Winter Cover Crop Seeding Rate and Variety Effects during Eight Years of Organic Vegetables: III. Cover Crop Residue Quality and Nitrogen Mineralization

Eric B. Brennan,* Nathan S. Boyd, and Richard F. Smith

ABSTRACT

Winter cover crops (CCs) can improve nutrient-use efficiency in tillage-intensive cropping systems. Shoot residue quality and soil mineral N following incorporation of rye (*Secale cereale* L.), legume–rye, and mustard CCs was determined in December to February or March during the first 8 yr of the Salinas Organic Cropping Systems trial in Salinas, CA. Legume–rye included *Vicia faba* L., *V. sativa* L., *V. benghalensis* L., *Pisum sativum* L., and rye; mustard included *Sinapis alba* L. and *Brassica juncea* Czern. Cover crops were planted in the fall at standard and three times higher seeding rates (SRs) before vegetables annually. Significant CC × year interactions occurred for C and N concentrations and C/N ratios of CC shoots. In general, C concentrations were higher in rye and legume–rye, N concentrations were higher in mustard and legume–rye, and C/N ratios were higher in rye. During the season, C concentrations and C/N ratios tended to increase, whereas N concentrations decreased. Compared with rye and mustard, legume–rye residue quality changed least during each season. Increasing the SR reduced N concentrations and increased C/N ratios; however, the effect varied with time and by residue. Following CC incorporation, soil mineral N varied between years and CC and was typically highest following legume–rye or mustard and lowest without CC. Rainfall after CC incorporation reduced soil N one year, suggesting that leaching occurred. We conclude that mustard and legume–rye produce higher quality residue that will decompose more rapidly and minimize tillage challenges for subsequent vegetables but may be more prone to post-incorporation N leaching.

Replacing bare winter fallows with cover crops is a best management practice for sustainable agricultural systems because cover crops can add C that is important for the soil food web, improve soil quality, reduce soil erosion and N leaching into groundwater, and may reduce supplemental N fertilizer inputs by recycling leachable N and by adding biologically fixed N_2 from legume cover crops (Ferris et al., 2012; Sainju and Singh, 1997; Shennan, 1992; Tonitto et al., 2006). Farmers can also use winter cover crops to comply with increasing regulations designed to reduce nutrient losses (Hartz, 2006); however, cover crop residue management can be a major obstacle to cover crop adoption in tillage-intensive vegetable systems. Residue management is challenging in such systems because it typically requires flail-mowing, multiple tillage operations to incorporate cover crops into the soil, and adequate decomposition time before planting subsequent cash crops (Van Horn et al., 2011). In California vegetable systems, these challenges are avoided in bare winter fallow fields where preformed beds are maintained weed-free with shallow tillage, herbicides, or flamers. Spring vegetable planting is therefore significantly easier and less expensive in bare winter fallowed fields than in cover cropped fields. Cover crop residue management challenges are complicated further when prolonged spring rainfall delays timely termination of winter cover crops and subsequent vegetable plantings.

To increase the adoption of winter cover crops, growers need regionally specific information on how cover crop biomass quantity and quality change during the winter. This information will help growers select the most appropriate cover crops to rotate with vegetables and make management decisions on termination date, tillage requirements, and length of the residue decomposition period. For example, tillage requirements for residue incorporation and the duration of the decomposition period generally increase as cover crop biomass increases and residue quality declines. Information on the temporal changes in cover crop residue quality throughout the season and over multiple years in California and other high-value crop production regions is lacking.

Crop residue quality is often characterized by C and N concentrations, C/N ratios, lignification, and polyphenol content (Kumar and Goh, 2000; Palm et al., 2001). Residue is generally considered higher quality if it has a lower C/N ratio (Handayanto et al., 1997), which hastens decomposition and is therefore more likely to result in net N mineralization and increase subsequent crop yields. One strategy to improve cover crop residue quality and minimize N immobilization is to use cover crop mixtures of nonlegumes and legumes because the N concentrations of such mixtures are often higher than those of nonlegume monocultures (Creamer et al., 1997; Griffin et al., 2000; Odhiambo and Bomke, 2000). Nonlegume cover crops such as mustards provide another strategy to minimize cover

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Abbreviations: DAI, days after incorporation; DM, dry matter; GDD, growing degree days; SR, seeding rate.

crop residue challenges because they can have relatively high N concentrations (37–41 g N kg^{-1} shoot dry matter) that are similar to legumes (Hartz et al., 2005).

In this study, we investigated the dynamics of residue quality and N mineralization of mustard, rye, and legume–rye cover crops in the Salinas Organic Cropping Systems (SOCS) trial. The SOCS trial is a commercial-scale, long-term, organic systems trial focused on high-value and high-input crops in Salinas, CA. The cover crops evaluated represent the three most common groups of winter cover crops (mustards, cereals, and legume–cereal mixtures) used in high-value production systems in the central coast region of California. This region is a major production area for organic and conventional cool-season vegetables and strawberries (*Fragaria* ×*ananassa* Duchesne ex Rozier) for U.S. consumption and export. The current study is the third in a series focused on the cover cropping phase of the SOCS trial that included six treatments that were cover cropped annually at either a typical (1×) or high (3×) seeding rate (SR) during the first 8 yr of the trial. The first two studies focused on cover crop densities and biomass production (Brennan and Boyd, 2012a) and N accumulation (Brennan and Boyd, 2012b).

Our objectives were to: (i) track cover crop shoot residue quality in December, January, and at season end (February–March); and (ii) evaluate N mineralization dynamics during the cover crop decomposition period of the first 2 yr. Specific questions of interest were: (i) Are there differences in residue quality between the nonlegume and legume–rye cover crops during the season? (ii) Does SR affect residue quality? (iii) Does residue quality vary across years and if so, what factors contribute to such variation? (iv) How do the N mineralization patterns differ between the cover crops during the post-incorporation period before vegetable planting?

MATERIALS AND METHODS

Site Description and History

More details on the history of the site and cropping sequence of the ongoing SOCS trial were provided by Brennan and Boyd (2012a). Briefly, the trial is located at the USDA-ARS certified organic research farm in Salinas, CA (36°37′ N, 121°32′ W). This site has been certified organic by the California Certified Organic Farmers since 1999. The site was used for conventional, winter oat (*Avena sativa* L.) hay production from 1990 to 1996, with frequent fallow periods and occasional organic vegetables and cover crops with minimal inputs from 1999 to 2003. The decomposed granite soil is a Chualar loamy sand (a fine-loamy, mixed, superactive, thermic Typic Argixeroll) with 77% sand, 15% silt, and 8% clay.

Cropping Sequence and Experimental Design

The experimental design is a randomized complete block with eight systems (i.e., treatments) in four replicates. The cover crop residue quality data presented were from six systems that were cover cropped annually for 8 yr and received identical compost, fertilizer, and irrigation inputs during vegetable production. The soil N mineralization dynamics of these six systems and post cover crop incorporation during the first 2 yr were compared with N mineralization of another system that received the same inputs but was fallow during the first two winter periods. The system plots are 12.2 m wide by 19.5 m long and are arranged in a grid of four plots wide by eight plots long within a 0.9-ha field. The annual rotation began with winter cover crops or fallow from October or November to February or March, followed by romaine lettuce (*Lactuca sativa* L. var. *longifolia* Lam.) from May to June or July each year, which was followed by baby leaf spinach (*Spinacia oleraceae* L., July–September, Year 1) or broccoli (*B. oleraceae* L. var. *italica* Plenck., July or August to September or October, Years 2–7). Dates for cover crop planting and previous crop residue incorporation varied slightly by year (Table 1). Supplemental dry and liquid organic fertilizers were applied to the vegetable crops at rates of 22 kg N ha^{-1} for spinach, 73 kg N ha^{-1} for lettuce, and 134 to 168 kg N ha^{-1} for broccoli; additional details on fertilizer inputs were provided by Brennan and Boyd (2012a). The seven systems received 7.6 Mg ha^{-1} (oven-dry basis) of urban yard-waste compost with an approximate C/N ratio of 22 before each vegetable crop. All systems occurred on the same plots annually to determine their cumulative effects. Local organic farmers and industry stakeholders provided advice on crop management and the personnel, expertise, and equipment needed for the commercial-scale harvest and sale of marketable vegetables from the trial. Thus, although the study occurs on a research station, the land is intensively managed to meet the same production standards and practices of a local organic farm.

