



Winter Cover Crop Seeding Rate and Variety Affects during Eight Years of Organic Vegetables: I. Cover Crop Biomass Production

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ABSTRACT

Long-term research on cover crops (CC) is needed to design optimal rotations. Winter CC shoot dry matter (DM) of rye (*Secale cereale* L.), legume-rye, and mustard was determined in December or March during the first 8 yr of the Salinas Organic Cropping Systems trial focused on high-value crops in Salinas, CA. By seed weight, legume-rye included 10% rye, 35% faba (*Vicia faba* L.), 25% pea (*Pisum sativum* L.), and 15% each of common vetch (*V. sativa* L.) and 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. Cover crop densities ranged from 131 to 854 plants m⁻² and varied by CC, SR, and year. Year, CC, and SR affected DM production, however, the effects varied across the season and interactions occurred. Averaged across years, final DM was greater in rye and legume-rye (7 Mg ha⁻¹) than mustard (5.6 Mg ha⁻¹), and increased with SR through January. Dry matter production through the season was correlated significantly with growing degree days (GDD). Legumes contributed 27% of final legume-rye DM. Season-end legume DM was negatively correlated with GDD at 30 d, and legume DM in the 3x SR increased during years with frequent late-season rainfall. Seed costs per Mg of final CC DM at 1x SR were approximately three times higher for legume-rye than rye and mustard.

CALIFORNIA'S ORGANIC PRODUCTION systems for high-value, cool-season vegetables such as lettuce (*Lactuca sativa* L.) and broccoli (*B. oleraceae* L. Italica Group) can be classified as high-input organic systems because they have high production costs (>\$18,000 ha⁻¹crop⁻¹) (Tourte et al., 2004a, 2004b), and typically use high-N supplemental organic fertilizers. Winter cover cropping is a best management practice for these shallow-rooted vegetables systems because the more extensive root systems of cover crops scavenge nutrients that might otherwise be lost by leaching or soil erosion, and because cover crops add organic matter that is critical to maintain and improve soil quality (Wyland et al., 1996; Fageria et al., 2005; Hartz, 2006). Despite their benefits in both organic and conventional systems, cover crops are much more common on organic than conventional vegetable farms in the central coast of California. Annual agricultural land rent here can exceed \$6000 ha⁻¹ yr⁻¹ and replacing a bare fallow with a winter cover crop can reduce the typical number of crops produced per ha per year from 2.5 to 2 or 1.5 due to delayed spring plantings (Klonsky and Tourte, 2011). The opportunity costs of forgone cash crop income are one of the largest costs of cover cropping and a major obstacle to increased adoption (Snapp et al., 2005). However, cover crop use on irrigated crop land in California

will likely increase due to the Irrigated Lands Regulatory Program that regulates discharges such as winter runoff from agricultural lands (CEPA, 2011).

The USDA National Organic Program standards (§205.203a) require that organic producers 'select and implement tillage and cultivation practices that maintain or improve the physical, chemical, and biological condition of soil and minimize soil erosion' (AMS, 2011). Maintaining and improving soil organic matter (SOM) in tillage-intensive vegetable production is challenging because postharvest crop residues that are incorporated into the soil are often low (i.e., 2.2 Mg ha⁻¹ for lettuce) (Mitchell, 1999). Furthermore, vegetables with greater residue such as broccoli, are unlikely to improve SOM because the low C/N ratio of the vegetable residue hastens their decomposition. Therefore, vegetable farmers typically apply compost and grow cover crops to add more recalcitrant forms of C to increase SOM. Compost from off-farm sources is a more convenient way than cover cropping to add SOM because fields are always available for cash cropping. However, cover cropping is a more sustainable approach because it reduces a farm's reliance on off-farm inputs and also provides essential ecosystem services such as nutrient scavenging.

