Winter Cover Crop Seeding Rate and Variety Affects during Eight Years of Organic Vegetables: II. Cover Crop Nitrogen Accumulation

Eric B. Brennan* and Nathan S. Boyd

Organic Agriculture & Agroecology

ABSTRACT

Winter cover crops (CC) can improve nutrient use efficiency by scavenging residual soil N. Shoot nitrogen accumulation (NA) of rye (*Secale cereale* L.), legume–rye, and mustard was determined in December to February or March during the first 8 yr of the Salinas Organic Cropping Systems (SOCS) trial focused on high-value crops in Salinas, CA. By seed weight, legume–rye included 10% rye, 35% faba bean (*Vicia faba* L.), 25% pea (*Pisum sativum* L.), 15% common vetch (*V. sativa* L.), and 15% purple vetch (*V. benghalensis* L.); mustard included 61% *Sinapis alba* L., and 39% *Brassica juncea* Czern. Cover crops were fall planted at 1x and 3x seeding rates (SR); 1x SR were 90 (rye), 11 (mustard), and 140 (legume–rye) kg ha^{-1}. Vegetables followed CC annually. Early-season NA was greatest in mustard. Nitrogen accumulation increased more gradually through the season in legume–rye than in other CC. Final NA (kg ha^{-1}) was lower in rye (110) and mustard (114), than legume–rye (151), and varied by year. During December, SR increased NA in legume–rye by 41% but not for the other CC. Legumes contributed 36% of final NA in legume–rye, presumably from N scavenging and biological fixation. Nitrogen accumulation was highly correlated with shoot dry matter of legume–rye but not of rye or mustard. Seed costs per kg of NA were more than two times higher for legume–rye than rye and mustard. We conclude that high SR are necessary to hasten early season NA and minimize N leaching potential in legume–rye mixtures.

There is a critical need to transition from "open and leaky" agricultural systems to "semi-closed and regenerative systems" (Pearson, 2007) with improved soil and nutrient management. This need is particularly evident with high-input, high-value vegetable systems in regions of the United States such as the Salinas valley in the central coast of California. Excessive nitrates in these systems remain in the top soil after fall harvests and are lost readily to surface and groundwater during rainy, bare winter fallows (Jackson et al., 1993). Bare fallows are common here because they simplify soil preparation for spring vegetable plantings. Regulatory pressure to improve N use efficiency has been relatively minimal in the United States compared with Europe (Robertson and Vitousek, 2009) where farmers in nitrate vulnerable zones of the European Union are required to implement practices to reduce N losses (Goodchild, 1998; Macgregor and Warren, 2006)

Salinas valley produces more than $1 billion of lettuce (*Lactuca sativa* L.) annually and is a major source of cool-season vegetables and strawberries (*Frageria* spp.) for national consumption and export (County of Monterey, 2010). Organic production here accounts for approximately 4% of $4 billion annual crop production value and California accounts for 96% of the area devoted to organic lettuce in the United States (NASS, 2007). Most organic farms here lack an animal component and are focused on high-value horticultural food crops. Analyses from other regions indicate that nitrate leaching can be problematic in organic and conventional farms with similar yields and cropping systems (Kirchmann and Bergstrom, 2001; Stopes et al., 2002) and that N use efficiency may be greater in some conventional systems (Torstensson et al., 2006; Aronsson et al., 2007).

Deep rooted winter cover crops add soil-building C that is critical to soil quality and function, and can reduce the "leaks" in agroecosystems by scavenging N at risk of leaching (Thorup-Kristensen et al., 2003; Fageria et al., 2005). Cover crops improve nutrient use efficiency when the nutrients in the cover crops are cycled back into the soil as green manure and are absorbed by subsequent cash crops (Ranells and Wagger, 1997b; Robertson and Vitousek, 2009). Therefore, cover crops should be an integral part of well-designed organic and conventional rotations for high-value annual crops.

Pioneering research on N scavenging by winter cover crops in Salinas valley occurred in conventional systems with nonlegume cover crops planted on narrow beds (i.e., 1 m wide) at relatively low SR (Jackson et al., 1993; Wyland et al., 1996). They reported up to a 70% reduction in nitrate leaching compared with a bare fallow even with relatively moderate levels of shoot dry matter (DM) production for this region (≈4 Mg ha^{-1}). Their rationale for growing cover crops on beds was to facilitate the use of lighter equipment to incorporate cover crop residue and recycle the beds for subsequent vegetables in the spring. Currently, winter cover crops here are much more common on organic than conventional farms and are typically drilled as solid stands, rather than on beds. Solid stands of monoculture and mixed cover crops typically produce two to three times more shoot DM than cover

E.B. Brennan, USDA-ARS, 1636 E. Alisal St., Salinas, CA 93905; N.S. Boyd, Nova Scotia Agricultural College, Truro, NS, Canada, B2N5E3. Received 8 Oct. 2011. *Corresponding author (eric.brennan@ars.usda.gov).

Published in Agron. J. 104:799–806 (2012)
Posted online 28 Mar 2012
doi:10.2134/agronj2011.0331

Abbreviations: CC, cover crops; DM, dry matter; GDD, growing degree days; NA, nitrogen accumulation; SOCS trial, Salinas Organic Cropping Systems trial; SR, seeding rates.

crops planted on bed tops (Brennan and Smith, 2005; Boyd et al., 2009; Brennan et al., 2011; Brennan and Boyd, 2012) and solid stands should therefore absorb more N.

Nonlegume cover crops are several times more effective at scavenging N and protecting groundwater quality than monoculture legume cover crops (Meisinger et al., 1991; McCracken et al., 1994; McLenaghen et al., 1996; Thorup-Kristensen et al., 2003; Rinnofner et al., 2008). Rye and mustards are the most common nonlegume cover crops in the central coast, and are usually grown on conventional farms and large-scale (i.e., >200 ha) organic farms focused on lettuce production. Mustard cover crops have become popular here in the past decade and were marketed aggressively as "biofumigants" to suppress lettuce drop disease which is caused by *Sclerotinia minor* Jagger; however, this biofumigant strategy was not effective (Bensen et al., 2009). Larger-scale organic farms with frequent lettuce production avoid cover crops such as phacalia (*Phacelia tanacetifolia* Benth.) and legumes (pea; lana vetch, *Vicia. dasycarpa* Ten.) that are known hosts of *S. minor* (Koike et al., 1996).

