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Winter cover crops in a vegetable cropping system: Impacts on nitrate leaching, soil water, crop yield, pests and management costs

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Abstract

Plant–soil relationships in the surface soil layer affect other processes in agroecosystems, including crop productivity, nitrate leaching and plant–pest interactions. This study investigated the effect of altering surface soil dynamics, using a winter cover crop rotation, on biotic and abiotic characteristics of the soil profile. Two cover crop treatments, phacelia and Merced rye (*Phacelia tanacetifolia* cv. 'Phaci', and *Secale cereale* cv. 'Merced'), with a fallow control, were planted in November after harvest of a broccoli crop on a commercial farm site, and were incorporated using reduced tillage techniques the following March. Changes in plant and soil N pools throughout the profile were described, emphasizing nitrate (NO_3^--N) leaching during winter, and N availability during the subsequent broccoli crop. Changes in other aspects of the ecosystem, such as plant–pest interactions and plant disease incidence, were monitored after cover crop incorporation. The on-farm economic costs of cover cropping were calculated. There was a 65–70% reduction in nitrate leaching from the cover-cropped plots compared with the fallow control during winter, because plant roots in the surface soil removed N and water that would have otherwise been lost from the profile. Incorporation caused sudden large surges in inorganic N pools, net mineralizable N, and microbial biomass N and C in the surface soil, which subsided within 6 weeks, by the time the broccoli crop was planted, but which did result in increased yield at harvest in the phacelia cover-cropped treatment. No insect or disease problems which threatened the cash crops were introduced or increased as a result of the cover crops. The economic analysis indicated that the costs of cover cropping were minor compared with conventional winter management of fallowed fields, and compared with the cost of producing broccoli. The cover crops therefore provided a clear advantage during winter by significantly reducing nitrate leaching, but the effects of one cover crop rotation on subsequent nutrient dynamics in the surface soil were mostly short-lived and possibly masked by large fertilizer applications.

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Abbreviations: MBN = Microbial biomass nitrogen; MBC = Microbial biomass carbon; IER = Ion exchange resin; SOM = Soil organic matter

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1. Introduction

An ecological approach to the study of agricultural systems provides valuable information about abiotic and biotic relationships that can be used in applied research to maximize crop productivity and minimize environmental degradation. In this study, we examined how plant–soil relationships in the surface soil layer affected other processes in an agroecosystem, including crop productivity, nitrate (NO_3^--N) leaching below the rootzone, and plant–pest interactions. To determine the impact of these ecological relationships on agricultural outcomes, the economic profitability of different management scenarios was assessed. The project was conducted in an on-farm trial, to generate results with a direct application to current farming practices.

The surface layer (about 0–15 cm depth) in agricultural soils is the zone of highest organic C and N pools, soil microbial biomass and microbial activity (Doran, 1987; Janzen et al., 1992; Van Gestel et al., 1992), and is consequently important for providing nutrients to plants (Campbell, 1978; Paul, 1984; Woods, 1989). The fluctuation of abiotic factors (e.g. soil moisture) in this zone also affects microbial activity and nutrient availability (Van Gestel et al., 1992). In the surface layer of most conventionally tilled agricultural soils, soil organic matter (SOM) has decreased with time, with attendant decreases in microbial activity and nutrient turnover (Carter and Rennie, 1984; Mann, 1986; Burke et al., 1989; Cambardella and Elliott, 1992). The labile or active SOM fraction, which plays a prominent role in soil nutrient dynamics (Parton et al., 1987), and which may function as a temporary nutrient reservoir (Paul, 1984), declines with cultivation (Cambardella and Elliott, 1994), and when a fallow period is included in the crop rotation (Janzen et al., 1992). These effects are more pronounced on soils of low clay content, because organic material is not protected from decomposers by clay aggregates (Parton et al., 1987; Burke et al., 1989). Regular addition of organic material to the soil causes rapid changes in microbial biomass (Schnürer et al., 1985; Ocio et al., 1991), but stable increases in SOM occur very slowly (Powlson and Jenkinson, 1981; Powlson et al., 1987).

Winter cover crops, which are grown during an otherwise fallow period, are one possible means of improving nutrient dynamics in the surface layer of intensively managed crop systems. Non-leguminous cover crops can deplete soil NO_3^--N and water from the surface layer, which leads to reduced NO_3^--N leaching below the rootzone (Lamb et al., 1985; Powlson, 1988; Martinez and Guiraud, 1990; Meisinger et al., 1991). Other benefits include increased SOM and microbial activity (Powlson et al., 1987), turnover of soil N (Doran and Smith, 1991), aggregate stability (Tisdall and Oades, 1982; Roberson et al., 1991), water infiltration (Williams, 1966), and contribution to the N content of the subsequent crop (Ladd et al., 1981). The risks of cover cropping include disrupting the spring planting schedule if the field is too wet to incorporate, or if residue decomposition is slow. Cover crops with a high C/N ratio (over 25) are undesirable in an intensive cropping schedule because prolonged microbial immobilization of available soil N in the surface layer can retard the early stages of crop growth (Wyland et al., 1995). The lower the C/N ratio of the plant residue, the higher the mineralization rate, which increases the availability of the residue N for immediate crop uptake (Norman et al., 1990).

Cover cropping may influence other aspects of the agroecosystem, either positively or negatively for agricultural purposes. The mechanisms may be biotic (e.g. microbial interactions, plant–pest interactions) or abiotic (e.g. soil physical factors; Lockwood, 1988). Cover crops and crop rotations can have various effects on soilborne diseases. The cover crop can act as a host for the soilborne pathogen, resulting in an inoculum increase for the subsequent agronomic crop (Dillard and Grogan, 1985). Incorporated cover crop residues may provide either an organic food base which encourages pathogen growth (Phillips et al., 1971) or organic compounds which predispose crop roots to infection by pathogens (Toussoun and Patrick, 1963; Patrick et al., 1963). Conversely, some crops, such as cruciferous plants, can actually decrease soil pathogen populations (Lewis and Papavizas, 1971; Subbarao et al., 1994b). More complex interactions also occur in which cover crops may cause one soilborne pathogen to increase while suppressing another (Gardner and Caswell-Chen, 1994). Organic amendments in general are thought to suppress soil pathogens, in part due to enhanced competition between soil microorganisms for C and N, and have long been used as a method of biocontrol (Cook and Baker, 1983). Cover crop residue and reduced tillage practices can also impact insect pest populations (Pimentel and Warneke, 1989; Stockdale et al., 1992), although they may also encourage beneficial predators (Ruppel and Sharpe, 1985; Bugg et al., 1990).