Table 1. Cover crop planting, sampling, and termination dates, cumulative growing degree days, and water received in the Salinas Organic Cropping Systems trial during 8 yr in Salinas, CA.

Year	Winter period	Planting	Cover crop sampling	Termination	Growing degree days† Dec.	Jan.	Feb.–Mar.	Precipitation + irrigation‡
					°C d			mm
1	2003–2004	16 Oct.	18 Dec., 15 Jan., 3–4 Mar.	8 Mar.	577	754	1059	248 + 45
2	2004–2005	15 Oct.	1 Dec., 24 Jan., 24 Feb.	11 Mar.	402	779	1028	305 + 13
3	2005–2006	17 Oct.	14–15 Dec., 11–13 Jan., 7–8 Feb.	11 Feb.	562	791	983	189 + 32
4	2006–2007	2 Nov.	18–20 Jan., 15–16 Mar.	18 Mar.	–	525	946	123 + 19
5	2007–2008	15 Oct.	17–18 Jan., 13–15 Feb.	19 Feb.	–	699	840	96 + 52
6	2008–2009	15 Oct.	16 Jan., 10–11 Mar.	13 Mar.	–	747	1121	219 + 42
7	2009–2010	29 Oct.	16 Jan., 16–17 Mar.	18 Mar.	–	525	815	246 + 49
8	2010–2011	27 Oct.	12–14 Jan., 7–9 Mar.	10–11 Mar.	–	565	959	234 + 19

† Cumulative growing degree days (GDD) during the cover cropping periods of 8 yr in Salinas, CA, from data at Station no. 89 of the California Irrigation Management System (www.cimis.water.ca.gov); GDD were calculated by the single sine method with a baseline threshold of 4°C using the online calculator at the University of California Statewide Integrated Pest Management Program site (www.ipm.ucdavis.edu).

‡ Irrigation was applied to establish the cover crops.

Field Preparation, Cover Crop Planting, and Management

Field preparation for planting the cover crops included a combination of disk and spring-tooth harrowing, spading, and ring rolling (Till an' Pak, T.G. Schmeiser Co.) as necessary to incorporate the previous crop's residue. Deep ripping to approximately 1 m below the surface was also necessary to break up compaction in the furrows caused by heavy, commercial-scale harvest equipment for the lettuce and broccoli. Cover crops were planted in a single pass with a 4.6-m-wide grain drill that was modified with four belt cones. Rhizobium inoculants (Rhizo Stick, Urbana Laboratories; N-DURE, INTEX Microbials) were added to the legume–rye seed before planting. The target planting date for the cover crops was 15 October; however, the actually dates ranged from 15 October to 2 November (Table 1) due to vegetable crop harvest dates and post-harvest tillage requirements. The 1× SR for each cover crop was the typically recommended rate for vegetable growers in this region. The 1× SRs were 90 kg ha^{-1} for rye, 11 kg ha^{-1} for mustard, 140 kg ha^{-1} for the legume–rye mixture; the 3× rates were three times greater. Seed was obtained from the L.A. Hearne Company. The rye cultivar used was Merced. The mustard was a mixture by seed weight of 61% white mustard (Ida Gold, *Sinapsis alba* L.) and 39% India mustard (Pacific Gold, *B. juncea* Czern.). By seed weight, the legume–rye mixture included 10% rye, 35% faba bean (*Vicia faba* L., a small-seeded type known as bell bean), 25% Magnus pea (*Pisum sativum* L.), 15% common vetch (*V. sativa* L.), and 15% purple vetch (*V. benghalensis* L.); commercially available mixtures with these legume species and rye or oat are relatively common in the region. Sprinkler irrigation was applied to stimulate germination before the onset of adequate winter rainfall (Table 1). The last irrigation during the cover cropping period typically occurred in mid to late November. Cover crops were terminated by flail mowing and incorporated into the soil with a single pass with a spader. The termination dates for the cover crops were selected to maximize cover crop biomass, prevent cover crop seed production, and allow adequate time for residue decomposition and field preparation for planting the subsequent lettuce crop in May. Sprinkler irrigation (38 mm) was applied during the cover crop decomposition period in Year 1.

The fallow system plots received the same overhead irrigation as was applied to establish the cover crops in the cover cropped systems. Weeds that germinated during the cover cropping period in the fallow system were controlled by a combination of flaming, shallow tillage to an approximate depth of 5 cm with a wheel hoe, and rototilling to an approximate depth of 10 cm as needed; this weed management strategy was similar to that applied to winter-fallowed fields in the region, except weed management is typically applied on peaked beds rather than on unbedded fields. The fallow system received the same spading tillage as the cover cropped systems when the cover crops were incorporated in the spring.

Cover Crop and Soil Sampling and Analysis

The shoot biomass of the cover crops was sampled by harvesting one 50- by 100-cm quadrat oriented to cover three adjacent rows for each plot at three (Year 1–3) or two (Year 4–8) sampling dates during each winter (Table 1). The harvested cover crop biomass of the legume–rye mixture was separated into the legume and rye components, and the cover crop biomass was oven-dried at 65°C for at least 48 h until the weight had stabilized to obtain shoot dry matter (DM). The cover crop biomass sampling dates were chosen to track changes in cover crop DM during the winter and to minimize sampling on rainy days. Cover crop DM samples were ground to pass through a 0.250-mm screen, and a 10-mg subsample was analyzed by a combustion gas analyzer method (AOAC, 2006) for total C and N at the University of California-Davis Analytical Laboratory (http://anlab.ucdavis.edu/analyses/plant/sop522) using a TruSpec CN analyzer (LECO Corp.). The reported concentrations of C and N from these analyses were on a 100% DM basis from drying samples to 105°C. Nitrogen analyses were conducted for all harvests. Carbon analysis was done for all years except for Year 1, when it was only done for the final harvest. The legume and rye components of the legume–rye mixture were analyzed separately.

A composite of 20 soil samples was taken with a 1.9-cm-diameter sampler to a depth of 30 cm approximately every 7 to 10 d after incorporation (DAI) of cover crop residues into the soil during the approximately 6-wk cover crop decomposition period. Soil samples from each plot were bulked and thoroughly mixed in the field. Soil was passed through a 2.8-mm sieve and a subsample was weighed and then oven-dried at 105°C until stable for determination of the gravimetric soil moisture content. A 10-g subsample of the soil was extracted in the field with 25 mL of 2.0 mol L^{-1} KCl to measure extractable NO_3–N and NH_4–N using the flow injection method (Hofer, 2003; Knepel, 2003) at the University of California-Davis Analytical Laboratory (http://anlab.ucdavis.edu/analyses/soil/312).

Statistical Analysis

All data were analyzed using SAS version 9.2 (SAS Institute). The 95% confidence intervals (CIs) of shoot cover crop N concentration, C concentration, and C/N ratios were calculated using the CLM option in the MEANS procedure. The CIs are provided to assist with means comparisons using the "rule of eye" method suggested by Cumming (2009), whereby intervals that overlap with a mean are not different, intervals that overlap by half of one interval arm are significantly different at $p \approx 0.05$, and intervals that barely touch are significant at $p \approx 0.01$. Analyses of the response variables were conducted using the MIXED procedure as a repeated measures model (Littell et al., 1996), with year as the repeated effect, an autoregressive AR(1) covariance structure, and cover crop × SR × block as the SUBJECT option; separate analyses were conducted for each harvest period. In the ANOVA, cover crop, year, and SR were treated as fixed effects and block and cover crop × SR × block were treated as random effects. The repeated measures approach was also used for the analysis of the rye in monoculture vs. rye in the legume–rye mixture, where year and SR were treated as fixed effects and block and SR × block were treated as random effects. A similar approach was also used to compare legume N concentration between SR, with SR as the fixed effect. Where necessary, the data were transformed to meet the equal-variance assumption of ANOVA, but back-transformed means are presented. Transformations were: $1/x$ for December and January analyses of the C/N ratio for rye in monoculture and legume–rye; $1/\sqrt{x}$

Table 2. Significance of tests of fixed effects and interactions of C and N concentrations and C/N ratios of total shoot dry matter of three cover crops planted at two seeding rates at three harvest periods during 8 yr in Salinas, CA. December harvests occurred only during the first 3 yr of the trial.