Legume-cereal cover crop mixtures are most common in this region on small- to medium-scale organic farms with greater crop diversity. Commercially-available mixtures here include oat (*Avena sativa* L.) or rye, and several legumes (*Vicia* spp. and pea). Meisinger et al. (1991) proposed that mixtures may conserve and add N to systems because they combine the N scavenging ability of the nonlegumes with the N fixing ability of legumes. Subsequent work confirmed this and showed that mixtures reduce N leaching (Ranells and Wagger, 1997a; Sainju et al., 2005; Moller et al., 2008; Rinnofner et al., 2008; Feaga et al., 2010). In other regions, cover crop mixtures have also increased vegetable yields compared with nonlegume cover crops (Burket et al., 1997; Griffin et al., 2000). It is unclear if these yield benefits will occur consistently enough in California vegetable systems to justify the higher seed cost of legume–cereal cover crops (Brennan and Boyd, 2012). We highlight this question because the legume biomass is seldom the dominant component, varies greatly between years, and declines through the season at some sites (Brennan et al., 2009, 2011; Brennan and Boyd, 2012); suppression of legume DM was most apparent in a high fertility soil, and has also been reported with mixtures in other regions with greater manure inputs (Moller et al., 2008). Watson et al. (2002) highlighted the need to develop effective soil fertility strategies for organic horticultural crops on farms that lack animal production and typically are most reliant on imported nutrients.

A commercial-scale, long-term, organic systems trial focused on high-value and high-input horticultural crops began at the USDA-ARS in Salinas, CA, in 2003. The trial was designed to address the needs of local organic farmers for long-term cover crop research to minimize off-farm inputs, and to optimize soil and pest management, yields, and profitability of high-value crops. The SOCS trial includes eight systems. The first paper from the study reported differences in shoot DM production between cover crop, SR, and years in six systems (Brennan and Boyd, 2012). In the present paper, we report on NA of cover crop shoot DM of six systems that were cover cropped annually with one of three winter cover crops (rye, a legume–rye mixture, and mustard mixture) and at either typical (1x) and 3x SR during the first 8 yr of the trial. The three cover crops represent the most common types of winter cover crops in this region, (i.e., cereals, mustards, and legume-cereal mixtures). We included the SR factor because (i) of its potential effect on cover crop weed suppression and weed management costs on subsequent cash crops, (ii) higher rates may increase NA due to greater DM production, and (iii) higher rates change competition dynamics in legume–cereal mixtures. Specific questions of interest were: (i) Are there differences in NA between nonlegumes and a legume–rye mixture at three times during the season? (ii) Does SR affect NA? (iii) Does NA vary across years and if so, what factors contribute to such variation?

MATERIALS AND METHODS

Site Description and History

More details on the history of the site, and cropping sequence of the ongoing SOCS trial are provided in Brennan and Boyd (2012). 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 California Certified Organic Farmers since 1999. The site was used for conventional, winter oat 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 (fine-loamy, mixed, superactive, thermic Typic Argixerol) with 77% sand, 15% silt, and 8% clay.

Cropping Sequence and Experimental Design

The present paper focuses on the six systems that were cover cropped annually, all of which received identical compost, fertilizer, and irrigation inputs during vegetable production. The experimental design is a randomized complete block with all systems in four replicates. The system plots are 12.2-m wide by 19.5-m long and 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 from October or November to February or March, followed by romaine lettuce (*L. sativa* L. var. *longifolia* Lam.) from May to June or July each year, and 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, Year 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. The six systems received 7.6 Mg ha^{-1} (oven dry basis) of urban yard-waste compost with an approximate C/N of 22 before each vegetable crop. All systems occurred on the same plots annually to determine their cumulative effects. Local organic farms provided advice on crop management, and personnel, expertise, and equipment for the commercial-scale harvests, and sold marketable vegetables from the trial. This novel research approach helped offset production costs of the trial and allowed it to evolve into the ongoing long-term systems trial that has not received external funding after a grant for the first 2.5 yr. Thus, although the study occurs on a research station, the land is managed intensively to meet the same production standards and practices of a local organic farm, and produces high-quality crops that compete on the local wholesale market.

Field Preparation, Cover Crop Planting, and Management

Field preparation for planting cover crops included a combination of disc and spring tooth harrowing, spading, and ring rolling,

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

Year	Winter period	Planting	Cover crop sampling	Termination	Growing degree days† 30 DAP‡	Growing degree days† Total	Precipitation + Irrigation
					°C	°C	mm
1	2003–2004	16 Oct.	18 Dec., 15 Jan., 3–4 Mar.	8 Mar.	342	1059	248 + 45
2	2004–2005	15 Oct.	1 Dec., 24 Jan., 24 Feb.	11 Mar.	287	1028	305 + 13
3	2005–2006	17 Oct.	14–15 Dec., 11–13 Jan., 7–8 Feb.	11 Feb.	325	983	189 + 32
4	2006–2007	2 Nov.	18–20 Jan., 15–16 Mar.	18 Mar.	273	946	123 + 19
5	2007–2008	15 Oct.	17–18 Jan., 13–15 Feb.	19 Feb.	337	840	96 + 52
6	2008–2009	15 Oct.	16 Jan., 10–11 Mar.	13 Mar.	335	1121	219 + 42
7	2009–2010	29 Oct.	16 Jan., 16–17 Mar.	18 Mar.	252	815	246 + 49
8	2010–2011	27 Oct.	12–14 Jan., 7–9 Mar.	10–11 Mar.	285	959	234 + 19

† 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 (http://www.cimis.water.ca.gov). The GDD are calculated with the single sine method with a baseline threshold of 4°C using the online calculator at the University of California Statewide Integrated Pest Management (http://www.ipm.ucdavis.edu).

‡ DAP, days after planting.

as necessary to incorporate previous crop 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, St. Joseph, MO; N-DURE Kentland, IN) were added to the legume–rye seed before planting. The target planting date for the cover crops was 15 October, however, the actual dates ranged across years from 15 October to 2 November (Table 1) due to vegetable crop harvest dates and postharvest tillage requirements. The 1x SR for each cover crop were the typically recommended rates for vegetable growers in this region. The 1x SR in kg ha^{-1} were rye (90), mustard (11), legume–rye (140), and the 3x rates were three times greater. Seed was obtained from L.A. Hearne Company (King City, CA). The rye variety used was Merced. The mustard was a mixture by seed weight of 61% white mustard ('Ida Gold', *S. alba* L.) and 39% India mustard ('Pacific Gold', *B. juncea* Czern.). The legume–rye mixture include included 10% rye, 35% faba bean, (small-seeded type known as “bell bean”), 25% pea ('Magnus'), 15% common vetch, and 15% purple vetch by seed weight. Sprinkler irrigation was applied to stimulate germination before the onset of adequate winter rainfall (Table 1). The last irrigation typically occurred in mid- to late November. Cover crops were terminated by flail mowing, and then incorporated into the soil with a single pass with a spader. The termination dates for the cover crops were selected to maximize cover crop DM, prevent cover crop seed production, and allow adequate time for residue decomposition and field preparation for planting the subsequent lettuce crop in May.