Economic productivity must be a primary consideration in developing sustainable agricultural practice recommendations. The direct costs of growing and incorporating a cover crop, as well as the indirect costs of possible disease enhancement or crop scheduling delays, must be weighed against the short- and long-term improvements of soil nutrient dynamics by cover cropping. Comprehensive economic analyses may be site- and date-specific, because they depend on highly variable market rates, but they are a useful means of comparing the profitability of different management practices within a given site and time frame.

Intensive vegetable crop rotations in the central coast region of California are highly susceptible to NO_3^--N loss via leaching and denitrification (Ryden and Lund, 1980; Jackson et al., 1993). The typical rotation includes two or three crops in rapid succession, followed by 3–4 months of winter fallow. Relatively little organic residue is returned to the soil after harvest of these vegetable crops. As a result, SOM in the surface soil has decreased markedly during the last century, as demonstrated for the sandy loam studied in this project (Table 1). In previous work, it was found that integration of winter cover crops into cropping schedules is facilitated if reduced tillage practices are used (Jackson et al., 1993). The present study was conducted on a commercial broccoli field with winter cover crops and reduced tillage practices. Seasonal changes in plant and soil N pools throughout the profile were described, with an emphasis on N availability, and microbial biomass N and C (MBN and MBC) in the surface layer. This work addressed two main objectives. The ecological objective was to examine how changes in plant–soil relationships in the surface layer affected system N dynamics, insect populations, and incidence of plant diseases, and the agricultural objective was to examine the management implications (e.g. scheduling of inputs, tillage, economic costs) of altering plant–soil relationships by using cover crops.

2. Methods

2.1. Crops and cultivation

The cover crop field trial was established in November 1992 on a 6.5 ha site located in the Salinas Valley of California. The soil was a Chualar loam (fine-loamy, mixed, thermic Typic Argixeroll), composed of 69% sand, 20% silt and 11% clay. In the surface 0–15 cm layer, soil pH was 7.7, CEC was 12.4 cmol kg^{-1} and organic C was 0.62%. Soil bulk density was 1.46 g cm^{-3} in the raised beds (top 15 cm) and averaged 1.64 g cm^{-3} in the lower soil depths (15–75 cm). A dense layer at 75–85 cm depth was largely impenetrable by plant roots. The field has been in long-term use for cool-season vegetable (e.g. lettuce, broccoli) production, with typically two crops per year grown on raised beds and irrigated with a linear-move system of overhead sprinklers. The field was divided into three replicate blocks of three randomized plots (252 m × 24 m), with two subplots, which were planted with phacelia (*Phacelia tanacetifolia* cv. 'Phaci') or Merced rye (*Secale cereale* cv. 'Merced') as winter cover crops, or left fallow. Prior to cover crop planting there had been a broccoli crop, which was harvested the third week in October, 1992. The field was then disked, beds were listed, and the cover crops were planted on November 24. Seed was planted in double rows on bed tops only, using about 3.1 kg phacelia seed ha^{-1}, and about 9.3 kg Merced rye seed ha^{-1}. Suction lysimeters, tensiometers, and ion exchange resin (IER) bags (Wyland and Jackson, 1993), each containing about 10 g of resin, were installed in each plot at 60 cm depth to monitor NO_3^--N leaching during winter. The field was irrigated once on 26

Table 1
Changes in soil properties at the study site during the past century. The original vegetation was oak savanna/annual grassland. Data are from the USDA soil surveys of the Salinas Valley, and field data collections in 1993

Year	Soil survey classification	Dominant cultivation	Depth measured (cm)	Organic C (%)	Organic N (%)	C/N	Sand (%)	Silt (%)	Clay (%)	Water at −0.03 MPa (%)	Water at −0.15 MPa (%)
1901 [a]	Placentia sandy loam [b]	Dry-farmed wheat with legume rotation	0–35	1.19	–	–	64.3	25.1	10.6	–	–
1925 [c]	Chualar sandy loam [d]	Dry-farmed barley with legume rotation	0–30	–	–	–	66.8	23.0	10.2	–	–
1975 [e]	Chualar loam [f]	Irrigated row and field crops	0–18	0.89	0.080	11.12	62.1	27.7	10.2	–	4.6
1993 [g]	Chualar loam [f]	Irrigated row crops	0–15	0.62	0.066	9.37	68.8	20.5	10.7	7.9	3.6

[a] Lapham and Heileman (1901).
[b] Site location is 40 km south of study site.
[c] Carpenter and Cosby (1925).
[d] Site location not given.
[e] USDA/SCS (1978).
[f] Site location is the same field as our current study.
[g] Field data collection, 1993.

November (50 mm), and the cover crops were rainfed thereafter. Total precipitation from cover crop planting to incorporation was 396 mm. Soil samples were collected at planting, again in early January and in February, and immediately before cover crop incorporation. The cover crops were flail mowed on 16–17 March, then incorporated to 15 cm soil depth using a 'Sundance System' on 19–20 March. The winter fallow plots were tilled in the same manner. The 'Sundance System' is a reduced tillage method, developed for subsurface drip-irrigated fields, which uses disks and lister bottoms to incorporate crop residue into the raised beds, and rework beds and furrows to a 10–15 cm soil depth. Surface soils were sampled frequently (every three to four days) during the 6 weeks between cover crop incorporation and planting of the first broccoli crop, in order to characterize soil dynamics following residue addition. There was one tillage event on 8 April, involving one pass with a lilliston. In late April, the entire field was cultivated, irrigated and then direct-seeded with broccoli (*Brassica oleracea* L. Italica group, cv. 'Green Belt'), using 10 cm in-row spacing. Planting was done in two rows, 30 cm apart, on 100-cm-wide beds. The total fertilizer N applied, including preplant and two foliar sprays of 18% NH_3-N for weed control, was 41.0 g N m^{-2}. The crop received a total of 440 mm irrigation water: 50 mm applied as pre-plant, 160 mm in the first 2 weeks after planting, and the remaining 230 mm at 1–2 week intervals until harvest. The NO_3^--N content of the irrigation water was about 10–15 μg NO_3^--N ml^{-1}. Soil samples were collected at planting, three times during crop development (prior to sidedress N applications), and at harvest. The crop was harvested in late July (first cut) and early August (second and third cuts). The field was then disked, ripped, spring-chiseled and irrigated, the beds were listed and shaped with a preplant fertilizer (5.6 g N m^{-2}), and a second broccoli crop planted on 14 August. This crop received a total of 450 mm irrigation water. Soil samples were collected twice during crop development, and once at harvest. Fertilizer was applied in five sidedresses, including one foliar spray, for a total of 41.6 g N m^{-2} applied to the second crop. This crop was harvested in three cuts in November. One soil sample was taken on 16 November, during the harvest.

