fig. 2*b*), and remained higher until 4 weeks after incorporation. Net mineralizable N in cover-cropped soils was significantly higher than the bare soil immediately after incorporation until day 7 (Fig. 2*c*).

Nitrate concentrations had much lower starting values at the time of incorporation in the first year of the study. Ammonium and net mineralizable N in cover-cropped soils also increased following incorporation in 1990, and then decreased as they did in 1991, although the peak concentrations attained in 1990 were much greater than in 1991 (NH_4-N concentrations of 17 and 19 μg NH_4-N/g dry soil and net mineralizable N concentrations of 49 and 81 μg NH_4-N/g dry soil for phacelia and Merced rye, respectively).

Soil NO_3-N and NH_4-N concentrations following lettuce planting and fertilization in late April 1991 were not affected by cover cropping. Data for the 0–15 cm soil depths are shown in Table 3. Nitrate

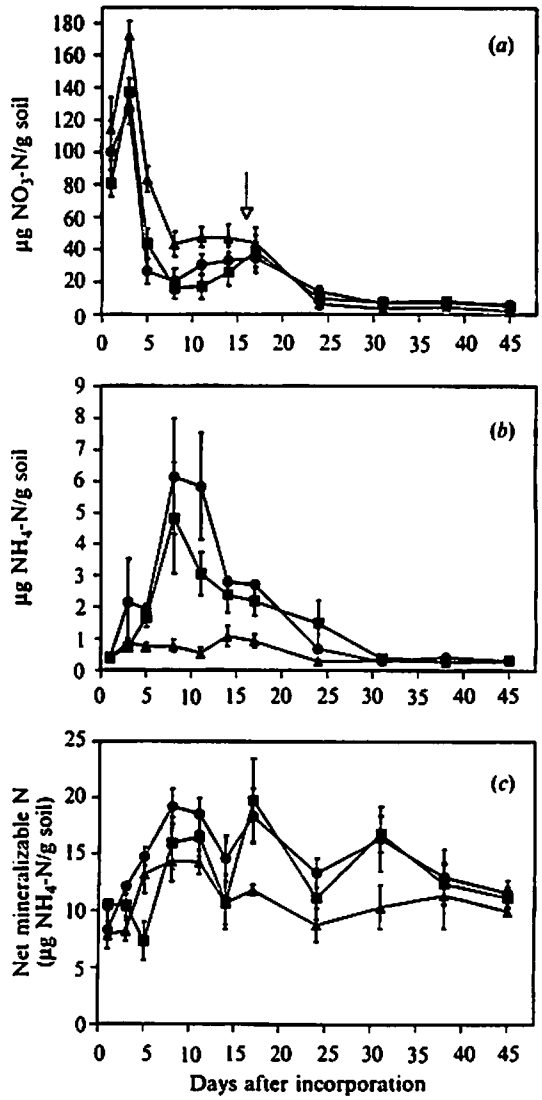

Fig. 2. Mean (*a*) soil nitrate, (*b*) ammonium and (*c*) net mineralizable N in the upper 15 cm soil depth following cover crop incorporation on 12 February 1991. Phacelia (■), Merced rye (●) and bare soil (▲). The arrow represents rainfall. Vertical lines represent S.E. (D.F. error = 15).

concentrations in the 15–30 cm depths ranged from 9·0 to 19·2 μg NO_3-N/g dry soil on all three sampling dates. Concentrations in the 30–60 cm depth ranged from 12·1 to 24·0 μg NO_3-N/g dry soil. Net mineralizable N in the top soil layer decreased in all treatments after fertilization of the lettuce crop (Table 3). There was no significant difference found between treatments at any soil depth.