Data Collection

A composite of 20 soil samples to a depth of 30 cm was taken from each plot within 1 wk before cover crop planting for analysis of NO_3^-. Shoot biomass of cover crops was sampled by harvesting one 50- by 100- cm quadrat oriented to cover three adjacent rows for each plot at three (Years 1–3) or two (Years 4–8) sampling dates during each winter (Table 1). Harvested cover crop biomass of the legume–rye mixture was separated into the legume and rye components, and cover crop biomass was oven-dried at 65°C for at least 48 h until the weight had stabilized to obtain shoot DM. Cover crop biomass sampling dates were chosen to track changes in cover crop DM over the winter and to minimize sampling on rainy days.

Soil and Cover Crop Shoot Analyses

Soil and cover crop shoot analyses were conducted at the Agriculture and Natural Resources Analytical Laboratory at the University of California. The soil samples taken prior to cover crop planting were analyzed for NO_3^- using the flow injection analyzer method (http://anlab.ucdavis.edu/analyses/soil/312). Cover crop DM samples were ground to pass through a 0.250 mm screen, and a subsample was analyzed with a combustion gas analyzer method for total N (http://anlab.ucdavis.edu/analyses/plant/sop522). The N concentrations from these analyses were on a 100% DM basis from drying samples to 105°C. However, to calculate NA in kg N ha^{-1} the N concentrations were adjusted, because DM ha^{-1} was on 98% DM basis from drying at 65°C. Cover crop N analyses were conducted for all harvests. The legume and rye components of the legume–rye mixture were analyzed separately. We did not differentiate NA in the legume component due to scavenging vs. biological N fixation.

Statistical Analysis

All data were analyzed using SAS ver. 9.2 (SAS Institute, Cary, NC). The 95% confidence intervals (CI) of cover crop NA were calculated using the CLM option in the MEANS procedure. The CI are provided to illustrate variability and assist with means comparisons using the “rule of eye” method suggested by Cumming (2009) whereby intervals that overlap with a mean are not different, and intervals that overlap by half of one interval arm are significantly different at $p \approx 0.05$, and intervals that barely touch are significantly different at $p \approx 0.01$. Analyses of the response variables were conducted with the MIXED procedure as a repeated measures models with year as the repeated effect, an autoregressive AR(1) covariance structure, and cover crop × SR × block as the SUBJECT option (Littell et al., 1996). 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 NA between SR, with

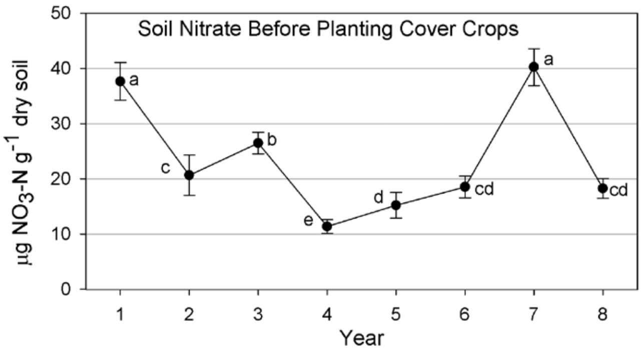

Fig. 1. Soil nitrate concentrations in the top 30 cm of the soil within 1 wk prior to the fall planting of winter cover crops during 8 yr in Salinas, CA. Points are back-transformed means ±95% confidence intervals averaged across the six systems that were cover cropped annually. Means followed by different letters were significantly different based on a Tukey–Kramer family-wise error rate of $p \leq 0.05$.

SR as the fixed effect. Data were tested to meet the assumptions of ANOVA. Pairwise comparisons were controlled at the family-wise error rate of $p \leq 0.05$ using Bonferroni or Tukey–Kramer adjustments (Westfall et al., 1999).

RESULTS AND DISCUSSION

Climate

Climatic patterns during the eight winters are presented in condensed form (Table 1), however, more details are in Brennan and Boyd (2012). Average daily air temperatures during cover cropping typically ranged from 5 to 15°C. Due to differences between years in planting date and subsequent air temperatures, there were differences in the rate of accumulated growing degree days (GDD) and the final GDD. Differences in the rate of GDD accumulation were clear by 30 d after planting (DAP) (Table 1). For example, Year 7 was a particularly cool year and only accumulated 252 GDD by 30 DAP, and the least number of GDD by season-end (815 GDD).

Table 2. Significance of tests of fixed effects and interactions on soil NO_3 concentrations in the fall before winter cover crop planting, and N accumulation of total shoot dry matter of three cover crops planted at two seeding rates at three harvest periods during 8 yr in Salinas, CA.

Effect	Fall soil NO_3†	N Accumulation		
		Dec.‡	Jan.	Feb./Mar.
Cover crop (CC)§	ns¶	***	*	***
Seeding rate (SR)#	ns	***	ns	ns
Year (Yr)	***	***	***	***
CC × SR	ns	**	ns	ns
CC × Yr	ns	*	***	***
SR × Yr	ns	ns	ns	ns
CC × SR × Yr	ns	ns	ns	**

* Significant at the $p \leq 0.05$ level.
** Significant at the $p \leq 0.01$ level.
*** Significant at the $p \leq 0.001$ level.
† Soil nitrate during the fall and within 1 wk before planting CC.
‡ December harvests only occurred during the first 3 yr of the trial.
§ CC include rye, a legume–rye mixture, and mustard.
¶ ns, not significant.
# Seeding rates in kg ha^{-1} were rye (90, 270), legume–rye (140,420), and mustard (11, 33).

Soil Nitrate before Cover Crop Planting

Nitrate concentrations in the top 30 cm of soil before cover crop planting were usually between 10 and 30 mg NO_3–N kg^{-1} of dry soil except during Years 1 and 7 when they were higher (Fig. 1). Year was the only fixed effect that influenced soil NO_3 concentrations significantly (Table 2). The annual variation in fall NO_3 concentrations can be explained by different amounts of time elapsed between incorporation of the previous cash crop residue and soil sampling. The higher NO_3 concentrations tended to occur during years where there was more time for mineralization of the previous residue before the soil sampling. For example, the lowest NO_3 concentrations occurred during Year 4 when the soil samples were taken 1 d after broccoli residue incorporation. In contrast, the highest NO_3 concentrations occurred during Year 7 when the soil sampling occurred 18 d after broccoli residue incorporation. The NO_3 concentrations in the fall in our study were considerably less than those in a conventional field in Salinas that had 83 and 67 mg NO_3 kg^{-1} of dry soil in the 0- to 15- and 15- to 30-cm depth, respectively (Jackson et al., 1993).