2.2. Sampling and analysis

Soil cores (6 cm diameter) were taken from the center of the beds, and subdivided into 0–15, 16–45, and 46–75 cm depth increments. Two samples were taken from each plot, and two cores were bulked per sample. Each well-mixed soil layer was subsampled in the field for gravimetric soil moisture content (50 g wet soil), KCl-extractable NO_3^--N and ammonium (NH_4^+-N) (10 g wet soil/25 ml 2 N KCl), and net mineralizable N (10 g wet soil) using a 7-day anaerobic incubation (Waring and Bremner, 1964). Additional subsamples (25 g wet soil) were sieved (4 mm) for measurement of MBN and MBC, using the fumigation–extraction technique of Brookes et al. (1985), a modified Kjeldahl digestion for N content determination (Wyland et al., 1994), and a dichromate digestion for C content (Vance et al., 1987). All extractions were initiated immediately after sampling. Inorganic N was measured using a Wescan ammonia analyzer (Alltech Assoc., Inc., Deerfield, IL) with a reduction column for NO_3^--N determination (Carlson, 1978; Carlson, 1986). Another subsample from the surface layer was mixed and divided into 100 g subsamples, soaked in a 1% Calgon (sodium polymetaphosphate) solution, and assayed for *Sclerotinia minor* sclerotia using a hydropneumatic root elutriator (Gillison's Fabrication, Benzonia, MI) (Subbarao et al., 1994a). Another subsample (100 g) was used to count soil insect populations. These samples were placed in Berlese funnels and the arthropods were collected in a 20% ethanol solution (Berry, 1981). All mites, symphylans and springtails were counted, and mites were further divided into plant-feeding and predatory groups.

Soil solution samples were collected weekly from soil water samplers (SoilMoisture, Santa Barbara, CA) beginning in mid-December until cover crop incorporation in March, and analyzed for NO_3^--N content. The IER bags were excavated in March, adsorbed NO_3^--N was extracted in 2 N KCl, and leached NO_3^--N was calculated on an area basis, according to Wyland and Jackson (1993).

Cover crop plantings were evaluated on 3 March for the presence of diseases. Ten evaluation areas (1 m^2) in each plot were examined for symptoms of both soilborne and non-soilborne diseases. The non-soilborne (airborne or insect-vectored) diseases were monitored due to concern that the cover crops could act as reservoirs for important foliar or viral diseases of vegetables. Symptomatic phacelia plants were tested for lettuce mosaic virus (LMV), using an enzyme-linked immunosorbent assay (ELISA) with antiserum specific for LMV (Falk and Purcifull, 1983), and were examined for virus particles using a transmission electron microscope (TEM).

Both broccoli plantings were examined for seedling diseases, and stand establishment was compared between treatments. Ten evaluation areas (2 m^2) in each plot were examined, seedlings exhibiting disease symptoms were counted, and plants were tested for pathogens. The roots and stems were rinsed thoroughly in distilled water, plated onto 2% water agar and acidified potato-dextrose agar, and incubated at 22°C. Resultant fungal colonies were examined and identified. Broccoli plants at harvest stage were also examined for disease symptoms.

Above-ground cover crop biomass samples were collected from two 1-m^2 areas in each plot on 5 January, 2 February, 22 February, 3 March and 11 March and cover crop root biomass samples were collected on 11 March. Plant samples were oven-dried at 65°C, weighed, and analyzed for N content with a Leco nitrogen gas analyzer (St. Joseph, MI). Root biomass samples were obtained by collecting 6 cm diameter soil cores directly over a phacelia or rye plant in each cover-cropped plot, another in the center of the bed, and another in the furrow. Each of these cores was divided into 0-15 (not present in the furrow cores), 16-45 and 46-75 cm depth increments, and then put through a hydropneumatic root elutriator (Gillison's Fabrication) to separate the roots from soil. Root length was measured with a Comair root scanner (Hawker de Haviland, Victoria, Australia). Roots were then oven-dried at 65°C and weighed.

Above-ground biomass samples of the first broccoli crop were collected from two 1-m^2 areas in each plot on 17 May, 1 June, 24 June, 13 July and 27 July and root samples were collected on 27 July. All plant material was processed and analyzed as above. Above-ground plant biomass from the second broccoli crop were collected on 31 August, 19 October, 2 November, and 16 November.

2.3. Estimation of drainage and nitrate leaching

A simplified water balance model was used to calculate drainage during winter in the three treatments. The model added water inputs from rainfall and irrigation, and subtracted water losses from ET, runoff, and the change in soil water storage from

Table 2

Above-ground biomass of cover crops during the winter (planting 24/11/1992, incorporation 16/3/1993), and of broccoli plants at various growth stages during the first broccoli crop in each treatment (broccoli planting 30/4/1993, harvest 27/7/1993). There are no significant differences between the phacelia and rye cover crop biomass or N content. The dry weight of broccoli grown in the phacelia plots was significantly higher than that of the broccoli grown in the bare plots on the harvest (27/7/1994) sample only. There was no difference in broccoli N content on any sample date

Date	Phacelia plots		Rye plots		Bare soil plots	
	g dry wt m^{-2}	g N m^{-2}	g dry wt m^{-2}	g N m^{-2}	g dry wt m^{-2}	g N m^{-2}
Cover crop						
5/1/1993	0.29 ± 0.023	0.01 ± 0.0001	0.81 ± 0.044	0.05 ± 0.003	-	-
3/2/1993	20.3 ± 2.09	1.11 ± 0.119	34.7 ± 3.68	2.1 ± 0.22	-	-
22/2/1993	121.9 ± 10.79	5.4 ± 0.49	139.9 ± 9.95	5.9 ± 0.58	-	-
3/3/1993	196.2 ± 14.85	6.9 ± 0.80	215.1 ± 26.57	7.8 ± 0.97	-	-
11/3/1993	364.0 ± 28.38	10.6 ± 1.04	372.7 ± 12.92	13.6 ± 0.95	-	-
Broccoli						
17/5/1993	0.4 ± 0.05	0.02 ± 0.003	0.4 ± 0.04	0.02 ± 0.002	0.3 ± 0.018	0.02 ± 0.001
1/6/1993	10.6 ± 0.91	0.6 ± 0.05	11.5 ± 0.98	0.7 ± 0.05	12.3 ± 1.04	0.7 ± 0.06
24/6/1993	136.0 ± 6.46	6.2 ± 0.25	121.5 ± 3.10	5.8 ± 0.22	128.5 ± 9.64	6.0 ± 0.40
13/7/1993	618.0 ± 31.42	26.7 ± 1.47	590.2 ± 22.35	25.9 ± 1.02	582.1 ± 25.14	24.8 ± 1.00
27/7/1993	957.3 ± 40.27	41.6 ± 1.54	867.2 ± 33.29	39.3 ± 1.63	830.3 ± 34.78	37.3 ± 2.74

cover crop planting (initial) to cover crop incorporation (final) in March (Wagenet, 1986). The NO_3^--N concentration in soil cores (0–60 cm) was averaged between initial and final measurements and multiplied by drainage to estimate NO_3^--N leaching (Wyland and Jackson, 1993). Estimates of NO_3^--N leaching from the suction lysimeters were made by multiplying the cumulative NO_3^--N concentrations of the 12 weekly soil solution samples with drainage calculated for each treatment.