Lettuce yield was not affected by cover cropping in 1991. Data were incomplete for the first year. Above-ground DM of lettuce at harvest in 1991 was 312, 290

Table 3. *Mean soil nitrate, ammonium and net mineralizable N concentrations* (μg *N/g dry soil*) *(0–15 cm depth) at three stages during the lettuce cropping period. 1991. Dates of cover crop incorporation, fertilization, and lettuce planting were 12 February, 25 April and 26 April, respectively*

Growth stage... Cover crop	Pre-planting 5 April	Thinning 6 June	Harvest 11 July
	Soil nitrate		
Phacelia	10	30	12
Merced rye	10	27	20
Bare soil	7	60	23
S.E. (10 D.F.)	1·3	9·5	4·3
	Soil ammonium		
Phacelia	0·2	0·5	0·2
Merced rye	0·3	0·5	0·3
Bare soil	0·3	0·8	0·2
S.E. (10 D.F.)	0·10	0·42	0·02
	Soil net mineralizable N		
Phacelia	10·7	3·7	5·8
Merced rye	10·2	4·0	3·2
Bare soil	8·2	6·1	4·5
S.E. (10 D.F.)	0·68	1·12	1·57

and 252 g DM/m² for the phacelia, Merced rye and bare treatments, respectively. There were no significant differences in lettuce N content between treatments.

DISCUSSION

The results of this study demonstrate that winter cover crops have the capacity to deplete soil NO_3-N pools relative to a fallow control even when grown for a short (13 week) period. This can effectively reduce residual soil NO_3-N after the autumn harvest without interfering with crop production schedules. Substantial net mineralization and nitrification apparently occurred during this period, as evidenced by the accumulation of NO_3-N in the drier year of the study. In addition, cover crops were shown to reduce soil moisture, which further decreases the potential for NO_3-N leaching. After incorporation, NO_3-N concentrations rose immediately, then were depleted during the next week. Depletion was greater in soils that had been cover cropped. In the cover-cropped soils, NH_4-N concentrations peaked 1 week following incorporation, then gradually decreased during the next 2 weeks. Ammonium concentration remained low in the bare soil plots after incorporation. Nitrogen uptake in the following lettuce crop was not affected by the cover crop treatment.

With the exception of annual ryegrass, there was little difference in growth between cover crop species. Cover crops quickly developed root systems to support rapid above-ground growth and enhance NO_3-N uptake (Table 1). The majority of the root material of all of the cover crops was found in the upper soil depths (0–30 cm), which was also the zone of greatest NO_3-N depletion. The large increase in cover crop biomass from January to time of incorporation in February 1991 demonstrates that both phacelia and Merced rye were able to recover from early drought and cold temperature stresses.

Soil NO_3-N concentrations decreased during winter in all treatments in the first year. At the time of incorporation, soil NO_3-N concentrations were *c.* 15 μg NO_3-N/g dry soil lower in the cover-cropped plots than in the bare soil plots (0–30 cm depth). This is equivalent to a difference of 63 kg NO_3-N/ha. Cover crop N uptake (N in above- plus below-ground plant material) averaged 160 kg N/ha in the 17-week growth period of the first year. Plant N uptake was therefore more than twice the difference in soil NO_3-N found between the bare and cover-cropped plots at incorporation, suggesting that a greater proportion of the NO_3-N in the bare plots had been lost during winter rains. In the 13-week growing period of the second year, N uptake by the cover crops averaged 75 kg N/ha. Soil NO_3-N concentrations (0–30 cm depth) in the cover-cropped plots averaged 24 μg NO_3-N/g dry soil lower than NO_3-N concentrations in the bare soil, which is equivalent to *c.* 100 kg N/ha. The lower concentrations of soil NO_3-N in the cover-cropped soils not accounted for by plant uptake have no obvious explanation, but may be due to sampling discrepancies or may reflect differences in N dynamics, e.g. lower denitrification in the drier cover-cropped soils (Ryden & Lund 1980).

In the second year there was little rainfall, which provided the opportunity to measure soil NO_3-N accumulation during winter without the leaching losses that would occur under normal rainfall. There was a net increase of *c.* 496–543 kg NO_3-N/ha in the upper 60 cm during winter in the cover-cropped plots and 657 kg NO_3-N/ha in the bare plots. This increase must be due to net mineralization and nitrification, since atmospheric deposition would account for < 2 kg N/ha/winter in coastal California (Holton *et al.* 1991). During this same period, there was only a slight net decrease in the soil NH_4-N pool from 0·46–0·65 μg NH_4-N/g dry soil (residual concentration at planting of cover crops) to 0·37–0·40 μg NH_4-N/g dry soil (concentration at incorporation). These data support previous observations that net mineralization during a winter fallow period can lead to NO_3-N accumulation (Lamb *et al.* 1985; Powlson 1988; Martinez & Guiraud 1990). Above normal temperatures in early February 1991 may have further contributed to the NO_3-N pool found in the soil by enhancing mineralization and nitrification rates (Cassman & Munns 1980).