Cover Crop Shoot Nitrogen Accumulation

Cover crop and year significantly affected NA at all harvests, but SR was only significant in December (Table 2). There were also significant two- and three-way interactions for NA, with significant cover crop × year interactions across all harvests. The significant effects and interactions will be described for each harvest period progressing through the season. The differential responses of cover crop to SR explain the cover crop × SR effect in December (Fig. 2). For example, SR had a marked effect on NA with the legume–rye mixture which increased by 41% from the 1x to 3x SR in December. In contrast, SR did not affect significantly NA by mustard or rye at any measurement period. The effect of SR on NA by the legume–rye mixture in December can be explained by the 60% higher shoot DM in the 3x than 1x SR (Brennan and Boyd, 2012).

Averaged across SR, NA tended to be greatest in mustard although this trend was only significant in Year 3, hence the significant cover crop × year interactions during December (Fig. 3A). There was also a significant cover crop × year interaction during January and season-end where NA differed between cover crops during half of the years (Fig. 3B, 3C). Greater NA by the legume–rye mixture than the nonlegumes during 4 of the 8 yr explains the cover crop × year interaction in January and at season-end. At season-end, the higher NA by the 3x legume–rye during Year 7 alone, explains the cover crop × SR × year interaction (Fig. 4B). The two- and three-way interactions for NA (Fig. 2–4) followed the same general pattern for the interactions for shoot DM accumulation in the companion paper (Brennan and Boyd, 2012).

Averaged across SR and year, the patterns of NA differed between cover crops through the season (Fig. 5). For example, of the three cover crops, mustard accumulated N most rapidly in December and there was no apparent change in NA by mustard from December onward. Rye had a similar pattern to mustard in NA, although rye achieved its maximum NA in January. In contrast, NA by the legume–rye mixture occurred more gradually through the season and peaked at season-end. We speculate that the slight but nonsignificant decline in NA by the nonlegumes from January to season-end may be due to abscission of shoot

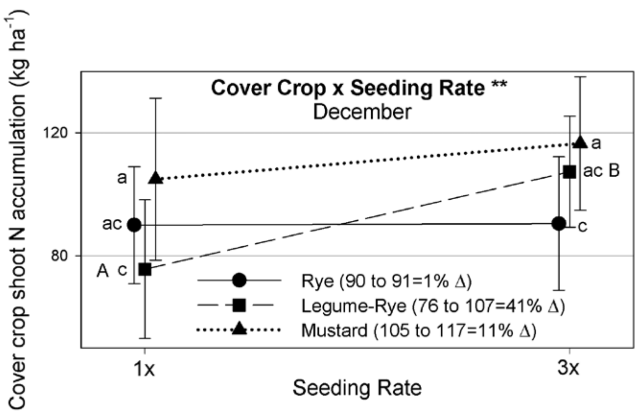

Fig. 2. Cover crop × seeding rate interaction for cover crop shoot N accumulation by three winter cover crops in December averaged across 3 yr in Salinas, CA. Seeding rates for the 1x and 3x rates (respectively) in kg ha^{-1} were rye (90, 270), legume–rye (140, 420), and mustard (11, 33). Points are means ±95% confidence intervals. Within seeding rate, points are offset to differentiate confidence intervals. Within rate, means adjacent to different lower case letters are significantly different; within cover crop variety, means adjacent to different upper case letters are significantly different based on a Bonferroni family-wise error rate of $p \leq 0.05$. ** indicates that the interaction was significant at $p \leq 0.01$. The numbers in parentheses following the legend for each cover crop variety are the amount of N accumulation of the 1x vs. 3x rates and the % change in N accumulation from the 1x to 3x seeding rates.

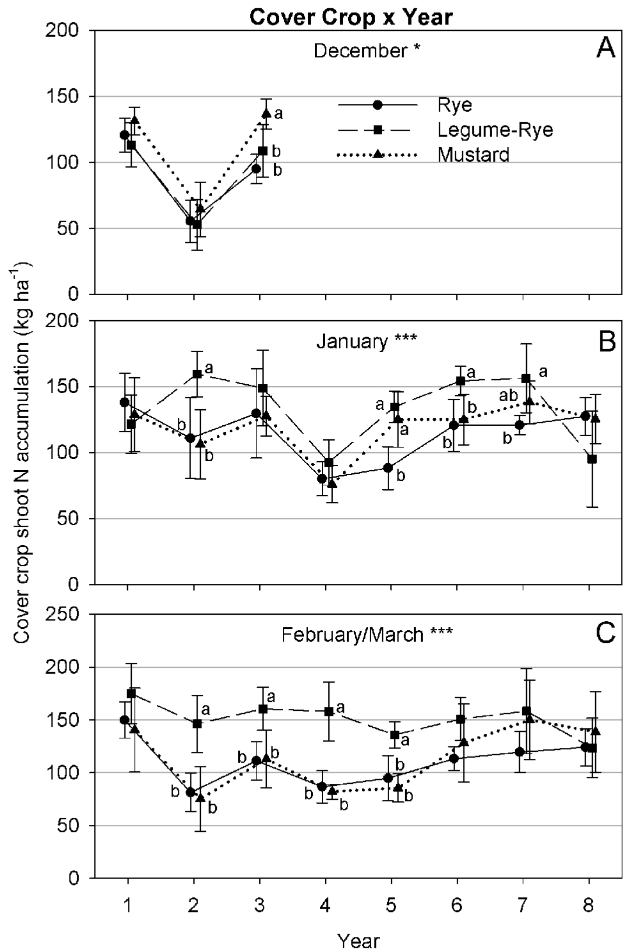

Fig. 3. Cover crop × year interactions for cover crop shoot N accumulation by three winter cover crops at December, January, and February/March harvests during 8 yr in Salinas, CA; * and * indicate the significance of the interaction at $p \leq 0.05$ and 0.001, respectively. The points are means ±95% confidence intervals averaged across seeding rates for each cover crop and in kg ha^{-1} were 90 and 270 for rye, 140 and 420 for the legume–rye mixture, and 11 and 33 for mustard. Within year, points are offset to differentiate confidence intervals. Within year and harvest, means adjacent to different letters are significantly different based on a Tukey–Kramer adjusted family-wise error rate of $p \leq 0.05$.**