2.4. Economic analysis

Detailed management records for the field site were analyzed using the Budget Planner program (Klonsky, 1991) to evaluate the total cost and profitability of winter cover cropping within the context of an intensive year-round vegetable cropping system. Baseline data files included all farm operations, equipment, materials and labor used throughout the year. The data are site-specific, yet are representative of this production system. Budgets were then developed from the baseline data and crop yields, using relevant market rates. The Budget Planner calculated gross returns, total costs, monthly cash flow and equipment schedules, and summaries of water, fertilizer, energy and labor use during winter and throughout the vegetable cropping season, with and without a winter cover crop rotation.

Statistical analyses were conducted using GLM procedures for analysis of variance (Statistical Analysis Systems Institute Inc., 1985). Significance was set at $P \leq 0.05$.

3. Results

3.1. Cover crop and broccoli growth

Phacelia and Merced rye produced substantial above-ground biomass (about 4 tons dry biomass ha^{-1}), and accumulated more than 100 kg N ha^{-1} in the short winter growing period (Table 2). There were no significant differences in above-ground biomass or N content between the two species at any sampling date, although rye tended to grow more quickly than phacelia. Final above-ground biomass was 364.0 g and 372.7 g dry weight m^{-2}, and N content was 10.6 g and 13.6 g N m^{-2} in phacelia and rye treatments, respectively. Both cover crops developed an extensive, fibrous root system which reached a depth of 75 cm after 16 weeks of growth, but the majority of the root system was located in the surface 15 cm (Table 3). Phacelia had significantly

Table 3
Root distribution of phacelia and rye cover crops sampled 4 days prior to incorporation (16/3/1993), and of broccoli at harvest of the first crop (27/7/1993). Core A was taken over the plant, core B was taken in the center of the bed, and core C was taken in the furrow (which is considered to have no top depth compared with the beds)

Depth	Root length ($cm\ cm^{-3}$)			Root weight ($mg\ cm^{-3}$)		
(cm)	Core A	Core B	Core C	Core A	Core B	Core C
Phacelia						
0–15	3.34 ± 0.693	3.96 ± 0.601	–	2.29 ± 0.693	0.10 ± 0.006	–
16–45	1.53 ± 0.126	2.27 ± 0.722	1.08 ± 0.695	0.04 ± 0.010	0.06 ± 0.012	0.02 ± 0.012
46–75	1.35 ± 0.158	1.48 ± 0.122	1.11 ± 0.845	0.02 ± 0.003	0.04 ± 0.006	0.02 ± 0.014
Merced rye						
0–15	7.88 ± 1.329	5.16 ± 0.640	–	0.81 ± 0.213	0.08 ± 0.010	–
16–45	2.46 ± 0.793	3.25 ± 0.979	0.83 ± 0.276	0.04 ± 0.016	0.06 ± 0.014	0.02 ± 0.007
46–75	2.32 ± 0.391	1.89 ± 0.413	1.01 ± 0.141	0.06 ± 0.008	0.05 ± 0.009	0.01 ± 0.004
Broccoli						
0–15	28.77 ± 0.976	3.80 ± 0.444	–	16.55 ± 0.819	0.09 ± 0.013	–
16–45	4.25 ± 0.229	3.13 ± 0.094	0.39 ± 0.041	0.17 ± 0.064	0.15 ± 0.031	0.01 ± 0.001
46–75	0.39 ± 0.025	1.93 ± 0.928	0.13 ± 0.022	0.04 ± 0.028	0.03 ± 0.015	0.001 ± 0.000

more root weight in the surface soil (0–15 cm) than rye at the time of incorporation, because of its taproot, but rye had significantly more root length in the surface soil. Both species had a low C/N ratio in the above-ground biomass at the time of incorporation (13.7 and 10.9, respectively, for phacelia and rye, assuming that 40% of the dry residue biomass was C).

The first broccoli crop, which was planted 6 weeks later, showed a typical growth pattern, with slow initial growth, followed by rapid biomass and N accumulation in the last month (Table 2). The dry weight of the broccoli grown in the phacelia plots was significantly higher than the broccoli grown in the bare plots only on the harvest sample date (27 July). There were no differences between treatments in broccoli N concentration on any sample date. Mean root length and weight measurements (Table 3) were from samples taken from the bare plots at harvest. The high root weight of broccoli in the surface layer is due to the thick taproot. The root length data indicate that the majority of the lateral roots were located in the top 15 cm of soil.

The second broccoli crop demonstrated the same general growth curve and N uptake as the first crop (data not shown). The seedlings in the rye plots (17 days after planting) had significantly higher biomass and N content compared with seedlings in the phacelia and bare plots. There were no differences between treatments in broccoli biomass or N content at any subsequent sample date. Yield from the second crop averaged 713.4 g dry weight m^{-2}.

3.2. Nitrate movement through the profile

Soil NO_3^--N pools were high when cover crops were planted, averaging 34 g NO_3^--N m^{-2} (0–75 cm soil depth) following the October 1992 broccoli crop and prior to the onset of winter rain (Fig. 1). Most of the winter rainfall occurred from mid-January through February (227 mm), during the period of increased N uptake by the cover crops. Soil NO_3^--N content (0–75 cm) was reduced by almost half between 4 January and 3 February (32.8 ± 4.93 g, 25.4 ± 3.29 g, and 27.5 ± 2.42 g NO_3^--N m^{-2} in phacelia, rye, and bare soil plots, respectively), and by the time of cover crop incorporation on 10 March, only 2.1 g, 0.6 g and 12.1 g NO_3^--N m^{-2} remained in the 0–75 cm depth in phacelia, rye and bare soil plots, respectively.