Typical winter cover crops in the central coast of California include mustards, cereals, and legume-cereal mixtures (Brennan and Smith, 2005). Mustard cover crops became popular here in the past 10 yr and were aggressively marketed for their potential biofumigation properties to suppress soil-borne diseases of lettuce; however, this tactic is not effective (Bensen et al., 2009). Several 2-yr studies (van Bruggen et al., 1990; Jackson et al., 1993, 2004; Brennan and Smith, 2005;

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Abbreviations: CC, cover crops; DDP, days with deficit precipitation; DM, dry matter; GDD, growing degree days; SOCS, Salinas Organic Cropping Systems; SOM, soil organic matter; SR, seeding rates.

Boyd and Brennan, 2006; Boyd et al., 2009; Brennan et al., 2009, 2011a) have provided valuable information on DM production by various winter cover crops in the region, but there is a need for longer-term, systems research on cover crop growth dynamics in vegetable rotations. There also is a need for comparisons of N scavenging nonlegume cover crops vs. legume–cereal mixtures that have the potential to contribute biologically fixed N from the legume and scavenged N from the cereal. Cherr et al. (2006) highlighted the need for repeated sampling of cover crop DM throughout the growth period to provide more meaningful information for cover crop selection and management. Such information can help growers make management decisions that may increase cover crop use, reduce cover crop costs and off-farm inputs, improve the sustainability of their systems, and meet increasing water quality regulations.

In 2003, a long-term, organic systems trial entitled the Salinas Organic Cropping Systems (SOCS) trial began at the USDA-ARS in Salinas, CA, to address the needs of local organic farmers for long-term research to minimize off-farm inputs, and to optimize soil and pest management, yields, and profitability of high-value crops. To our knowledge, the SOCS trial is the longest-running, commercial-scale systems study with high-value, high-input, cool-season, organic crops in the United States; another relatively long-term organic vegetable cropping systems study that includes a pasture component began in 2003 in Washington (Pritchett et al., 2011). The present paper is the first in a series that will focus on the results from the first 8 yr of vegetables in rotation with winter cover crops. In this paper we introduce the trial and focus on cover crop densities and shoot DM production in six systems with three winter cover crops (rye, a legume–rye mixture, or a mustard mixture) planted at typical (1x) and 3x SR; the typical seeding rates were the rates that were commonly used on farms in this region when the trial began. The three cover crops evaluated represent the most common winter cover crop types in this region, namely cereals, mustards, and legume–cereal mixtures. Rye was chosen as the cereal because it is the most common cereal cover crop here. Seeding rate was evaluated because it affects cover crop DM production, competition between legume and cereal mixture components, and weed suppression (Boyd et al., 2009; Brennan et al., 2009). The six systems evaluated received the same inputs and management during the vegetable production phase that usually included lettuce and broccoli annually. Our objectives of this component of the study were to evaluate cover crop densities at the beginning of the season, and cover crop shoot DM production in December, January, and at season-end (February/March) during eight consecutive winter periods. Specific questions of interest were: (i) Does cover crop shoot DM differ between the nonlegumes and a legume–rye mixture? (ii) Does SR have a consistent effect on DM production of the three cover crops? (iii) Does SR affect the proportions and amount of legume vs. rye DM produced by the legume–rye mixture? (iv) Does DM production vary across years, and if so, what factors contribute to such variation? Nitrogen accumulation of the cover crops are presented in a companion paper (Brennan and Boyd, 2012).

MATERIALS AND METHODS

Site Description and Land History

The ongoing SOCS trial is located at the USDA-ARS organic research land 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 vegetable and cover crops with minimal additions of compost or supplemental organic fertilizers 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. During the year before the onset of the trial, three cover crops were grown including a legume–rye mixture (10% rye 'Merced', 35% faba bean, 25% pea 'Magnus', 15% common vetch, and 15% purple vetch) during winter, and summer cover crop of vetch–mustard (95% common vetch, 5% *B. juncea* Czern.), and buckwheat (*Fagopyrum esculentum* Moench); mixture percentages were by seed weight. The buckwheat received 1.3 Mg ha⁻¹ of pre-plant organic fertilizer (8N–5P–5K). Other soil amendments that were broadcast and soil-incorporated during the year before the trial included urban yard-waste compost at approximately 22 Mg ha⁻¹ (wet weight basis), and mined 75% gypsum at approximately 12.3 Mg ha⁻¹. The field has a slope of approximately 0.8% in the planting direction and was laser-leveled before the trial began to ensure even drainage.