tissue (leaves, flowers). Averaged across SR and years, shoot NA by season-end did not differ between rye (110 kg N ha^{-1}) and mustard (114 kg N ha^{-1}), but was greater in the legume–rye mixture (151 kg N ha^{-1}). Presumably a portion of the 41 kg ha^{-1} greater NA in the legume–rye mixture vs. rye monoculture was due to biological N fixation by the legumes. Across a range of legumes and locations, Peoples et al. (2009) estimated 30 to 40 kg of fixed N Mg^{-1} legume DM. Assuming that this range of N fixation occurred in our study, we estimate that between 57 and 76 kg N ha^{-1} were derived from N fixation in the legume–rye mixture because it produced 1.9 Mg ha^{-1} of legume DM by season-end averaged across SR and years (Brennan and Boyd, 2012). The amount of NA by rye vs. the legume–rye mixture in the present study were similar to those of rye and similar legume–rye mixtures (90% legume-10% rye) in a separate 2-yr study at the same site in Salinas (Brennan et al., 2011). However, NA by the cover crops in that study at a higher fertility site in Hollister, CA, were considerably higher (≈180 kg N ha^{-1}) and did not differ between rye and legume–rye mixtures. It is unclear if legume-cereal cover crops provide any benefits over pure cereals in situations where the NA is equivalent in the mixture vs. the monoculture. However, it is important to note that measures of NA in winter cover crops likely underestimate total NA due to N losses from leaf senescence and plant mortality between harvest periods; we assume that N losses from leaf senescence would be more of an issue with dicot cover crops such as legumes and mustard where leaf abscission is more apparent during the cover cropping period than with monocot cover crops where senesced leaves remain attached to the stem.

Several interesting patterns occurred with NA by the legume and rye components of the legume–rye mixture (Fig. 5). First, there was a gradual increase in the percentage of legume NA through the season (i.e., 31 to 36%), compared with a gradual reduction in the rye percentage of NA (i.e., 69 to 64%). These differences occurred because NA from December to season-end increased by 93% (i.e., from 28 to 54 kg ha^{-1}) with the legume component compared with only 52% (i.e., from 64 to 97 kg ha^{-1}) with the rye component. Second, the rate of NA by rye in the monoculture vs. rye in the legume–rye mixture differed. The increase in NA from December to season-end was only 22% (i.e., from 90 to 110 kg ha^{-1}) in monoculture rye compared with 52% (i.e., from 64 to 97 kg ha^{-1}) for the rye component in the legume–rye mixture. We speculate that this difference may have been caused by a transfer of fixed N from the legume to the rye in the mixture. Transfer of N from legumes to associated intercrops is known to occur and could be of value in cover crops (Hauggaard-Nielsen and Jensen, 2005; Dahlin and Stenberg, 2010). Less lodging of rye in the mixture than in the monoculture may also explain the differences in the rates of NA. Less lodging of rye in the mixture was observed and was

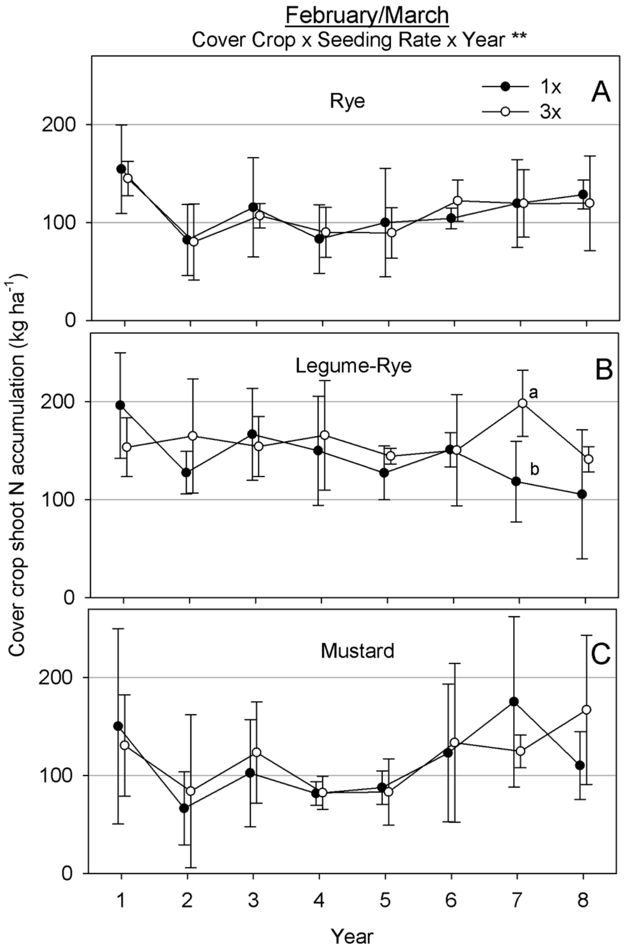

Fig. 4. **Cover crop × seeding rate × year interactions for cover crop shoot N accumulation of three winter cover crops at the season-end harvests in February or March during 8 yr. in Salinas, CA. ** indicates the significance of the interaction at $p \leq 0.01$. The points are means ±95% confidence intervals averaged across seeding rates for each cover crop and in kg ha^{-1} were 90 and 270 for rye, 140 and 420 for the legume–rye mixture, and 11 and 33 for mustard. Within year, points are offset to differentiate confidence intervals. Within year and cover crop, means adjacent to different letters are significantly different based on a Bonferonni adjusted family-wise error rate of $p \leq 0.05$.**

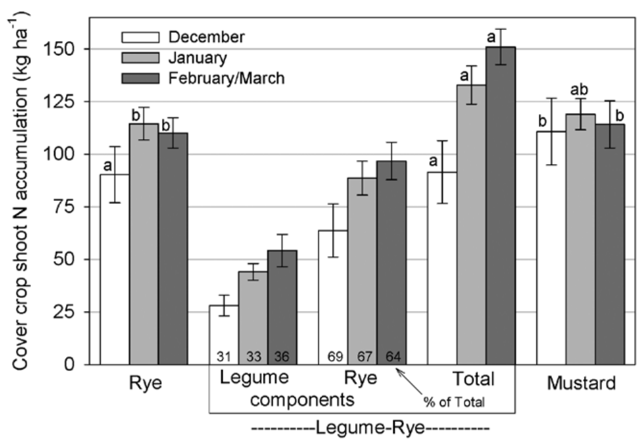

Fig. 5. Nitrogen accumulation of cover crop shoots during three harvest periods during 8 yr and averaged across two seeding rates in Salinas, CA. Seeding rates in kg ha^{-1} were 90 and 270 for rye, 140 and 420 for the legume–rye mixture, and 11 and 33 for mustard. December harvests were during Years 1 to 3, while other harvests were all 8 yr. Bars are means ± 95% confidence intervals. Within a harvest period, means topped with different letters are significantly different based on a Tukey–Kramer family-wise 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 of one interval arm are significantly different at $p \approx 0.05$ (Cumming, 2009). The percentages of the legume and rye components of total legume–rye dry matter are shown above the *x* axis. Nitrogen accumulation means were 90, 92, and 111 in December; 114, 133, and 119 in January; and 110, 151, and 114 in February/March for rye, the legume–rye mixture, and mustard, respectively.