IER bags, soil extractions, and soil water samplers indicated significantly more leaching during winter from the bare soil plots. Nitrate leaching measured by IER bags, which does not rely on drainage estimations, was 9.1 ± 0.74 g, 7.4 ± 1.88 g, and 25.5 ± 7.71 g NO_3^--N leached m^{-2} in phacelia, rye and bare plots, respectively. The drainage estimates calculated from the water balance model were 3.92 ml, 3.62 ml, and 6.02 ml H_2O cm^{-2} in the phacelia, rye and bare soil plots, respectively, from

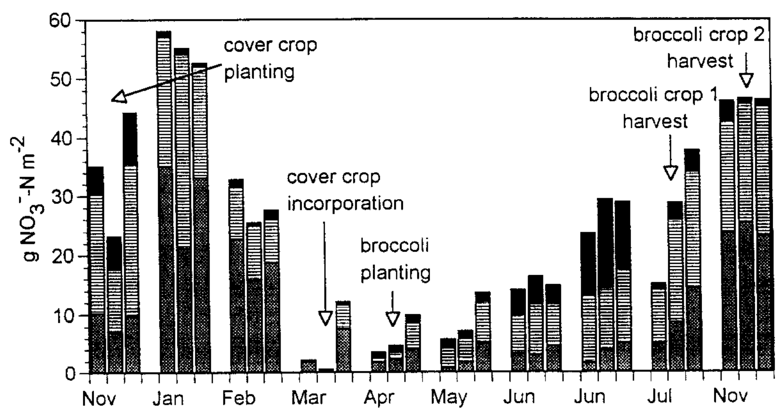

Fig. 1. NO_3^--N in the soil profile divided into depth increments: 0–15 cm (gray, top), 15–45 cm (striped, middle), and 45–75 cm (black, bottom). The columns are in groups of three, representing soil in the phacelia, rye and bare treatments (left to right, respectively) on each sample date.

cover crop planting in November until cover crop incorporation in March. Nitrate leaching calculated from the NO_3^--N concentration in soil extractions and drainage estimates corresponded well with IER bag leaching measurements: 9.1 ± 1.45 g, 6.5 ± 1.22 g, and 28.2 ± 4.85 g NO_3^--N leached m^{-2} in phacelia, rye and bare soil plots, respectively. Calculations based on NO_3^--N concentrations in soil water

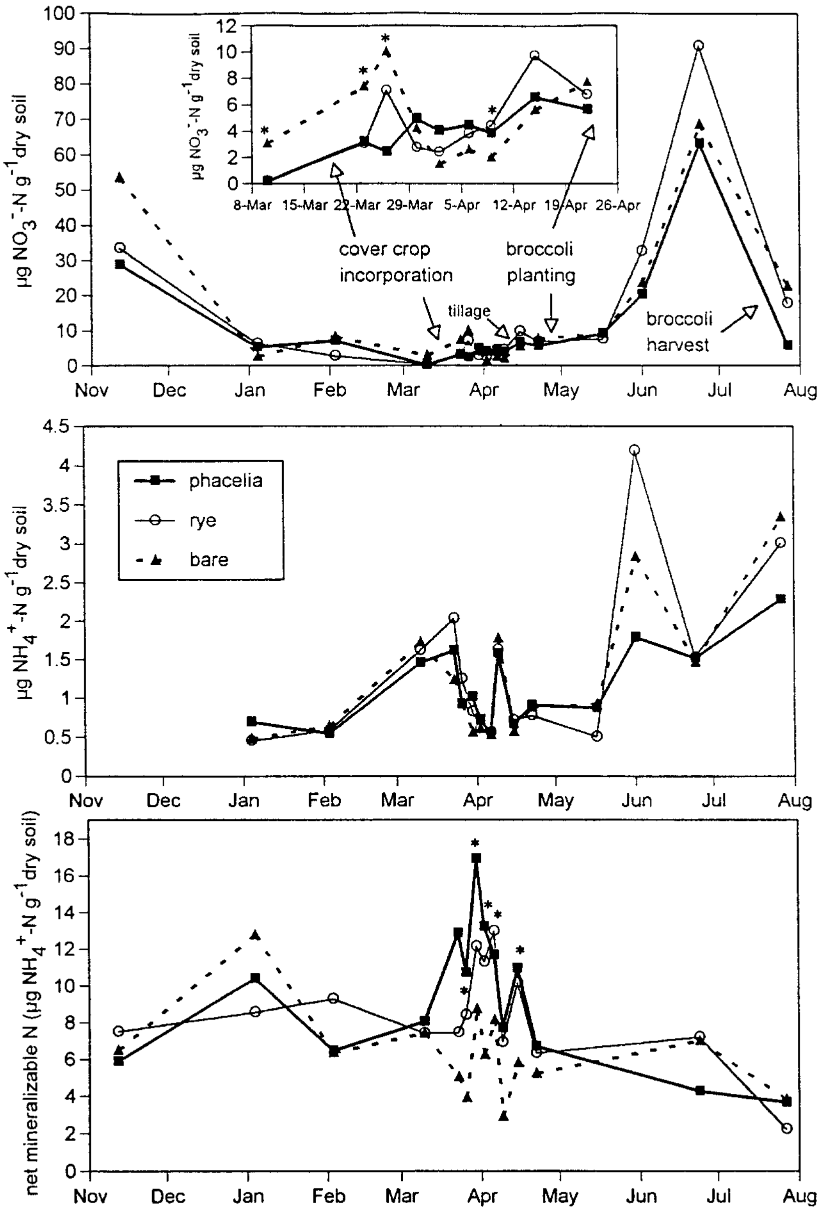

Fig. 2. NO_3^--N, NH_4^+-N, and net mineralizable N concentrations in the surface soil (0–15 cm) from cover crop planting in November 1992 to harvest of the first broccoli crop in July 1993, in phacelia (■), rye (○) and bare (▲) plots. Asterisks indicate a significant difference between cover-cropped and bare soil treatments at $P \leq 0.05$. The insert shows NO_3^--N concentration during the period following cover crop incorporation.

samplers, however, gave values an order of magnitude larger than the other two methods (155 g NO_3^--N leached m^{-2} in phacelia and rye plots, and 281 g NO_3^--N m^{-2} in the bare plots). Over-estimation of NO_3^--N leaching by suction lysimeters has been noted in previous studies (Van der Ploeg and Beese, 1977; Barbee and Brown, 1986; Wyland and Jackson, 1993), yet the relative differences between treat-