A rapid increase in net mineralizable N and NO_3-N concentrations occurred in all treatments in the first few days following incorporation (Fig. 2*c*). The

increased mineralization in the bare soils is probably due to tillage (Goss *et al.* 1988), the immediate effects of which declined within 2 weeks of incorporation. The pulse of NO_3-N released immediately following incorporation (Fig. 2*a*) may be the result of enhanced microbial activity caused by soil mixing and aeration. Thereafter, the decrease in NO_3-N concentration could be due to denitrification and/or to microbial immobilization. Soil moisture was sufficiently low ($< -0{\cdot}5$ MPa, as determined by gravimetric measurements and moisture retention curves for this soil) to limit denitrification (Rolston 1981). Increased microbial biomass shortly following cover crop incorporation (Ocio *et al.* 1991) increases demand for inorganic N, which could account for depletion of both NO_3-N and NH_4-N. Although microbial immobilization of NO_3-N is considered energetically less efficient than NH_4-N, substantial NO_3-N immobilization can occur due to spatial compartmentalization of the two N sources (Paul 1984; Jackson *et al.* 1989; Schimel *et al.* 1989). After the initial response to incorporation, the timing of N availability to the subsequent crop is affected by the rate of N mineralization and immobilization (Huntington *et al.* 1985; Smith *et al.* 1987). Powlson *et al.* (1985) found that wheat straw incorporation into the soil reduced ^{15}N-labelled NO_3-N losses during winter from 60 to 47% through immobilization, but that only 12% of this N was recovered by the subsequent crop; 78% still remained in the soil 1 year after incorporation. The effect of microbial immobilization and slow release of organically-derived N may be to further reduce nitrate leaching losses, and may also provide a more sustained N source for subsequent crops (Ladd *et al.* 1981; Ladd & Amato 1986).

Phacelia and Merced rye were selected as a representative dicotyledon and monocotyledon from the first year's cover crops for more extensive monitoring in the second year of the study. Both species possess characteristics desirable in a cover crop (i.e. rapid growth, late flowering, extensive rooting in the upper profile), without the negative attributes of the brassicas, such as a thick taproot, which makes incorporation more difficult, and the potential to act as a host for diseases such as turnip mosaic potyvirus, which was identified on the cruciferous cover crops (S. Koike, personal communication). Incorporation of the cover crops directly on beds with a rotary tiller was facilitated when plants were short and succulent, with few stalks and no seed heads. In practice, phacelia, oilseed radish, and white senf mustard have all been used successfully as cover crops to reduce NO_3-N leaching during winter in other cropping systems and as trap crops for cyst nematodes in sugar beet rotations (Schlang 1985; Armstrong 1990). Phacelia was found to be mildly susceptible to beet western yellows luteovirus (J. Duffus & S. Benzen, personal communication) and mature, flowering stands were found to harbour *Lygus* (W. Chaney, personal communication). In other cropping systems, the cultivation of phacelia may lead to the increase of some soil fungal pathogens (Krober & Beckman 1975), although no damping-off (due to *Pythium* spp.; Bruehl 1973) was observed in this field trial or in several other local trials.

The potential benefits of cover cropping for improved N cycling and reduced NO_3-N leaching are indicated by this study, although further study of the many components of soil N dynamics following cover crop incorporation is warranted. The fate of NO_3-N, either to microbial immobilization or to denitrification, is of particular interest. Alternative methods of incorporation may encourage the more widespread use of cover crops in conventional vegetable production operations, which traditionally have had no means of controlling NO_3-N leaching losses during a winter fallow.

We thank the University of California Farm Advisors W. Chaney, J. Inman, S. Koike and R. Smith for their assistance throughout the course of the study. We appreciate the input of F. Kegel and S. Temple during initiation of the project and thank G. S. Pettygrove for review of the manuscript. Partial funding for this study was provided by the California Iceberg Lettuce Research Program.