likely caused by the lower rye densities and greater structural support for rye provided by the erect faba bean and intertwined vetch and pea. Higher SR are known to increase lodging (Ball et al., 2000; Spink et al., 2000), and lodging can be reduced in mixtures (Karpenstein-Machan and Stuelpnagel, 2000; Juskiw et al., 2001). Finally, the similarity in NA at season-end by rye in the monoculture (110 kg ha^{-1}) and the rye in the mixture (97 kg ha^{-1}) illustrates rye's remarkable ability to compensate for lower plant densities and scavenge N. Rye densities in plants m^{-2} averaged across years were 320 (rye 1x), 854 (rye 3x), 45 (legume-rye 1x), and (126 (legume-rye 3x) (Brennan and Boyd, 2012).

Practical Implications

Seasonal dynamics of NA of winter cover crops provide information growers need to make cover crop management decisions to optimize nutrient use efficiency. Our data show that NA occurred most rapidly with mustard, followed by rye, and then legume–rye (Fig. 5). Furthermore, across years and SR there was a relatively strong correlation between shoot DM and NA in the legume–rye mixture ($r^2 = 0.75$) compared the weak correlation with rye ($r^2 = 0.25$) and mustard ($r^2 = 0.34$) (Fig. 6). These differences suggest that greater amounts of shoot DM are required to maximize NA in the legume–rye than nonlegume cover crops. Mustard would be the best cover crop to maximize NA in the shortest period possible with the least amount of DM production because NA by mustard peaked in December (Fig. 5) with relatively low DM (2.3 Mg ha^{-1}; Fig. 9 of Brennan and Boyd, 2012). Assuming that the soil was dry enough for tractor operations, the low residue mustard could be mowed, easily incorporated, and seeded with a vegetable immediately due to the low residue level. This process could be achieved most efficiently if the cover crop was planted on the tops of wide beds (i.e., 2 m) that would also be used for the subsequent vegetable crop. Wide bed tops would be preferable to narrow beds used by Jackson et al. (1993) because less area is devoted to bare furrows and wide beds would reduce the area for weed growth and runoff, and likely improve N scavenging. Furthermore standard grain drills can plant more effectively on wide vs. narrow beds. A potential challenge with incorporating cover crop residue in December may be an increased risk of N leaching from the low C:N ratio of cover crop residue. Cover crop residue decomposition and N mineralization depend on soil temperature and moisture (Ruffo and Bollero, 2003). There is a need for research to determine (i) the potential benefits and risks of low-residue, fall or winter cover crop scenarios in this region and (ii) optimal timing for seeding subsequent vegetables post-incorporation to minimize potential insect pest and stand establishment issues. For example, planting subsequent crops too soon after incorporating cover crops can cause problems from seedcorn maggots [*Delia platura* (Meigen)] that feed on decomposing cover crop residue and roots of subsequent crops (Hammond and Cooper, 1993; Bugg et al., 2011).

The lower seed cost of rye (1x = \$ 69 ha^{-1}) and mustard (1x = \$ 73 ha^{-1}) makes them approximately two times more cost-effective per kg of NA than the legume–rye mixture (1x = \$ 227 ha^{-1}); details on seed costs are provided in the companion paper (Brennan and Boyd, 2012). For example, the costs of NA by season-end in \$ kg N^{-1} were 0.63 (rye), 0.64 (mustard), and 1.50 (legume–rye) at the 1x SR, and three times greater at the 3x SR because SR did not increase final NA. An important question is whether the greater NA from the legume–rye mixture is worth the several times higher seed costs per ha.

CONCLUSIONS

This paper provides robust information from the first 8 yr of the SOCS trial on NA of three common types of winter cover crops available to farmers in high-value cropping systems in the central coast region of California. The results of this long-term study are also relevant to high-input, tillage intensive systems in other regions where winter cover crops can be used to improve soil management and minimize nitrate leaching. This paper and the companion paper (Brennan and Boyd, 2012) are timely, considering the increasing regulatory pressure for farmers in this region to improve soil management and increase nutrient use efficiency (CEPA, 2011). The ability of rye, mustard, and the legume–rye mixture to assimilate at least 90 kg N ha^{-1} in shoot biomass by December indicate that they are all effective N scavengers, but that mustard was most effective in early-season. Season-end shoot NA (kg ha^{-1}) was 110 (rye), 114 (mustard), and significantly greater in the legume–rye mixture (151). There was a high correlation between cover crop shoot DM and NA over the season with the legume–rye mixture but not with the nonlegumes. Nitrogen accumulation by the nonlegumes peaked in January, but increased through the season with the legume–rye mixture. The greater NA by the legume–rye was due presumably to N fixation by the legume component. The study provides novel information on the benefits of higher SR on NA in legume–rye mixtures whereby higher rates increased NA by 41% in early-season and should therefore reduce the risk of N leaching. Based on differences in cover crop seed costs, the nonlegumes were more cost-effective N scavengers than the legume–rye mixture. It is likely that all three winter cover crops evaluated could be used effectively within the same farm depending on the cash crop planting schedules and the short- and long-term soil and nutrient management goals. Additional research is needed (i) to develop profitable strategies that allow growers to regularly integrate winter cover crops in vegetable rotations to improve soil management and nutrient use efficiency, and (ii) to determine if the higher NA in legume–cereal mixtures can reduce the supplement N fertilizer inputs in high-value, tillage intensive organic crops compared with using nonlegumes in this region.