	C concentration			N concentration			C/N ratio		
Effect	Dec.	Jan.	Feb.–Mar.	Dec.	Jan.	Feb.–Mar.	Dec.	Jan.	Feb.–Mar.
Cover crop (CC)†	***	***	***	***	***	***	***	***	***
Seeding rate (SR)‡	ns	ns	ns	*	*	ns	ns	*	ns
Year (Yr)	***	***	***	*	***	***	ns	***	***
CC × SR	ns	ns	ns	ns	ns	ns	ns	ns	ns
CC × Yr	*	***	***	*	***	***	ns	***	***
SR × Yr	ns	ns	ns	ns	ns	ns	ns	ns	ns
CC × SR × Yr	ns	ns	ns	ns	ns	ns	ns	ns	ns

* Significant at the $p \leq 0.05$ level; ns, not significant..

*** Significant at the $p \leq 0.001$ level.

† Cover crops included rye, a legume–rye mixture, and mustard.

‡ Seeding rates were 90 and 270 kg ha^{-1} for rye, 140 and 420 kg ha^{-1} for legume–rye, and 11 and 33 kg ha^{-1} for mustard.

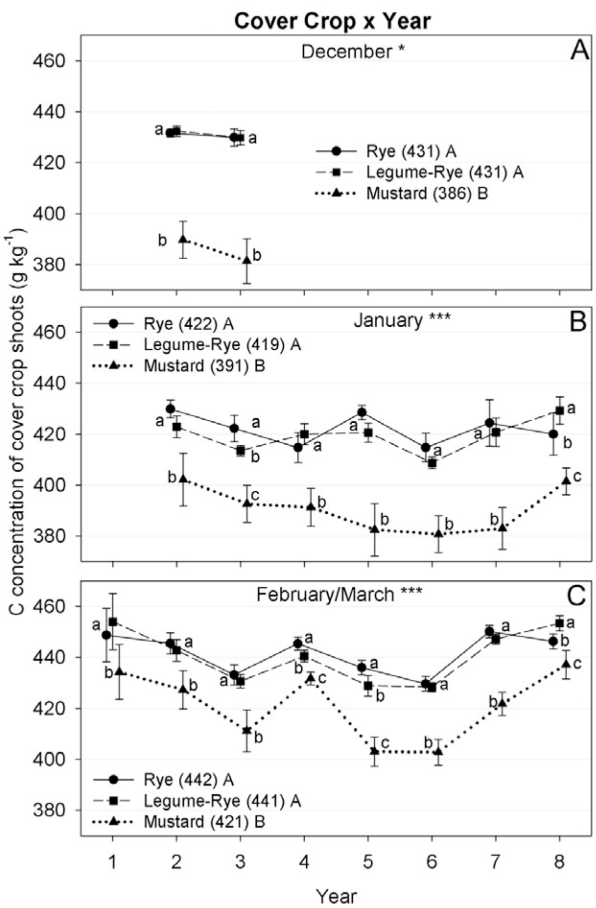

Fig. 1. Cover crop × year interactions for C concentration of cover crop shoot dry matter for three cover crops at (A) December, (B) January, and (C) February–March harvests in Salinas, CA. *Significant interactions at $p \leq 0.05$; ***significant interactions at $p \leq 0.001$. The points are means ±95% confidence intervals averaged across two seeding rates for rye (90 and 270 kg ha^{-1}), legume–rye (140 and 420 kg ha^{-1}), and mustard (11 and 33 kg ha^{-1}). Within years, points are offset to differentiate confidence intervals. Within years and harvests, means with different lowercase letters are significantly different based on a Tukey–Kramer adjusted familywise error rate at $p \leq 0.05$. The numbers in parentheses following the legend for each cover crop are the mean C concentrations averaged across years and rates; within each harvest, numbers in parentheses adjacent to different uppercase letters are significantly different based on a Tukey–Kramer adjusted familywise error rate at $p \leq 0.05$.

for total C/N ratio analysis at January and season end; and natural logarithm for C/N analyses of rye in monoculture vs. legume–rye mixture. Pairwise comparisons were controlled at the familywise error rate of $p \leq 0.05$ using Bonferroni or Tukey–Kramer adjustments.

RESULTS AND DISCUSSION

Cover Cropping Period Weather

A detailed description of weather differences during the cover cropping periods was presented by Brennan and Boyd (2012a). Briefly, the average daily air temperatures during cover cropping typically ranged from 5 to 15°C, and rainfall was from 96 to 305 mm (Table 1). Years 4 and 5 were drier than normal and received <50% of the typical rainfall of 313 mm between October and March from 1994 to 2011. Differences among years in planting date and subsequent air temperatures caused differences in accumulated growing degree days (GDD) that ranged from 815 to 1121. These weather differences among years affected cover crop shoot DM production (Brennan and Boyd, 2012a), N accumulation (Brennan and Boyd, 2012b), and residue quality (discussed below).

Cover Crop Shoot Carbon Concentrations

Carbon concentrations of cover crop shoots differed by cover crop and year, with significant cover crop × year interactions at all harvests; C concentrations were unaffected by SR (Table 2). These cover crop × year interactions are illustrated for each harvest in Fig. 1. Within each harvest period, the cover crop × year interaction was due to greater year-to-year variability in C concentrations of mustard than of rye and legume–rye and differences in rye vs. legume–rye during some years. Furthermore, season-end C concentrations did not differ between rye and legume–rye except during Years 4 and 5, when it was greater for rye, and Year 8, when it was greater for legume–rye (Fig. 1C).

Carbon concentrations of rye and legume–rye were consistently higher than that of mustard across all years and harvests. The differences in C concentrations of mustard vs. the other cover crops diminished from 45 g C kg^{-1} DM in December to 21 g C kg^{-1} DM at season end. There was also a trend of increasing C concentrations through the season within a cover crop and year; this pattern was most consistent for mustard. The increased lignification that occurs in plant shoots with

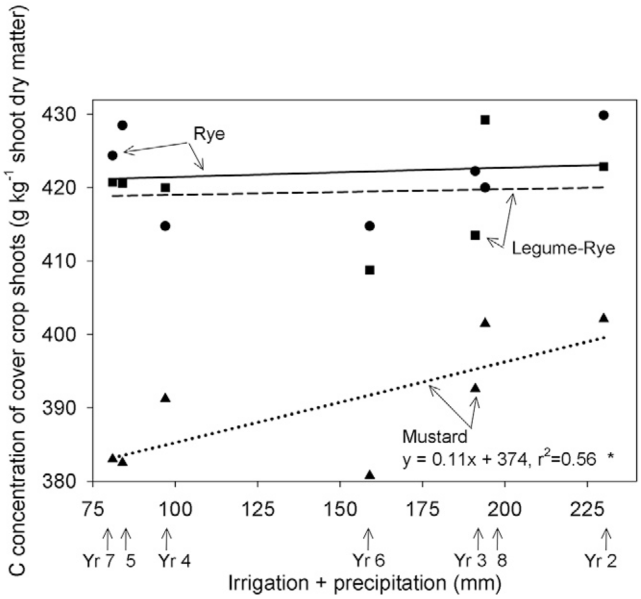

Fig. 2. Relationship between the amount of irrigation plus precipitation that three cover crops received (from cover crop planting up to the January harvest) and the January C concentration of the cover crop shoot dry matter in Salinas, CA. Each point is the mean of four replicates averaged across two seeding rates for rye (90 and 270 kg ha^{-1}), legume–rye (140 and 420 kg ha^{-1}), and mustard (11 and 33 kg ha^{-1}). The arrows below the *x* axis indicate year; C concentrations were not determined during Year 1. The regression was not significant for the rye and legume–rye cover crops. *Significant regression for mustard at $p \leq 0.05$.

increased age (Kilcher and Troelsen, 1973; Rencoret et al., 2011) may explain why the C concentrations tended to increase in the cover crop shoots during the season.

Crop residues typically contain 400 to 500 g C kg^{-1} DM (Kumar and Goh, 2000), and while cover crop studies often report C/N ratios of the residue, relatively few have reported C concentrations. Season-end C concentrations for rye in our study (442 g kg^{-1}) were similar to those in previous studies for rye leaves and stems (455–456 g kg^{-1}) (Quemada and Cabrera, 1995) but higher than for rye shoots (395 g kg^{-1}) (Sainju et al., 2005a). Carbon concentrations of mustard (*S. alba*) mature leaves (355 g kg^{-1}) and stems (398 g kg^{-1}) (Chaves et al., 2004) were comparable to mustard in our study in January (391 g kg^{-1}); *S. alba* produced most of the mustard biomass in our study. To our knowledge, our study presents the first detailed information on the dynamics of cover crop C concentrations across the seasons of multiple years.