REFERENCES

ARMSTRONG, M. (1990). Sugar beet – towards a greener crop. *British Sugar Beet Review* **58** (3), 20–24.

BOLTON, H., JR., ELLIOT, L. F., PAPENDICK, R. I. & BEZDICEK, D. F. (1985). Soil microbial biomass and selected soil enzyme activities: effect of fertilization and cropping practices. *Soil Biology and Biochemistry* **17**, 297–302.

BRUEHL, G. W. (1973). Systems and mechanisms of residue possession by pioneer fungal colonists. In *Biology and Control of Soil-borne Plant Pathogens* (Ed. G. W. Bruehl), pp. 77–83. St. Paul, MN: American Phytopathological Society.

CARLSON, R. M. (1978). Automated separation and conductimetric determination of ammonia and dissolved carbon dioxide. *Analytical Chemistry* **50**, 1528–1532.

CARLSON, R. M. (1986). Continuous flow reduction of nitrate to ammonium with granular zinc. *Analytical Chemistry* **58**, 1590–1591.

CASSMAN, K. G. & MUNNS, D. N. (1980). Nitrogen mineralization as affected by soil moisture, temperature, and

depth. *Soil Science Society of America Journal* 44, 1233–1237.

ESTLER, M. (1991). Conservation of soil and water by using a new tillage system for row crops. In *Cover Crops for Clean Water* (Ed. W. L. Hargrove), pp. 34–36. Ankeny, IA: Soil Water Conservation Society.

FLOCKER, W. J., AGAMALIAN, H. & LUGG, J. (1959). Effect of winter cover cropping and subsoiling on some physical properties of Chualar sandy loam. *Department of Vegetable Crops Series 100*, University of California, Davis, USA.

GOSS, M. J., COLBOURN, P., HARRIS, G. L. & HOWSE, K. R. (1988). Leaching of nitrogen under autumn-sown crops and the effects of tillage. In *Nitrogen Efficiency in Agricultural Soils* (Eds D. S. Jenkinson & K. A. Smith) Vol. 1, pp. 269–282. New York: Elsevier Applied Science.

HOLTON, B., BARBOUR, M. G. & MARTENS, S. N. (1991). Some aspects of the nitrogen cycle in a Californian strand ecosystem. *Madroño* 38, 170–184.

HUNTINGTON, T. G., GROVE, J. H. & FRYE, W. W. (1985). Release and recovery of nitrogen from winter annual cover crops in no-till corn production. *Communications in Soil Science and Plant Analysis* 16, 193–211.

JACKSON, L. E., SCHIMEL, J. P. & FIRESTONE, M. K. (1989). Short-term partitioning of ammonium and nitrate between plants and microbes in an annual grassland. *Soil Biology and Biochemistry* 21, 409–415.

KROBER, H. & BECKMAN, E. O. (1975). Pilzparasitare Schaden an *Phacelia tanacetifolia* Benth. *Nachrichtenblatt des Deutschen Pflanzenschützdienstes* 27, 177–180.

LADD, J. N. & AMATO, M. (1986). The fate of nitrogen from legume and fertilizer sources in soils successively cropped with wheat under field conditions. *Soil Biology and Biochemistry* 18, 417–425.

LADD, J. N., OADES, J. M. & AMATO, M. (1981). Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. *Soil Biology and Biochemistry* 13, 251–256.

LAMB, J. A., PETERSON, G. A. & FENSTER, C. R. (1985). Fallow nitrate accumulation in a wheat-fallow rotation as affected by tillage system. *Soil Science Society of America Journal* 49, 1441–1446.

MARTINEZ, J. & GUIRAUD, G. (1990). A lysimeter study of the effects of a ryegrass catch crop, during a winter wheat/maize rotation, on nitrate leaching and on the following crop. *Journal of Soil Science* 41, 5–16.

MEISINGER, J. J., HARGROVE, W. L., MIKKELSEN, R. L., WILLIAMS, J. R. & BENSON, V. W. (1991). Effects of cover crops on groundwater quality. In *Cover Crops for Clean Water* (Ed. W. L. Hargrove), pp. 57–68. Ankeny, IA: Soil Water Conservation Society.