History of the Salinas Organic Cropping Systems Trial and System Descriptions

The USDA-ARS has increased its research efforts on organic farming over the past decade (Bull, 2007) and the SOCS trial is one example of this change. In 2002, an advisory group of ten organic farmers from the central coast of California indicated that weed and soil fertility management, and cover crops were major areas of common research need across a diversity of high-value cropping systems and scales. The SOCS trial was established in 2003 as a 2.5-yr trial to begin to address these research needs, and received partial funding during this phase with a grant from the University of California Specialty Crops Research Program. During this first phase we developed collaborative arrangements with local farms to provide the personnel, expertise, and equipment needed for the commercial-scale harvest, and wholesale of marketable vegetables from the trial. With guidance from cooperative extension farm advisors, local organic farmers, and harvest supervisors, the lead author of the paper developed the skills needed to act as the 'farmer' and to produce the high-quality produce necessary to offset the vegetable production costs, and allow the study to evolve into the ongoing systems trial. This novel research approach was facilitated by agreements between the USDA-ARS and the Community Alliance with Family Farmers. 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, and produce high-quality crops for the wholesale market.

The trial includes eight systems with the same annual high-value vegetable crop sequence. The current paper focuses on the six annually cover cropped systems that received the same compost and supplemental fertilizer inputs during the

Table 1. Descriptions of the winter cover crops and seed costs used in the six systems that received cover crop annually in the Salinas Organic Cropping Systems trial at Salinas, CA.

Cover crop	Seeding rate		Seed cost†	
	1x	3x	\$ kg ⁻¹ ‡	\$ ha ⁻¹ §
Rye¶	90	270	0.77	69.30
Mustard mixture#	11	33	6.59	72.49
Legume-rye mixture††	140	420	1.62 (1.55)	226.80

† Seed costs (\$ kg⁻¹) in September 2010. The legume seed costs were *V. sativa* L. (1.74), organic *V. benghalensis* L. (1.82), organic *V. faba* L. (1.87), organic *P. sativum* L. (1.43). Seed costs for organically produced seed are given where it was commercially available because USDA National Organic Program standards require that organically produced seed be used in such cases.

‡ The numbers in parentheses are the cost of the legume seed in each mixture.

§ Seed costs per ha are for the 1x seeding rate; multiply per ha cost of the 1x rate by 3 to obtain the per ha cost for the 3x rate.

¶ Rye, 'Merced' (*Secale cereale* L.).

By seed weight, the mustard mixture included 61% white mustard, 'Ida Gold' *Sinapis alba* L., and 39% India mustard, 'Pacific Gold' *Brassica juncea* Czern.

†† By seed weight, the legume-rye mixture included 10% Rye, 35% faba bean, (*Vicia faba* L.; small-seeded type known as 'bell bean'), 25% Pea, 'Magnus' *Pisum sativum* L., 15% common vetch, *V. sativa* L., and 15% purple vetch, *V. benghalensis* L.

vegetable production phase, but only differed in winter cover crop type (rye, legume-rye mixture, or mustard mixture) and SR (1x, 3x) (Table 1).

Cropping Sequence and Experimental Design

The experimental design was a randomized complete block with the eight systems in four replicates. System plots were 12.2 m wide by 19.5 m long, and arranged in a grid of four plots wide by eight plots long in a 0.9-ha field within 9 ha of organic research land. The annual rotations began with winter cover crops 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, and then followed by baby leaf spinach (*Spinacia oleraceae* L.) (July–September, Year 1) or broccoli (July or August–September or October, Year 2–7). Thus, the annual rotation sequence is: winter cover crop or fallow, vegetable crop 1, vegetable crops 2. Briefly, the spinach was seeded in 30 rows on 203.2-cm wide beds from furrow center to furrow center whereas the lettuce and broccoli were grown from transplants in two rows on 101.6 cm wide beds. Pelleted, pre-plant organic fertilizer made from chicken (*Gallus gallus*) manure and feather meal (Foster Poultry Farms, 4N–4P–2K; True Organic, Helm, CA, 8N–1P–1K) were used at a rate of