There was a significant, positive, linear relationship ($r^2 = 0.56$, $p \leq 0.05$) between the amount of water (irrigation + rainfall) that the cover crops received by the January harvests and the C concentration of mustard but not of rye or legume–rye (Fig. 2). This finding agrees with those of Stubbs et al. (2009), who found higher C concentrations of spring barley (*Hordeum vulgare* L.) during a wet than a dry year, and work by Alam et al. (2011), who found higher C concentrations in *Brassica napus* L. that was irrigated than that which was drought stressed. The significant correlation between water received and C concentrations for mustard in our study suggests that, compared with the other cover crops, mustard was more sensitive to dry conditions.

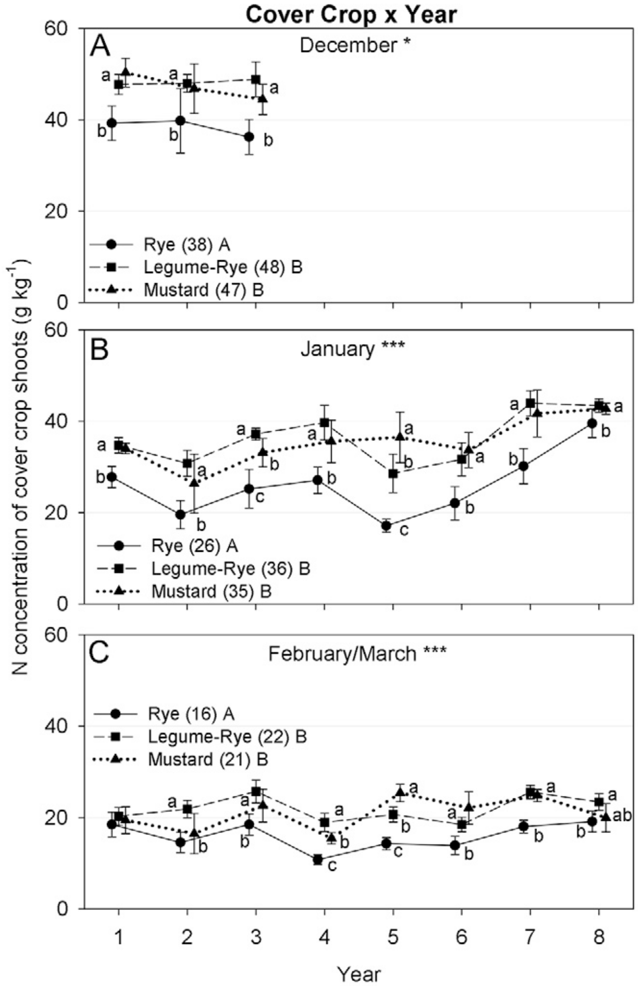

Fig. 3. Cover crop × year interactions for N concentration of cover crop shoot dry matter of three cover crops at (A) December, (B) January, and (C) February–March harvests in Salinas, CA. *Significant interactions at $p \leq 0.05$; ***significant interactions at $p \leq 0.001$. The points are means ±95% confidence intervals averaged across two seeding rates for rye (90 and 270 kg ha^{-1}), legume–rye (140 and 420 kg ha^{-1}), and mustard (11 and 33 kg ha^{-1}). Within years, points are offset to differentiate confidence intervals. Within years and harvests, means adjacent to different lowercase letters are significantly different based on a Tukey–Kramer adjusted familywise error rate at $p \leq 0.05$. The numbers in parentheses following the legend for each cover crop are the mean N concentrations averaged across years and rates; within a harvest, numbers in parentheses adjacent to different uppercase letters are significantly different based on a Tukey–Kramer adjusted familywise error rate at $p \leq 0.05$.

Cover Crop Shoot Nitrogen Concentrations

Shoot N concentrations were affected significantly by cover crop, year, and their interaction at all harvests and by SR in December and January (Table 2). The cover crop × year interaction occurred because of differences in the relative ranking of N concentrations among cover crops during some years (Fig. 3). For example, during January of Year 1, mustard and the legume–rye mixture had the same N concentration (35 g kg^{-1}), whereas during Year 5 mustard had a higher concentration (36 g kg^{-1}) than the legume–rye mixture (29 g kg^{-1}) (Fig. 3B). Averaged across SR and years, the N concentrations were higher in legume–rye and mustard than in rye throughout the season; however, these differences among cover crops declined

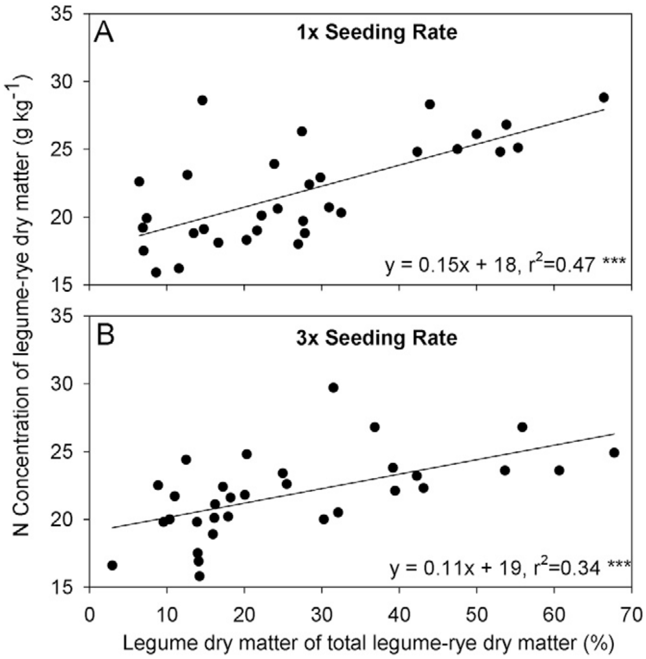

Fig. 4. Relationship between the legume dry matter component of the total legume–rye dry matter and the N concentration of the legume–rye dry matter at season end for (A) 1× and (B) 3× seeding rates during 8 yr in Salinas, CA. Seeding rates for the legume–rye mixture were 140 and 420 kg ha^{-1}. ***Significant linear regression relationship at $p \leq 0.001$. Each point is one of four replicates for each of the 8 yr.

through the season as N concentrations also declined (Fig. 3). The percentage decline in the N concentrations from December to season end was 58% for rye (from 38 to 16 g kg^{-1}), 55% for mustard (from 47 to 21 g kg^{-1}), and 54% for legume–rye (from 48 to 22 g kg^{-1}). The relatively low N concentrations (16 g kg^{-1}) of the rye monoculture at season end in our study are comparable to the range (14–18 g kg^{-1}) from a previous study in the central coast region of California (Brennan et al., 2011). Muramoto et al. (2011) reported 21 g N kg^{-1} at season end in a legume–oat cover crop from an organic farm in Santa Cruz, CA, a concentration that was nearly identical to the N concentrations at season end for legume–rye and mustard in our study. In other regions of the United States, N concentrations at season end were similar to our study for rye but were often 30 g kg^{-1} or more for vetch–rye mixtures (Griffin et al., 2000; Sainju et al., 2005b). The higher N concentrations of the legume–rye mixture than the rye monoculture were due to the presence of the legume component. Regression analysis illustrates that at both the 1× and 3× SR, the N concentration of the legume–rye mixture at season end increased as the percentage of the legume component in the mixture increased; however, the r^2 value was greater for the 1× (0.47) than 3× (0.34) SR (Fig. 4). The critical N concentration for net N mineralization of cover crop DM is generally 14 to 18 g kg^{-1} (Kuo et al., 1997; Odhiambo and Bomke, 2000) and suggests that N immobilization at season end would be more likely with the residue of rye than the other cover crops.

Averaged across years and cover crops, an increased SR caused a relatively small but statistically significant reduction in the total cover crop N concentration during December and January but not at season end (Table 2). For example, in December, the N concentrations of the 1× vs. 3× rates were 41 vs. 36 g kg^{-1} for rye, 50 vs. 47 g kg^{-1} for the legume–rye, and 48 vs. 47 g kg^{-1} for mustard. Similarly in January, N concentrations of the 1× vs. 3× rates were 28 vs. 25 g kg^{-1} for rye, 37 vs. 35 g kg^{-1} for legume–rye, and 36 vs. 35 g kg^{-1} for mustard. The negative effect of the increased SR on N concentrations up to January was presumably because higher seeding rates increased DM production (Brennan and Boyd, 2012a) and the demand for N.