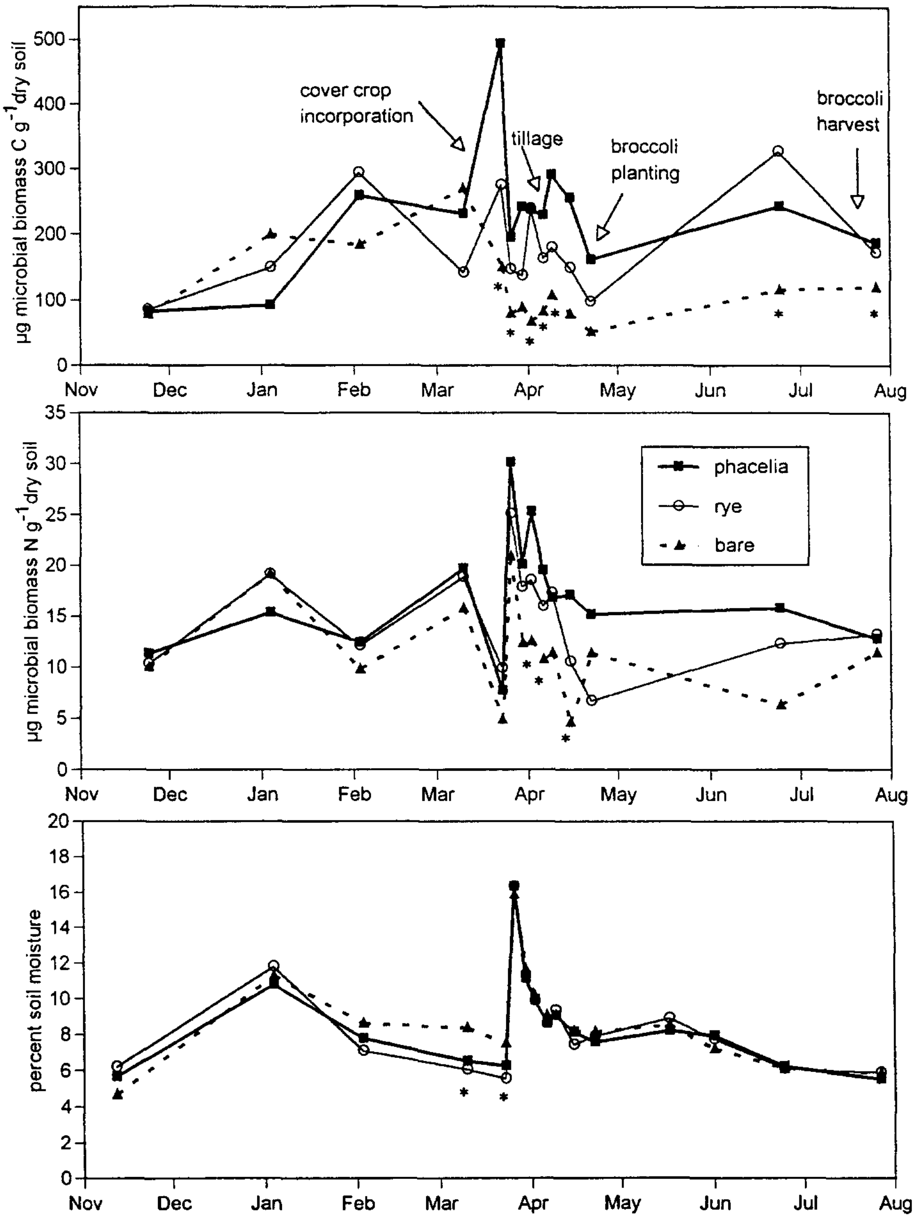

Fig. 3. MBC, MBN and percent soil moisture in the surface soil (0–15 cm) from cover crop planting in November 1992 to harvest of the first broccoli crop in July 1993, in phacelia (■), rye (O) and bare (▲) plots. Asterisks indicate a significant difference between cover-cropped and bare soil treatments at $P \leq 0.05$.

ments is confirmed by this method, i.e. there was significantly more NO_3^--N leached from the bare plots during winter.

3.3. Inorganic N in the surface soil

Nitrate concentrations in the surface layer were reduced substantially during the first winter rains, to less than 1.5 g NO_3^--N m^{-2} in January in all treatments (Fig. 1). Nitrate concentrations in the surface layer were higher in the bare plots toward the end of the cover crop rotation, but this NO_3^--N was not retained after the first rain event following incorporation on 24 March (Fig. 2). Inorganic N concentrations in the surface soil increased as a result of the first spring tillage, but both NO_3^--N and NH_4^+-N declined to levels below pre-incorporation soil concentrations within 10 days. Soil NH_4^+-N continued to decline, except for a brief, tillage-induced spike, until broccoli planting, when subsequent increases reflect fertilizer applications. Nitrate in the surface layer reached a maximum midway through the first broccoli crop (Fig. 2), and then declined to very low levels by the time of harvest in both crops, despite continued fertilizer N applications to the surface. Nitrate accumulated in the lower soil depths (15–75 cm), however, so that very large residual NO_3^--N pools remained after harvest of each broccoli crop (Fig. 1). Residual NO_3^--N in the lower soil depths averaged 24.5 ± 4.87 g NO_3^--N m^{-2} after the first crop, and 44.3 ± 6.68 g NO_3^--N m^{-2} after the second broccoli crop.

3.4. Microbial biomass and mineralization in the surface soil

During most of the year, MBC and MBN were very low in the surface soil (i.e. less than 350 μg C g^{-1} dry soil, and less than 20 μg N g^{-1} dry soil). Tillage to incorporate cover crops and cultivate the bare plots caused sudden large surges in net mineralizable N, MBC and MBN in the surface soil, due to rapid residue decomposition and soil mixing and aeration (Figs. 2 and 3). Fluctuations subsided within 6 weeks, and there was little difference between treatments by the time of broccoli planting other than a higher MBC in the cover-cropped soils. Soil moisture was significantly lower in the cover-cropped plots at the time of incorporation. The initial response to incorporation/tillage was an increase in MBC in the cover-cropped plots, particularly in the phacelia plots, and a decrease in MBC in the bare soil plots (Fig. 3). MBC remained higher in the cover-cropped plots continuously until broccoli harvest, although this difference was not always significant. MBN decreased in all plots initially, then increased in all plots when soil moisture increased (Fig. 3). MBN in the cover-cropped plots remained higher than the bare plots until the first broccoli crop was planted, although these differences were not always significant. The surge in MBC and MBN following incorporation was greater in the phacelia plots, and the subsequent decline was less pronounced than it was in the rye cover-cropped plots. Net mineralizable N increased immediately after incorporation in the phacelia plots, and remained significantly higher than in the bare plots continuously until broccoli planting (Fig. 2). The increase in net mineralizable N was delayed for three days in the rye plots, but reached the level of the phacelia plots within 1 week. Net mineralizable N decreased after incorporation/tillage in the bare soil plots.