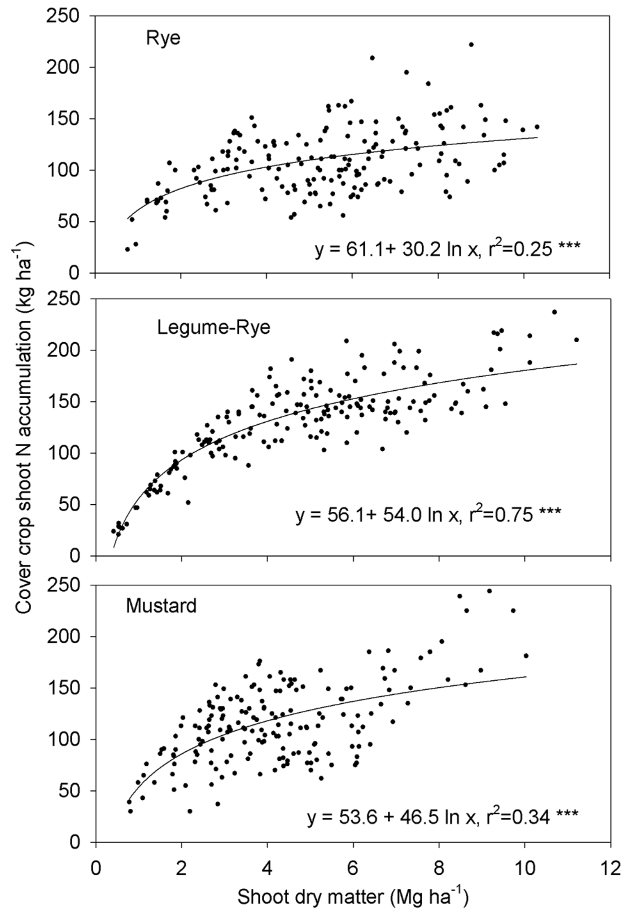

Fig. 6. Relationship between shoot dry matter production and shoot N accumulation of three cover crops across harvests in December, January, and February/March for two seeding rates during 8 yr in Salinas, CA. Seeding rates in kg ha^{-1} were 90 and 270 for rye, 140 and 420 for the legume–rye mixture, and 11 and 33 for mustard. * indicates the significance of the regression equation at $p \leq 0.001$.**

ACKNOWLEDGMENTS

The authors thank Patrick Headley, Cristal Cisneros, Joel Thomas, Adriana Marquez, Jared Burchard, and Jose Rico for laboratory assistance; Geraldo Ochoa, David Lara, and Jim Leap for assistance with planting the cover crops; David Lara, Jose Orozco, and Jim Leap for assistance with harvesting and incorporating covers crops; and Bruce Mackey for statistical assistance. The first 2.5 yr of this study was partially funded by a grant from the University of California Specialty Crops Research Program. We appreciate the input on the design of the trial from Michael Cahn, Steve Fennimore, Howard Ferris, Laura Tourte, and Richard Smith. We also thank the Community Alliance with Family Farmers for establishing agreements with the USDA-ARS to facilitate the collaborations with local organic farms.

REFERENCES

Aronsson, H., G. Torstensson, and L. Bergstrom. 2007. Leaching and crop uptake of N, P and K from organic and conventional cropping systems on a clay soil. Soil Use Manage. 23:71–81. doi:10.1111/j.1475-2743.2006.00067.x

Ball, R.A., L.C. Purcell, and E.D. Vories. 2000. Optimizing soybean plant population for a short-season production system in the southern USA. Crop Sci. 40:757–764. doi:10.2135/cropsci2000.403757x

Bensen, T.A., R.F. Smith, K.V. Subbarao, S.T. Koike, S.A. Fennimore, and S. Shem-Tov. 2009. Mustard and other cover crop effects vary on lettuce drop caused by sclerotinia minor and on weeds. Plant Dis. 93:1019–1027. doi:10.1094/PDIS-93-10-1019

Boyd, N.S., E.B. Brennan, R.F. Smith, and R. Yokota. 2009. Effect of seeding rate and planting arrangement on rye cover crop and weed growth. Agron. J. 101:47–51. doi:10.2134/agronj2008.0059

Brennan, E.B., and N.S. Boyd. 2012. Winter cover crop seeding rate and variety effects during eight years of organic vegetables: I. Cover crop biomass production. Agron. J. 104:684–698 (this issue).

Brennan, E.B., N.S. Boyd, R.F. Smith, and P. Foster. 2009. Seeding rate and planting arrangement effects on growth and weed suppression of a legume-oat cover crop for organic vegetable systems. Agron. J. 101:979–988. doi:10.2134/agronj2008.0194x

Brennan, E.B., N.S. Boyd, R.F. Smith, and P. Foster. 2011. Comparison of rye and legume-rye cover crop mixtures for vegetable production in California. Agron. J. 103:449–463.

Brennan, E.B., and R.F. Smith. 2005. Winter cover crop growth and weed suppression on the central coast of California. Weed Technol. 19:1017–1024. doi:10.1614/WT-04-246R1.1

Bugg, R.L., W.H. Settle, W.E. Chaney, and O. Daugovish. 2011. Arthropods. In: R.F. Smith et al., editors, Cover cropping for vegetable production: A grower's handbook. Univ. of California, Oakland. p. 61–68.

Burket, J.Z., D.D. Hemphill, and R.P. Dick. 1997. Winter cover crops and nitrogen management in sweet corn and broccoli rotations. HortScience 32:664–668.

California Environmental Protection Agency. 2011. Irrigated lands regulatory program. California Environmental Protection Agency. http://www.waterboards.ca.gov/water_issues/programs/agriculture/ (accessed 7 Dec. 2011).

County of Monterey. 2010. Monterey County Crop Report. Montery County Agricultural Commissioner, Salinas, CA. http://www.co.monterey.ca.us/assets/resources/assets/163/cropreport_2010.pdf (accessed 6 Feb. 2012).

Cumming, G. 2009. Inference by eye: Reading the overlap of independent confidence intervals. Stat. Med. 28:205–220. doi:10.1002/sim.3471

Dahlin, A.S., and M. Stenberg. 2010. Transfer of N from red clover to perennial ryegrass in mixed stands under different cutting strategies. Eur. J. Agron. 33:149–156. doi:10.1016/j.eja.2010.04.006

Fageria, N.K., V.C. Baligar, and B.A. Bailey. 2005. Role of cover crops in improving soil and row crop productivity. Commun. Soil Sci. Plant Anal. 36:2733–2757. doi:10.1080/00103620500303939

Feaga, J.B., J.S. Selker, R.P. Dick, and D.D. Hemphill. 2010. Long-term nitrate leaching under vegetable production with cover crops in the Pacific Northwest. Soil Sci. Soc. Am. J. 74:186–195. doi:10.2136/sssaj2008.0178

Goodchild, R.G. 1998. EU Policies for the reduction of nitrogen in water: The example of the Nitrates Directive. Environ. Pollut. 102:737–740. doi:10.1016/S0269-7491(98)80106-1

Griffin, T., M. Liebman, and J. Jemison. 2000. Cover crops for sweet corn production in a short-season environment. Agron. J. 92:144–151. doi:10.2134/agronj2000.921144x

Hammond, R.B., and R.L. Cooper. 1993. Interaction of planting times following the incorporation of a living, green cover crop and control measures on seedcorn maggot populations in soybean. Crop Prot. 12:539–543. doi:10.1016/0261-2194(93)90096-2