Table 3. Significance of tests of fixed effects and interactions with N concentrations and the C/N ratio of rye shoot dry matter from a monoculture and a legume–rye mixture planted at two seeding rates at three harvest periods during 8 yr in Salinas, CA. December harvests occurred only during the first 3 yr of the trial.

	N concentration			C/N ratio		
Effect	Dec.	Jan.	Feb.–Mar.	Dec.	Jan.	Feb.–Mar.
Cover crop (CC)†	***	***	***	***	***	***
Seeding rate (SR)‡	**	**	ns	**	***	ns
Year (Yr)	ns	***	***	ns	***	***
CC × SR	ns	ns	ns	ns	ns	ns
CC × Yr	ns	**	*	ns	*	*
SR × Yr	ns	ns	ns	ns	ns	ns
CC × SR × Yr	ns	ns	ns	*	ns	ns

* Significant at the $p \leq 0.05$ level; ns, not significant.
** Significant at the $p \leq 0.01$ level.
*** Significant at the $p \leq 0.001$ level.
† Cover crops include rye, a legume–rye mixture, and mustard.
‡ Seeding rates were 90 and 270 kg ha^{-1} for rye, 140 and 420 kg ha^{-1} for legume–rye, and 11 and 33 kg ha^{-1} for mustard.

Nitrogen concentrations of rye in the monoculture and legume–rye mixture were affected significantly by cover crop at all harvests, SR in December and January, and year during January and February–March; however, a cover crop × year interaction also occurred during the latter two harvests (Table 3). The cover crop × year interaction for the N concentration and C/N ratio of rye in both monoculture and mixture followed the same pattern and therefore are discussed below for the C/N ratio. The SR effect on the rye N concentration in the monoculture and mixture was evaluated with regression analysis across four rye densities and revealed high negative correlation between rye density and rye N concentration in December ($r^2 = 0.96$) and January ($r^2 = 0.98$) (Fig. 5). Increased competition for soil N at higher rye densities was the probable cause of the lower rye N concentrations at higher densities.

Nitrogen concentrations of the legume component of the legume–rye mixture were significantly affected by SR and SR × year interaction during December (Table 4). The SR × year interaction for the legume component occurred in December because increasing the SR increased the legume N concentration during Year 1 (from 42 to 46 g kg^{-1}) and Year 2 (from 43 to 47 g kg^{-1}) but decreased it during Year 3 (from 47 to 44 g kg^{-1}). The SR did not affect the legume N concentration during January or at season end. We speculate that greater cover crop density in the 3× SR reduced the soil N concentrations, which in turn may have increased N_2 fixation and N concentrations in the legume component during Years 1 and 2; it is unclear if the reduction in legume N concentration with increasing SR during Year 3 was due to the lower overall density of legumes and greater legume DM that year or climatic

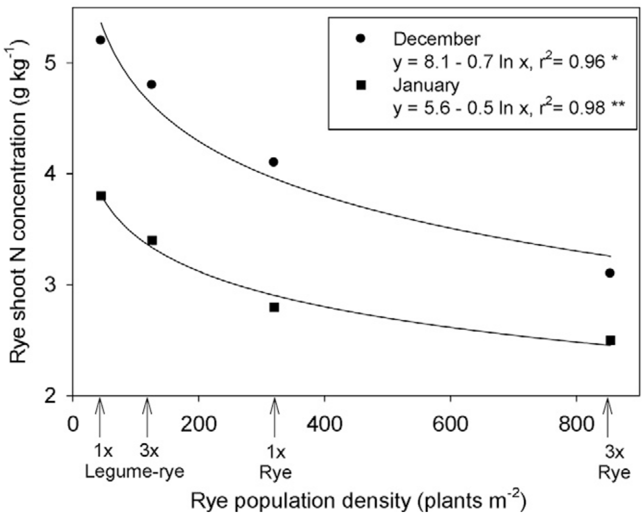

Fig. 5. Relationship between average rye population density and rye shoot dry matter N concentration in a legume–rye mixture and rye monoculture averaged across 3 yr (December) and 8 yr (January) in Salinas, CA. Population densities were determined in November or December and are indicated with vertical arrows along the *x* axis and in sequential order were 45, 126, 320, and 854 plants m^{-2}. Cover crop seeding rates were 140 and 420 kg ha^{-1} for legume–rye and 90 and 270 kg ha^{-1} for rye. *Significant regression at $p \leq 0.05$; **significant regression at $p \leq 0.01$.

or other differences among years (Brennan and Boyd, 2012a). Legumes are known to derive more N from fixation when soil N concentrations are reduced by strategies such as intercropping legumes with cereals (Peoples et al., 2009).

Shoot Carbon/Nitrogen Ratios of Cover Crop Residue

The total shoot C/N ratios varied significantly by cover crop across all harvests, and significant year and cover crop × year effects occurred in January and at season end (Table 2). Relatively small differences in the ranking of the C/N ratios within a year explain the cover crop × year interactions (Fig. 6B–6C). For example, during January there were seldom differences in the C/N ratios of mustard and the legume–rye mixture, except during Year 5 when all cover crops differed and Year 8 when there were no differences (Fig. 6B). The C/N ratios increased through the season in all cover crops, and averaged across SR and years, the C/N ratios were greater in rye than in legume–rye and mustard (Fig. 7); the means in Fig. 7 are slightly different from those in Fig. 6, where back-transformed means are presented for January and February–March. The lower C/N ratio of the legume–rye mixture compared with rye agrees with previous studies from this region (Brennan et al., 2011) and elsewhere (Rosecrance et al., 2000; Teasdale and Abdul-Baki, 1998).

Seeding rate had a significant effect on the C/N ratio of the total cover crop shoots during January (Table 2). Averaged across years, the C/N ratio of shoots increased from the 1× to 3× SR by 4% in legume–rye (from 11.3 to 11.8) and mustard (from 10.9 to 11.3), and 14% in rye (from 15.6 to 17.8). To our knowledge, this is the first report that the SR can influence C/N ratios.

The C/N ratio of rye in the monoculture and rye in the legume–rye mixture differed significantly between these

Table 4. Significance of tests of fixed effects and their interaction with N concentration and the C/N ratio of legume shoot dry matter in the legume–rye mixture at three harvest periods during 8 yr in Salinas, CA. Nitrogen concentrations were determined only during the first 3 yr for December harvests; C/N ratios were determined only during Years 2 and 3 for December harvests and during Years 2 to 8 for January harvests.

	N concentration			C/N ratio		
Effect	Dec.	Jan.	Feb.–Mar.	Dec.	Jan.	Feb.–Mar.
Seeding rate (SR)†	**	ns	ns	ns	ns	*
Year (Yr)	ns	***	***	ns	**	***
SR × Yr	**	ns	ns	***	ns	ns

* Significant at the $p \leq 0.05$ level; ns, not significant.
** Significant at the $p \leq 0.01$ level.
*** Significant at the $p \leq 0.001$ level.
† Seeding rates were 140 and 420 kg ha^{-1}.