3.5. Insects and disease pathogens

The entire experimental area contained extremely low levels of *S. minor* sclerotia (data not shown). Sclerotia counts did not differ significantly between treatments before or after cover crop incorporation. No root or crown diseases were found on either the phacelia or rye cover crops. Rust and powdery mildew foliar diseases were prevalent on the rye, but both of these diseases are host-specific and do not threaten broccoli or other vegetable crops. Phacelia leaves exhibited a slight mottling which resembled virus disease symptoms, but ELISA assays for LMV were negative, and TEM examination of leaf tissue detected no virus particles. The number of diseased broccoli seedlings was extremely low in both crops, and there were no differences between treatments. Of the seedlings collected and tested, no damping-off organisms (*Pythium* species or *Rhizoctonia solani*) or other soilborne pathogens were isolated. There were no disease problems in the mature broccoli plants in either crop.

In the soil insect survey, emphasis was placed on

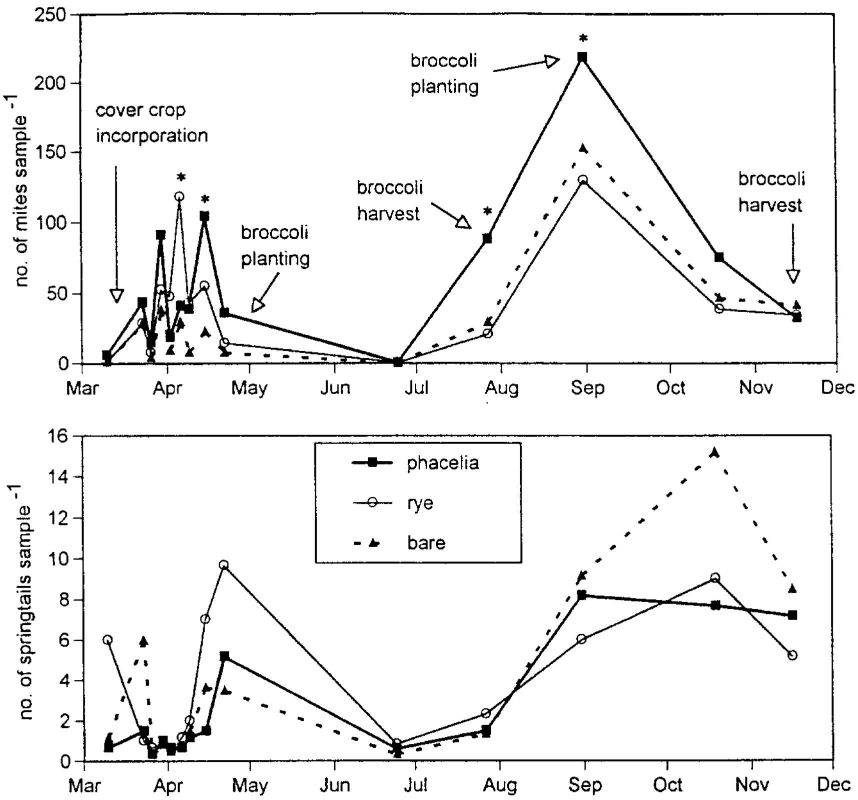

Fig. 4. The population of bulb mites and springtails in the surface soil (0–15 cm) from cover crop incorporation in March 1993 to harvest of the second broccoli crop in November 1993, in phacelia (■), rye (○) and bare (▲) plots. Soil samples were 500 cm^{-3} field-moist soil. Asterisks indicate a significant difference between cover-cropped and bare soil treatments at $P \leq 0.05$.

the three soil-inhabiting arthropods considered most likely to become pests due to changes in soil organic matter content: springtails, symphylans and mites (Getzin, 1985; Eltoum and Berry, 1985; Shanks, 1985; University of California Statewide IPM Project, 1985). The most common springtail observed was *Onychiurus armatus* Tullberg (over 92%), a species considered to be a pest of seedling vegetable plants and a feeder on decaying organic matter. The symphylan found was the garden centipede *Scutigerella immaculata* (Newport), a pest of many young plants, yet the population was barely de-

Table 4
Percentage of total costs required for each operation to produce and incorporate the cover crop

Operation	Operation time	Cost			
	($h\ ha^{-1}$)	Labor	Fuel, lube and repairs	Materials	Total
List beds (contract)	0.44	–	–	–	10.6
Plant cover crop	0.47	2.5	2.5	19.1	24.1
Sprinkler irrigation	1.83	14.9	0	29.8	44.7
Cultivate/break furrows	0.44	2.1	2.2	0	4.3
Mow cover crop	0.49	2.5	2.5	0	5.0
Incorporate cover crop	0.82	3.5	7.8	0	11.3
Total	4.49	25.5	15.0	48.9	100

tectable and not affected by cover crop treatment. The most common plant-feeding mite (about 80%) was *Rhizoglyphus echinopus* (Fumouze & Robin), the bulb mite, known to be a pest of seedling crops. The populations of springtails and mites changed in response to both cover crop and broccoli residue incorporation (Fig. 4). Populations surged immediately after incorporation, then declined to previous levels within 3–5 weeks.

3.6. Economic cost of cover cropping

Approximately 14% of the operating costs to grow and incorporate the cover crops represented charges for operations which would have been done on fallow ground during winter, such as listing beds and cultivating/breaking furrows. The actual cost of cover cropping was roughly 5% of the cost of producing one broccoli crop. The cost of cover crop incorporation, which represented the majority of the equipment and machine labor outlay (Table 4), was calculated for reduced tillage, which involves flail mowing and incorporating with a 'Sundance' or lilliston to 15 cm depth in three passes. The difference in machine labor and repair costs (about 5% of total crop production costs) between the first and second broccoli crops was due primarily to the difference in cost of reduced- and conventional tillage for field preparation. The single greatest expense in growing the cover crop in this example was the cost of a single irrigation to germinate the cover crop seed, which accounted for almost half of the operating cost (Table 4).

4. Discussion

The N balance of the soil profile, driven primarily by N transformations in the surface soil layer, was significantly influenced by winter cover cropping. Leaching of soil NO_3^--N, from residual fertilizer and from net N mineralization in the soil surface during winter, was significantly less from the cover-cropped plots because extensive rooting in the surface layer removed N and water from the system. These findings are corroborated by previous studies, which found that winter cover crops can be used to reduce NO_3^--N leaching in agroecosystems that have a high residual soil NO_3^--N content after harvest, high N mineralization rates, and/or a rainy season which is typically left fallow (Lamb et al., 1985; Powlson, 1988; Martinez and Guiraud, 1990; Meisinger et al., 1991; Jackson et al., 1993). The temporary increase in N turnover in the surface soil after residue incorporation may have contributed to subsequent nutrient availability to the broccoli crop, resulting in increased yield at harvest from the phacelia plots. More pronounced effects on crop yield from residue addition were probably masked by large fertilizer applications in all treatments. The use of minimum tillage techniques on semi-permanent beds can reduce both the cost of incorporation and the risk of disrupting tight planting schedules, compared with disking and planting a flat field and rebedding in the spring. Cover cropping was found to be commercially viable as a vegetable crop rotation because it neither introduced nor enhanced any insect or disease pathogens which threatened the crop, it did not increase soilborne disease problems, and the costs were small relative to conventional winter management of fallowed soil. Protection of the groundwater from NO_3^--N leaching is a clear environmental benefit of cover cropping, partially offset by potential increases in denitrification resulting from increased C and NO_3^--N in the surface soil after incorporation of residues (Aulakh et al., 1992).