22 kg N ha⁻¹ for spinach, and approximately 56 kg N ha⁻¹ for lettuce, and 112 (Year 2) or 134 (Years 3–7) kg N ha⁻¹ for broccoli. Supplemental, liquid organic fertilizers (Biolizer GP, 2.5N–2P–1.5K, California Liquid Fertilizer, Gonzales, CA; Agrolizer, 6N–2P–0K, AgroMar, San Diego, CA; Tierra Fertil 5N–1P–1K, Mar Y Tierra Fertilizantes Orgánicos, Ensanada, Mexico) made from plant or fish material were injected through a drip irrigation system for the lettuce and broccoli crops to bring the total N application rates up to 73 kg N ha⁻¹ for lettuce, and 134 (Year 2) or 168 kg N ha⁻¹ (Years 3–7) for broccoli. The six systems of focus received urban yard-waste compost annually, with an approximate C/N ratio of 22, that was broadcast at approximately 7.6 Mg ha⁻¹ (oven-dry basis), and incorporated in the soil before each vegetable crop. All systems occurred on the same plots annually to determine their cumulative effects. Vegetables met industry quality standards and were harvested for the wholesale market except for spinach in Year 1 and broccoli in Year 2 due to insect pests and disease; these unmarketable crops were incorporated back into the soil.

Cover Crop Planting and Management

Field preparations for cover crop planting included disc harrowing (John Deere, Moline, IL), spring tooth harrowing, spading (Falc, Faenza, Italy) and ring rolling (T.G. Schmeiser Co., Inc., Fresno, CA) as necessary to incorporate previous crop residue. However, spading was the primary tillage method because it achieved the highest degree of residue incorporation in the fewest passes through the field, and it minimized soil movement between plots. Deep ripping to approximately 1 m below the surface was also necessary to break up furrow compaction caused by heavy, commercial-scale harvest equipment for the lettuce and broccoli. There was more than a 10-d period from the time that the previous crop residue was flail mowed and soil incorporated until cover crop planting, except during Year 4 when cover crops were planted 2 d after residue incorporation (Table 2).

Cover crops were planted with a 4.6 m wide grain drill (model 1500, Great Plains Mfg., Salina, KS) that made 12 continuous passes over the field. The drill had 28 double disc openers that preceded 28 rubber press wheels, and was modified with four belt cones (Kinkaid Equipment Mfg., Haven, KS) for precise control of SR in small plots. Adjacent passes overlapped by approximately one row to prevent gaps between passes. Due to limitations in the capacity of seed distributed

Table 2. Dates for cover crop management activities and sampling during eight consecutive winters periods in the Salinas Organic Cropping Systems trial at Salinas, CA.

Year	Winter period	Previous crop residue incorporation†	Planting	Population density count	Last cover crop irrigation	Cover crop dry matter sampling	Cover crop termination
1	2003–2004	30 Sept.	16 Oct.	5 Nov.	25 Nov.	18 Dec., 15 Jan., 3–4 Mar.	8 Mar.
2	2004–2005	≈ 11 Sept	15 Oct.	4 Nov.	24 Nov.	1 Dec., 24 Jan., 24 Feb.	11 Mar.
3	2005–2006	21–29 Sept.	17 Oct.	7–9 Nov.	17 Nov.	14–15 Dec., 11–13 Jan., 7–8 Feb.	11 Feb.
4	2006–2007	30–31 Oct.	2 Nov.	20 Nov.	5 Nov.	18–20 Jan., 15–16 Mar.	18 Mar.
5	2007–2008	4 Oct.	15 Oct.	13–14 Nov.	8 Dec.	17–18 Jan., 13–15 Feb.	19 Feb.
6	2008–2009	29 Sept.	15 Oct.	5 Nov.	21 Nov.	16 Jan., 10–11 Mar.	13 Mar.
7	2009–2010	7–8 Oct.	29 Oct.	24 Nov.	24 Nov.	16 Jan., 16–17 Mar.	18 Mar.
8	2010–2011	14 Oct.	27 Oct.	8 Dec.	18 Nov.	12–14 Jan., 7–9 Mar.	10–11 Mar.