MONTEREY COUNTY FLOOD CONTROL and WATER CONSERVATION DISTRICT (1988). *Nitrates in groundwater, Salinas Valley, California.*

MULLER, J. C., DENYS, D., MORLET, G. & MARIOTTA, A. (1988). Influence of catch crops on mineral nitrogen leaching and its subsequent plant use. In *Nitrogen Efficiency in Agricultural Soils* (Eds D. S. Jenkinson & K. A. Smith) Vol. 2, pp. 85–98. New York: Elsevier Applied Science.

OCIO, J. A., BROOKES, P. C. & JENKINSON, D. S. (1991). Field incorporation of straw and its effects on soil microbial biomass and soil inorganic N. *Soil Biology and Biochemistry* 23, 171–176.

PAUL, E. A. (1984). Dynamics of organic matter in soils. *Plant and Soil* 76, 275–285.

POWLSON, D. S. (1988). Measuring and minimising losses of fertilizer nitrogen in arable agriculture. In *Nitrogen Efficiency in Agricultural Soils* (Eds D. S. Jenkinson & K. A. Smith) Vol. 1, pp. 231–245. New York: Elsevier Applied Science.

POWLSON, D. S., JENKINSON, D. S., PRUDEN, G. & JOHNSTON, A. E. (1985). The effect of straw incorporation on the uptake of nitrogen by winter wheat. *Journal of the Science of Food and Agriculture* 36, 26–30.

RADKE, J. K., ANDREWS, R. W., JANKE, R. R. & PETERS, S. E. (1988). Low-input cropping systems and efficiency of water and nitrogen use. In *Cropping Strategies for Efficient Use of Water and Nitrogen* (Ed. W. L. Hargrove), pp. 193–218. Madison, WI: ASA, CSSA and SSSA.

ROBERSON, E. B., SARIG, S. & FIRESTONE, M. K. (1991). Cover crop management of polysaccharide-mediated aggregation in an orchard soil. *Soil Science Society of America Journal* 55, 734–739.

ROBERTS, B. W. & CARTWRIGHT, B. (1991). Alternative soil and pest management practices for sustainable production of fresh-market cabbage. *Journal of Sustainable Agriculture* 1, 21–35.

ROLSTON, D. E. (1981). Nitrous oxide and nitrogen gas production in fertilizer loss. In *Denitrification, Nitrification, and Atmospheric Nitrous Oxide* (Ed. C. C. Delwiche), pp. 127–149. New York: J. Wiley and Sons.

RYDEN, J. C. & LUND, L. J. (1980). Nature and extent of directly measured denitrification losses from some irrigated vegetable crop production units. *Soil Science Society of America Journal* 44, 505–511.

SAS INSTITUTE. (1985). *SAS User's Guide: Statistics.* 5th edn. Cary, NC: SAS Institute Inc.

SCHIMEL, J. P., JACKSON, L. E. & FIRESTONE, M. K. (1989). Spatial and temporal effects on plant-microbial competition for inorganic nitrogen in a California annual grassland. *Soil Biology and Biochemistry* 21, 1059–1066.

SCHLANG, J. (1985). Zür Populationsentwicklung von *Heterodera schachtii* unter dem Einfluss von *Phacelia tanacetifolia. Mededelingen van de Faculteit Landbouwetenschappen Rijksuniversiteit* 50, 774–784.

SCHNÜRER, J., CLARHOLM, M. & ROSSWALL, T. (1985). Microbial biomass and activity in an agricultural soil with different organic matter contents. *Soil Biology and Biochemistry* 17, 611–618.

SMITH, M. S., FRYE, W. W. & VARCO, J. J. (1987). Legume winter cover crops. *Advances in Soil Science* 7, 95–139.

TISDALL, J. M. & OADES, J. M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science* 33, 141–163.

WARING, S. A. & BREMNER, J. M. (1964). Ammonium production in soil under waterlogged conditions as an index of nitrogen availability. *Nature (London)* 201, 951–952.

WILLIAMS, W. A. (1966). Management of nonleguminous green manures and crop residues to improve the infiltration rate of an irrigated soil. *Soil Science Society of America Proceedings* 30, 631–634.