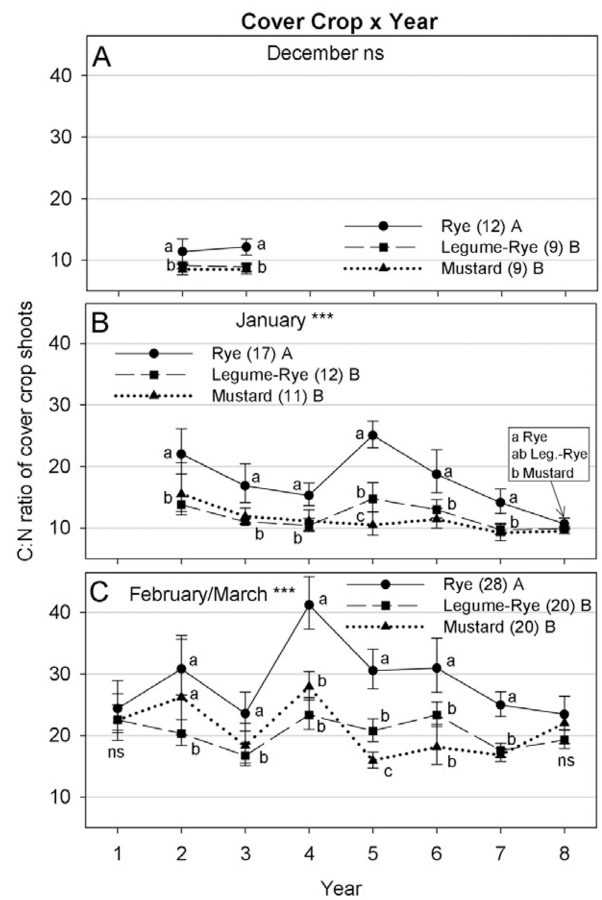

Fig. 6. Cover crop × year interactions for the C/N ratio of shoot dry matter of three cover crops at (A) December, (B) January, and (C) February–March harvests in Salinas, CA. ***Significant interaction at $p \leq 0.001$; ns, not significant. The points are means ±95% confidence intervals averaged across seeding rates for rye (90 and 270 kg ha^{-1}), legume–rye (140 and 420 kg ha^{-1}), and mustard (11 and 33 kg ha^{-1}). Within years, points are offset to differentiate confidence intervals. Within years and harvests, means adjacent to different lowercase letters are significantly different based on a Tukey–Kramer adjusted familywise error rate of $p \leq 0.05$; lowercase letters follow cover crop labels in box insert for January of Year 8. The numbers in parentheses following the legend for each cover crop are the mean C/N ratios averaged across years and rates; within harvests, these means followed by different uppercase letters are significantly different based on a Tukey–Kramer adjusted familywise error rate of $p \leq 0.05$. Means are back-transformed for January and February–March harvests.

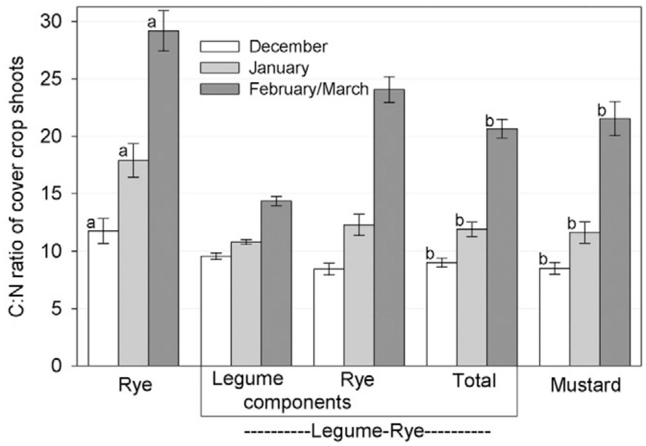

Fig. 7. Ratio of C/N of shoot dry matter of three cover crops at December, January, and February–March harvests and averaged across seeding rates in Salinas, CA. Seeding rates were 90 and 270 kg ha^{-1} for rye, 140 and 420 kg ha^{-1} for legume–rye, and 11 and 33 kg ha^{-1} for mustard. Data are from Years 2 to 3 for December, Years 2 to 8 for January, and all 8 yr for February–March. Bars are means ±95% confidence intervals. Within a harvest period, bars with different letters are significantly different based on a Tukey–Kramer adjusted familywise error rate of $p \leq 0.05$. Comparisons within a cover crop or between the legume–rye components and the monocultures can be made using the "rule of eye" method whereby intervals that overlap with a mean are not different and intervals that overlap by half an interval arm are significantly different at $p \approx 0.05$ (Cumming, 2009). The C/N ratio means were 12, 9, and 9 in December; 18, 12, and 12 in January; and 29, 21, and 22 in February–March for rye, the legume–rye mixture, and mustard, respectively. The C/N ratio means of legume–rye components were 10, 11, and 14 for the legume and 8, 12, and 24 for the rye for December, January, and February–March, respectively. The means are slightly different from those in Fig. 6 where back-transformed means are presented for January and February–March.

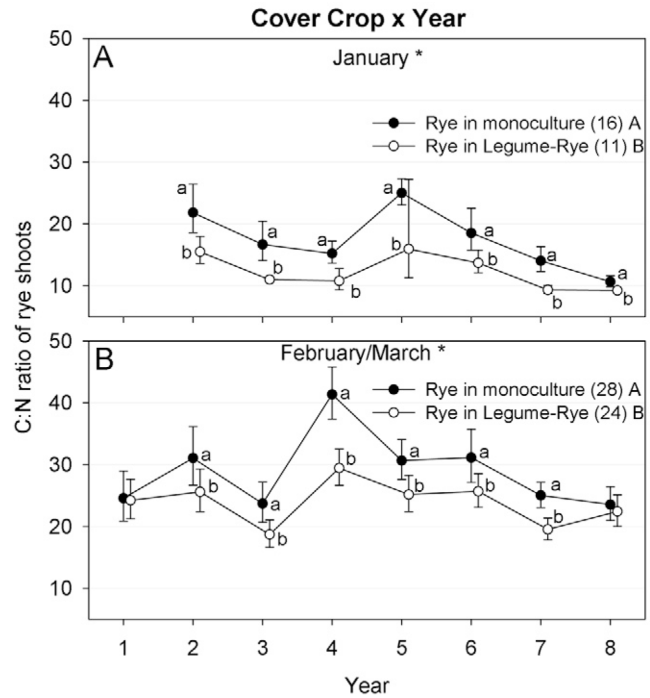

Fig. 8. Cover crop × year interactions for the C/N ratio of rye shoot dry matter in the rye monoculture and the legume–rye mixture during January and February–March harvests in Salinas, CA. *Significant interaction at $p \leq 0.05$. The points are means ±95% confidence intervals averaged across seeding rates for each cover crop. Seeding rates for the 1× and 3× rates, respectively, were 90 and 270 kg ha^{-1} for rye and 140 and 420 kg ha^{-1} for legume–rye. Within years, points are offset to differentiate confidence intervals. Within years and harvests, means adjacent to different lowercase letters are significantly different based on a Tukey–Kramer adjusted familywise error rate of at $p \leq 0.05$. The numbers in parentheses following the legend for each cover crop are the C/N ratios averaged across years and rates; within a harvest, numbers in parentheses adjacent to different uppercase letters are significantly different based on a Tukey–Kramer adjusted familywise error rate of $p \leq 0.05$. Means and confidence intervals are back-transformed.

cover crops at all harvests, and there were significant year and year × cover crop effects at January and season end (Table 3). The cover crop × SR × year interaction for rye C/N ratios in December occurred because the ratio increased from Years 2 to 3 in the monoculture and legume–rye 3× SR but declined in legume–rye 1× SR (data not shown). The C/N ratio of monoculture rye was greater than rye in the legume–rye mixture during all years in January and during 6 of 8 yr at season end (Fig. 8); the C/N ratio of rye in monoculture in January was slightly less in Fig. 8 than in Fig. 6 and 7 because a different transformation was needed to homogenize the variance for the data shown in Fig. 6 and 7. We speculate that the low rainfall relative to the high number of GDD may have contributed to the particularly high C/N ratios of rye in the monoculture (41) and rye in the legume–rye mixture (29) during Year 4 (Fig. 8b). For example, the ratio of accumulated GDD to water received from rainfall and irrigation was 6.7 (946 GDD/142 mm) during Year 4 when the C/N ratios were highest compared with 3.8 (959 GDD/253 mm) during Year 8 when the C/N ratios were lowest in the monoculture rye.

Seeding rate had a significant effect on the C/N ratios of rye in monoculture and rye in the legume–rye mixture during December and January (Table 3). Averaged across years, increasing the SR from 1× to 3× increased the C/N ratio of rye in the monoculture from 10 to 13 during December and from 15 to 17 during January. Similarly, averaged across years, increasing the SR from 1× to 3× increased the C/N ratio of rye in the legume–rye mixture from 8 to 9 during December and from 11 to 12 January.

The C/N ratio of the legume component of the legume–rye mixture was affected significantly by the SR × year interaction (December), year (January and season end), and SR (season end) (Table 4). The SR × year interaction occurred because from Years 2 to 3 the C/N ratio of the legume component declined from 10 to 9 for the 1× SR but increased from 9 to 10 for the 3× SR. Averaged across years, increasing the SR from 1× to 3× increased the C/N ratio of the legume shoot residue significantly from 13 to 14 (Table 4). Figure 9 illustrates the increase in the C/N ratio of the legume component from 9.6 to 14.3 during the season and the effect of year through the season.

The relationship between cover crop shoot C/N ratios and N concentrations followed the same pattern reported by Vigil and Kissel (1991) (Fig. 10). The relatively narrow spread of the data for the legume–rye plot compared with that of the rye plot illustrates greater seasonal changes in the quality of the rye vs. legume–rye residue. Whereas the changes in residue quality of the mustard cover crop was intermediate to that of rye and legume–rye.