4.1. Surface soil dynamics

Incorporation of low C/N residues was expected to result in short-term increases in MBN and MBC, increased fluxes through inorganic N pools, decreased NO_3^--N pools available for leaching or denitrification losses, and possibly greater N availability to the subsequent crop (Ladd et al., 1981; Doran and Smith, 1991). There was a short-term (6 week) increase in microbial biomass and net mineralizable N after residue addition, and the corresponding decline in inorganic N pools during that time may have been due in part to short-term microbial N immobilization followed by net N mineralization, although denitrification could also account for some of the NO_3^--N loss. By the time of crop planting, however, N mineralization and MBN had declined to the level of the bare soil plots, and there were no differences in soil inorganic N content between treatments. Sandy loam soils have been shown to have higher rates of organic decomposition and nutrient turnover than clay soils, resulting in lower retention of C inputs (Van Veen et al., 1985). The only indications of a sustained effect from residue addition were higher MBC in the cover-cropped plots throughout the broccoli crop, and a significant increase in plant biomass at harvest of the first crop in the phacelia plots.

Tillage has been shown to cause depletion of SOM in surface soils (Doran, 1980; Voroney et al., 1981; Carter and Rennie, 1984; Burke et al., 1989; Cambardella and Elliott, 1994), particularly of the labile fraction which is critical to soil nutrient dynamics (Janzen et al., 1992). The historic loss of organic C during the last century of increasingly intensive cultivation in this soil has been documented (Table 1). Microbial biomass may be primarily carbon-limited in intensively tilled soils, as suggested by the decline in MBC in bare soils after the first spring tillage event, compared with the increase in MBC in the cover-cropped soils (Fig. 1). Low soil moisture may contribute to lower C availability, and/or microbial consumption of available C, since a later tillage event (9 April), when soil moisture was somewhat higher, resulted in temporary increases in MBC in all treatments. These short-duration spikes and declines in microbial activity after cultivation demonstrate the potentially damaging effect of frequent tillage on the retention of soil organic C.

Low soil moisture is known to inhibit microbial activity and nutrient turnover (Campbell and Biederbeck, 1976; Van Gestel et al., 1992). There is a surge in microbial biomass and a respiratory pulse when dry soil is rewetted, which is attributed to the mineralization of newly available decomposable organic compounds (Jenkinson and Powlson, 1976). Some of this organic material is derived from soil biota killed by desiccation, and some from non-biomass SOM (Van Gestel et al., 1991). In this study, soil moisture was low prior to incorporation, particularly in the cover-cropped plots (about -0.30 MPa), and decreased just afterwards (about -0.35 MPa in the cover-cropped plots). There was a corresponding decline in MBN until soil moisture increased. N uptake appears to be more sensitive to soil moisture content than C assimilation, which increased when residue incorporation occurred, despite the decrease in soil moisture. These changes suggest differences in microbial C/N ratios that may be related to microbial population composition, e.g. higher C/N ratios in fungal-dominated populations.

4.2. Nitrogen utilization and nitrate loss

The broccoli crop received frequent fertilizer applications, which totaled over 41.0 g N m^{-2} per crop. Five sidedresses were applied to each crop, either banded in the top 5 cm of soil, or as foliar sprays. Nevertheless, a gross N budget indicates that little or no NO_3^--N leaching must have occurred during the broccoli crops, because broccoli N uptake was nearly 400 kg N ha^{-1}, and the large NO_3^--N pools in the lower soil depths at harvest account for the remaining fertilizer N plus initial soil N content and the additional N introduced via irrigation water. Net N mineralization also undoubtedly contributed to the inorganic N inputs. The residual NO_3^--N in the lower depths after broccoli harvest has a high risk of leaching below the rootzone during subsequent winter rains, however, unless another cash crop or cover crop is planted to deplete NO_3^--N and water from the profile.

4.3. Insect pests and diseases

The cover crops neither introduced nor enhanced any soil-borne diseases which threatened the broccoli crops. No root, crown or foliar diseases which concern vegetable crops were observed on the cover crops, and no disease problems occurred in the broccoli seedlings or mature plants of either crop. Stand counts after the establishment of each crop showed no differences due to cover crop treatment. The populations of mites and springtails were less than half the size of populations found in fields with stand establishment problems. The implication of these results is that a three week period after cover crop incorporation is sufficient for pest populations to decline to a level that poses no threat to the subsequent crop. Growers can therefore minimize potential pest problems, yet optimize crop scheduling and N contribution from the cover crop by planting vegetables *c.* one month after incorporation.

4.4. Management considerations

The economic analysis indicated that the costs of cover cropping were minor relative to the costs of vegetable production. The greatest barrier to replacing the winter fallow with a cover crop lies in the risk of disrupting the spring vegetable planting schedule. Growers claim that the window of opportunity to grow and incorporate a cover crop, and then prepare the field for vegetable planting is very short in this production system. The results of this study showed that cover crop transpiration reduced soil moisture, which may allow earlier entry of equipment into the field for spring vegetable planting. Cover crop N uptake may reduce soil N availability at vegetable crop planting, but most of the soil NO_3^--N present at planting is leached during the heavy irrigations to germinate the crop (Fig. 1). The extent to which gradual mineralization of cover crop residues may be able to reduce N fertilizer requirements during the vegetable crop is not clear from this study, due to high N applications, but fertilizer costs could potentially be reduced. The use of semi-permanent beds and reduced tillage techniques may make cover cropping a viable option in intensive vegetable production, because beds are already shaped for planting in the spring, and minimum tillage equipment is lighter weight and will cause less compaction than disking in wet soil.

The long-term environmental and economic costs of groundwater pollution and soil degradation resulting from high-input, intensive cropping schedules cannot be quantified within the scope of this study, nor can the potential benefits of long-term cover cropping be assessed. It is difficult to attach an economic value to the protection of environmental resources, just as it is hard to balance immediate costs with promises of improved productivity in the long-term. Nevertheless, sustainable management practices will not be undertaken by growers without careful consideration of their practical implications. This one year study indicates that minimum tillage practices can be used to grow cover crops without detriment to vegetable crop yields, and with minimal costs, and thereby reduce NO_3^--N losses below the root zone.

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