Hauggaard-Nielsen, H., and E.S. Jensen. 2005. Facilitative root interactions in intercrops. Plant Soil 274:237–250. doi:10.1007/s11104-004-1305-1

Jackson, L.E., L.J. Wyland, and L.J. Stivers. 1993. Winter cover crops to minimize nitrate losses in intensive lettuce production. J. Agric. Sci. 121:55–62. doi:10.1017/S0021859600076796

Juskiw, P.E., J.H. Helm, and P.A. Burnett. 2001. Three-component barley mixtures: Ratio effects in replacement series. Can. J. Plant Sci. 81:651–656. doi:10.4141/P00-145

Karpenstein-Machan, M., and R. Stuelpnagel. 2000. Biomass yield and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on a subsequent maize crop. Plant Soil 218:215–232. doi:10.1023/A:1014932004926

Kirchmann, H., and L. Bergstrom. 2001. Do organic farming practices reduce nitrate leaching? Commun. Soil Sci. Plant Anal. 32:997–1028. doi:10.1081/CSS-100104101

Koike, S.T., R.F. Smith, L.E. Jackson, L.J. Wyland, J.I. Inman, and W.E. Chaney. 1996. Phacelia, Lana woollypod vetch, and Austrian winter pea: Three new cover crop hosts of Sclerotinia minor in California. Plant Dis. 80:1409–1412. doi:10.1094/PD-80-1409

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS Systems for mixed models. SAS Inst., Cary, NC.

Macgregor, C.J., and C.R. Warren. 2006. Adopting sustainable farm management practices within a Nitrate Vulnerable Zone in Scotland: The view from the farm. Agric. Ecosyst. Environ. 113:108–119. doi:10.1016/j.agee.2005.09.003

McCracken, D.V., M.S. Smith, J.H. Grove, C.T. Mackown, and R.L. Blevins. 1994. Nitrate leaching as influenced by cover cropping and nitrogen-source. Soil Sci. Soc. Am. J. 58:1476–1483. doi:10.2136/sssaj1994.03615995005800050029x

McLenaghen, R.D., K.C. Cameron, N.H. Lampkin, M.L. Daly, and B. Deo. 1996. Nitrate leaching from ploughed pasture and the effectiveness of winter catch crops in reducing leaching losses. N. Z. J. Agric. Res. 39:413–420. doi:10.1080/00288233.1996.9513202

Meisinger, J.J., W.L. Hargrove, R.L. Mikkelson, and V.W. Benson. 1991. Effects of cover crops on groundwater quality. In: W.L. Hargrove, editor, Cover crops for clean water. Soil and Water Conserv. Soc., Jackson, TN. p. 57–68.

Moller, K., W. Stinner, and G. Leithold. 2008. Growth, composition, biological N-2 fixation and nutrient uptake of a leguminous cover crop mixture and the effect of their removal on field nitrogen balances and nitrate leaching risk. Nutr. Cycling Agroecosyst. 82:233–249. doi:10.1007/s10705-008-9182-2

NASS. 2007. 2007 Census of Agriculture. Organic Production Survey (2008), USDA, Natl. Agric. Statistics Serv., Washington, DC.

Pearson, C.J. 2007. Regenerative, semiclosed systems: A priority for twenty-first-century agriculture. Bioscience 57:409–418. doi:10.1641/B570506

Peoples, M.B., J. Brockwell, D.F. Herridge, I.J. Rochester, B.J.R. Alves, S. Urquiaga, R.M. Boddey, F.D. Dakora, S. Bhattarai, S.L. Maskey, C. Sampet, B. Rerkasem, D.F. Khan, H. Hauggaard-Nielsen, and E.S. Jensen. 2009. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis 48:1–17. doi:10.1007/BF03179980

Ranells, N.N., and M.G. Wagger. 1997a. Grass-legume bicultures as winter annual cover crops. Agron. J. 89:659–665. doi:10.2134/agronj1997.00021962008900040019x

Ranells, N.N., and M.G. Wagger. 1997b. Nitrogen-15 recovery and release by rye and crimson clover cover crops. Soil Sci. Soc. Am. J. 61:943–948. doi:10.2136/sssaj1997.03615995006100030033x

Rinnofner, T., J.K. Friedel, R. de Kruijff, G. Pietsch, and B. Freyer. 2008. Effect of catch crops on N dynamics and following crops in organic farming. Agron. Sustain. Dev. 28:551–558. doi:10.1051/agro:2008028

Robertson, G.P., and P.M. Vitousek. 2009. Nitrogen in agriculture: Balancing the cost of an essential resource. Annu. Rev. Environ. Resour. 34:97–125. doi:10.1146/annurev.environ.032108.105046

Ruffo, M.L., and G.A. Bollero. 2003. Modeling rye and hairy vetch residue decomposition as a function of degree-days and decomposition-days. Agron. J. 95:900–907. doi:10.2134/agronj2003.0900

Sainju, U.M., W.F. Whitehead, and B.P. Singh. 2005. Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron. J. 97:1403–1412. doi:10.2134/agronj2004.0274

Spink, J.H., T. Semere, D.L. Sparkes, J.M. Whaley, M.J. Foulkes, R.W. Clare, and R.K. Scott. 2000. Effect of sowing date on the optimum plant density of winter wheat. Ann. Appl. Biol. 137:179–188. doi:10.1111/j.1744-7348.2000.tb00049.x

Stopes, C., E.I. Lord, L. Philipps, and L. Woodward. 2002. Nitrate leaching from organic farms and conventional farms following best practice. Soil Use Manage. 18:256–263. doi:10.1079/SUM2002128

Thorup-Kristensen, K., J. Magid, and L.S. Jensen. 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79:227–302. doi:10.1016/S0065-2113(02)79005-6

Torstensson, G., H. Aronsson, and L. Bergstrom. 2006. Nutrient use efficiencies and leaching of organic and conventional cropping systems in Sweden. Agron. J. 98:603–615. doi:10.2134/agronj2005.0224

Watson, C.A., D. Atkinson, P. Gosling, L.R. Jackson, and F.W. Rayns. 2002. Managing soil fertility in organic farming systems. Soil Use Manage. 18:239–247. doi:10.1079/SUM2002131

Westfall, P.H., R.D. Tobias, D. Rom, R.D. Wolfinger, and Y. Hochberg. 1999. Multiple comparisons and multiple tests using SAS. SAS Inst., Cary, NC.

Wyland, L.J., L.E. Jackson, W.E. Chaney, K. Klonsky, S.T. Koike, and B. Kimple. 1996. Winter cover crops in a vegetable cropping system: Impacts on nitrate leaching, soil water, crop yield, pests and management costs. Agric. Ecosyst. Environ. 59:1–17. doi:10.1016/0167-8809(96)01048-1