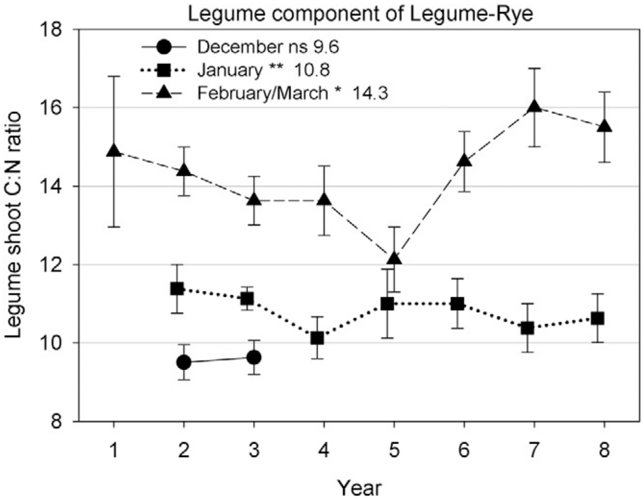

Fig. 9. Legume component shoot C/N ratio of the legume–rye cover crop at December, January, and February–March harvests in Salinas, CA. *Significant year at $p \leq 0.05$; **significant year at $p \leq 0.01$; ns, not significant. The points are means ±95% confidence intervals averaged across seeding rates for each cover crop. Numbers following the legend for each harvest period are means. The 1× and 3× seeding rates were 140 and 420 kg ha^{-1}, respectively. Within years, points are offset to differentiate confidence intervals.

Figure 10 also illustrates that the C/N ratio of the cover crop residue can be estimated readily from the residue N concentration, and this can save researchers the extra cost of C analyses.

Cover Crop Decomposition Period Weather

There were differences in soil temperature and rainfall patterns during the cover crop decomposition periods of Years 1 and 2 (Fig. 11A). Soil temperatures were several degrees cooler in the first week after cover crop incorporation during Year 1 than Year 2. Furthermore, during the decomposition period, Year 1 had only a single rain event (8 mm at 17 DAI) compared with the more frequent rainfall during Year 2, including 35 mm on 11 DAI and 102 mm total. These differences between years help explain the differences in soil mineral N during the cover crop decomposition period (discussed below). Due to the dry conditions during Year 2, 38 mm of supplemental irrigation was applied to promote cover crop decomposition.

Soil Nitrogen Mineralization

Soil N mineralization patterns differed markedly between Years 1 and 2 and between fallow and cover cropped systems within a year (Fig. 11B–11C). Averaged across systems, mineral N levels were 4 mg N kg^{-1} dry soil within the first 2 DAI both years, and the overlap of the 95% confidence intervals indicates similar N levels among systems; however, the highest N followed the legume–rye both years. During Year 1, soil mineral N increased more rapidly in the cover cropped systems than the fallow system through the first 20 DAI; however, there were no apparent differences among systems by the latter sampling dates (23 and 36 DAI) when mineral N peaked at approximately 20 to 25 mg kg^{-1} dry soil. Application of soil amendments and bed shaping between the last two sampling dates of Year 1 had no apparent effect on soil mineral N levels. Averaged across systems during Year 2, there was a trend of increasing soil mineral N up to 10 DAI, followed by an overall decline

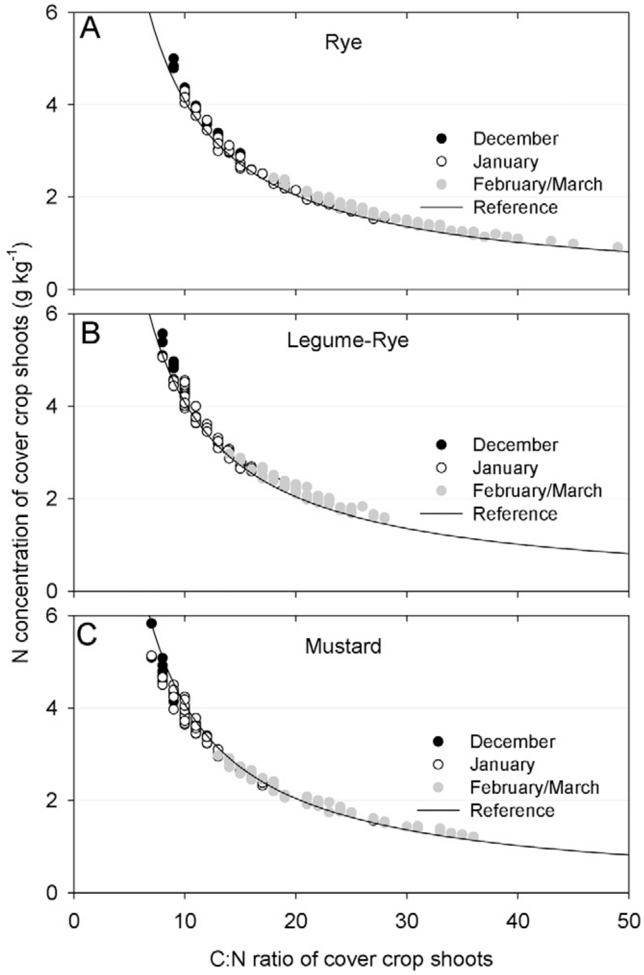

Fig. 10. Relationship between the C/N ratio and N concentration of shoots of (A) rye, (B) legume–rye, and (C) mustard cover crops at three harvest periods during 8 yr in Salinas, CA. The equation for the reference line ($y = 40.8/x$) was reported by Vigil and Kissel (1991) across a variety of plant residues. Each point is one of four replicates for each of 8 yr.

that probably was due to N leaching below the 30-cm sampling depth following the 35 mm of rainfall on 11 DAI that nearly doubled the gravimetric soil water content (data not shown). There were clear patterns of higher soil mineral N following the legume–rye cover crop up to 17 DAI during Year 2 and higher N from 24 to 44 DAI following the legume–rye and mustard cover crops. By the last sampling date of Year 2, mineral N was <10 mg kg^{-1} dry soil in the fallow and rye systems compared with an average of 14 mg kg^{-1} dry soil following legume–rye and mustard cover crops.

Practical Implications of Residue Quality and Nitrogen Mineralization Dynamics for Vegetable Production Systems

Integrating the cover crop DM production and N accumulation results from the companion studies (Brennan and Boyd, 2012a, 2012b) with the residue quality and soil mineral N results for Years 1 and 2 in the present study provides important insights into the complex dynamics and practical implications of cover cropping in tillage-intensive systems. For example, similarities in the soil mineral N within the cover cropped systems during Year 1 were probably because

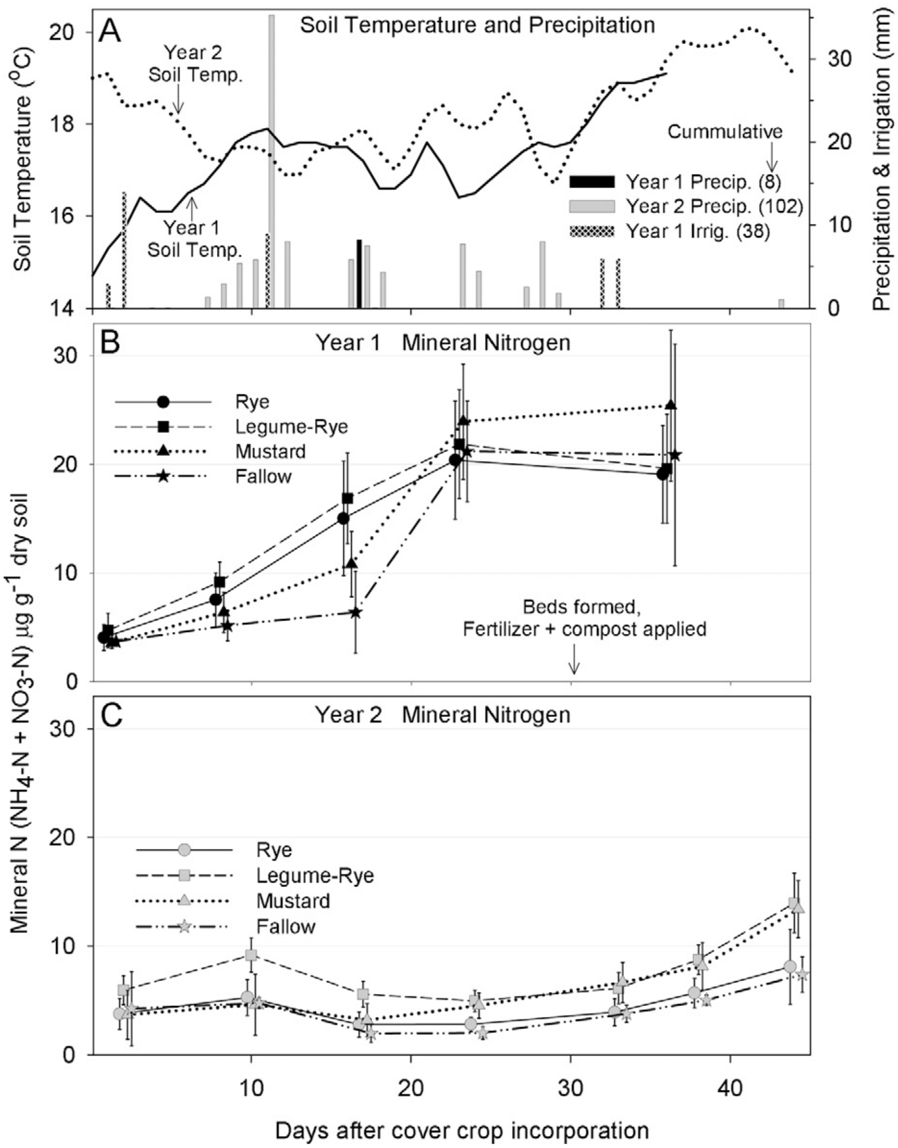

Fig. 11. (A) Soil temperature and precipitation, and soil mineral N during the cover crop post-incorporation period before vegetable planting for three winter cover crops vs. fallow during (B) Year 1 and (C) Year 2 in Salinas, CA. Soil temperatures are the daily average at the 15-cm depth. Weather data were from Station no. 89 of the California Irrigation Management System (www.cimis.water.ca.gov). Cover crops were averaged across two seeding rates for rye (90 and 270 kg ha^{-1}), legume–rye (140 and 420 kg ha^{-1}), and mustard (11 and 33 kg ha^{-1}). The points are means ±95% confidence intervals; means are offset within a sampling date to differentiate confidence intervals. Comparisons within a year and sampling date can be made using the "rule of eye" method whereby confidence intervals that overlap with a mean are not different and intervals that overlap by half an interval arm are significantly different at $p \approx 0.05$ (Cumming, 2009). Soil samples were taken at the 0- to 30-cm depth in flat plots on most sampling dates except for the last sampling date of Year 1, when sampling occurred in the centers of beds prepared for vegetable planting.

there were no differences in the cover crop DM production (7.3–8.8 Mg ha^{-1}; Brennan and Boyd, 2012a), shoot N accumulation (141–175 kg ha^{-1}; Brennan and Boyd, 2012b), or C/N ratios (23–24; Fig. 6C) at the time of cover crop incorporation. In contrast, at 10 and 17 DAI during Year 2, the higher soil N levels following the legume–rye cover crop compared with the other cover crops was probably because shoot N accumulation was considerable higher for legume–rye (146 kg ha^{-1}) than rye (81 kg ha^{-1}) or mustard (75 kg ha^{-1}) (Brennan and Boyd, 2012b), and C/N ratios were also lower for legume–rye than rye or mustard (Fig. 6C). We speculate that during Year 2, the lower C/N ratio of legume–rye (20) than mustard (26) increased the residue decomposition rate and N leaching of the soil amended with legume–rye vs. mustard residue and may explain why legume–rye and mustard systems had similar soil mineral N levels from 24 to 44 DAI (Fig. 11C); this similarity is remarkable considering that the mustard shoots contained nearly half as much N as the legume–rye shoots during Year 2 (Brennan and Boyd, 2012b). The low levels of soil mineral N in the rye systems during Year 2 were probably caused by the high C/N ratio of the rye residue (31). It is important to note that while rye and mustard shoots accumulated equivalent amounts of N by season end during Year 2 (mustard, 75 kg ha^{-1}; rye, 81 kg ha^{-1}; Brennan and Boyd, 2012b, Fig. 3C), the mineralization rate was greater for mustard than rye from 17 to 44 DAI (Fig. 11C). This suggests that the potential for N leaching was greater for mustard than rye residue after incorporation.

Comparing the soil mineral N levels in the fallow vs. cover cropped systems illustrates the practical challenge of predicting how cover crops will affect soil N levels after incorporation. For example, our data suggest that differences in rainfall between Years 1 and 2 during the decomposition period had more influence on soil mineral N dynamics than whether the system had received cover crop residue. Contrary to our expectations, the large amounts of cover crop shoot residue inputs in the cover cropped systems did not consistently increase soil N levels above those in the fallow system during Year 1. Other researchers in this region reported considerable variability in soil mineral N among sites and years following fallow vs. legume–oat cover crops (Muramoto et al., 2011).

Cover crop residue adds labile C to the soil that provides energy for soil food web organisms that enhance nutrient cycling and soil health (Abawi and Widmer, 2000; Ferris and Matute, 2003). We estimated the annual C inputs from the three cover crops by multiplying the DM production in the companion study (Brennan and Boyd, 2012a) by the C concentration in the present study and determined that C inputs from the cover crop shoots would be approximately 30% greater for rye (3.1 Mg C ha^{-1}) and legume–rye (3.2 Mg C ha^{-1}) than for mustard (2.4 Mg C ha^{-1}). Despite these differences, soil health based on nematode faunal analysis during the vegetable production phase of the present study revealed no consistent differences in soil health among the three cover crop types and indicated that frequent (i.e., annual) cover cropping had a greater effect on the soil food web than annual compost additions (Ferris et al., 2012).

An important economic question to consider regarding cover crop residue quality is whether the higher quality residue of a legume–cereal mixture justifies the higher seed cost compared with the lower seed cost of using a nonlegume such as rye that has lower quality residue. Seed cost details for the three cover crops were presented in Brennan and Boyd (2012a). The seed costs of legume–rye planted at a high enough SR to provide excellent winter weed suppression (i.e., 3× SR, 420 kg ha^{-1}) (Brennan, unpublished data, 2003–2012) were nearly 10 times more (US\$680 ha^{-1}) than the seed costs for a nonlegume cover crop (rye at 1× SR, US\$69 ha^{-1}). The higher quality residue such as mustard or legume–rye that may decompose more rapidly could theoretically shorten the decomposition period and allow vegetable planting to occur sooner than with a lower quality residue such as rye. Cover crop seed in the region typically accounts for only 20 to 30% of the total cover cropping costs (i.e., labor to plant, irrigate, and terminate, fuel, etc.) in high-value vegetable production systems in California (Klonsky and Tourte, 2011; Tourte et al., 2004, p. 18).

This study provides valuable information on residue quality changes of three cover crops during the winter cover cropping period of 8 yr and N mineralization dynamics during the first 2 yr of a high-value organic systems trial. As the season progressed, there were trends toward increasing C concentrations and C/N ratios and decreasing N concentrations of the cover crop residue. The study provides novel information on the effects of SR on residue quality whereby the C/N ratios of rye in the monoculture and mixture increased with SR, and there was high negative correlation between early-season rye density and N concentration up to January. In contrast, increasing SR in the legume–rye mixtures increased the N concentration of the legume component during December of most years, presumably because the higher SR reduced soil N and increased N_2 fixation. It is unlikely, however, that the relatively small but statistically significant effect of cover crop SR on residue quality would be of practical significance. We conclude that mustard and the legume–rye mixture had higher residue quality than monoculture rye throughout the season. Furthermore the legume component in the legume–rye mixture improved the residue quality of the rye component. These differences suggest that shoot residue from the rye monoculture has the greatest potential to immobilize N when incorporated at season end and may require a longer decomposition period than the residue of mustard and legume–rye before subsequent vegetable planting. Soil mineral N following cover crop incorporation varied considerably between years and appeared to be influenced by spring weather patterns as much as by winter soil management. Additional research is needed to develop management strategies to help growers maximize the benefits of nutrient cycling from incorporated cover crop residue into subsequent crops and reducing the risk of N leaching for cover crops such as legume–cereal mixtures that may contain large amounts of N in their biomass and nonlegumes such as mustard with a relatively low C/N ratio. Nitrogen leaching may be particularly important when shallow-rooted vegetables such as lettuce (Jackson, 1995) follow winter cover crops.

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