† Crop residue preceding the winter cover crops was buckwheat (Year 1), baby leaf spinach (Year 2), and broccoli all other years.

Table 3. Thousand seed weights for cover crops used during 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA.

Cover crop	Year								Mean ± 95% CI†	CV
	1	2	3	4	5	6	7	8		
Rye	22	17	22	20	15	18	16	17	18 ± 2	0.15
Mustard mixture										
<i>S. alba</i> ‡	2.1	2.1				2.7	2.5		2.3 ± 0.3	0.11
<i>B. juncea</i>	4.7	4.7	5.1	5.1	5.2	5.0	5.3	5.5	5.1 ± 0.3	0.06
Mixture§	3.2	3.2				3.8	3.7	3.6	3.5 ± 0.4	0.08
Legume-rye mixture										
Rye	22	17	22	20	15	18	16	17	18 ± 2	0.15
Faba bean	417	404	304	433	344	300	337	346	360 ± 43	0.14
Pea	239	228	203	201	191	171	226	195	207 ± 19	0.11
Purple vetch	32	40	35	35	41	36	37	42	37 ± 3	0.09
Common vetch	54	55	60	60	56	46	71	68	59 ± 7	0.14
Mixture§	72	70	73	72	65	64	69	72	69 ± 3	0.05

† The 95% confidence intervals were calculated in the Means procedure in SAS and are based on three to five samples of seed for each type.

‡ 1000 seed weights for mustard were not collected for all years.

§ The 1000-seed weights of the mixtures were calculated based on the 1000-seed weights of the components and the percentage of each component in the mixtures.

with a single revolution of each cone and the high 3x SR of the legume-rye mixture, the cones were calibrated to plant the entire plot length in two cone revolutions. Thus, two seed packets were prepared for loading into each cone with the first at the beginning of each plot and the second half way across each plot. The seed packets were prepared by either weighing the seed for each packet separately or by using the calibrated cup scoop method (Brennan, 2011). For the legume-rye mixture, the faba bean and pea components were each weighed or scooped separately, whereas a homogenous mixture of the rye and vetch components at the appropriate ratios were either weighed or scooped together. Seed packets of the mustard mixture were also prepared by weighing or scooping a homogenous mixture of the mustards. This seed packet preparation method ensured that each seed packet contained the desired proportions of seed of each component (Table 1) and that mixture components were planted simultaneously. This procedure for planting mixtures from pre-made seed mixtures mimicked how farmers plant mixtures here, and ensured that all mixture components were evenly distributed in each plot. Rhizobium inoculants (Rhizo Stick, Urbana Laboratories, St. Joseph, MO; N-DURE Kentland, IN) were added to the seed packets with the legume-rye mixture. The target planting date for cover crops was 15 October, however, actual dates ranged from 15 October to 2 November (Table 2) due to variation in vegetable crop harvests and postharvest tillage requirements. Sprinkler irrigation was applied with a linear-move irrigation system to germinate and maintain the cover crops before the onset of consistent winter rainfall. The last irrigation typically occurred in mid- to late November (Table 2). The 1x SR for each cover crop were the typically recommended SR for vegetable growers in this region. All seed were obtained from L.A. Hearne Company (King City, CA), and the 1000-seed weights (g) are listed in Table 3. Although the 1000-seed weights varied somewhat between years, the SR (kg ha⁻¹) was held constant across years to mimic the typical grower practice in this region.

The cover crops were terminated by flail mowing and the residue was incorporated with one pass using a spader. The termination dates were within 1 wk of the last biomass sampling

during all years except Year 2 when it was 16 d due to rainfall that delayed cover crop termination. Termination dates 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. Termination dates occurred after flowering of rye, mustard, and most legumes had commenced.

Data Collection

Between 4 November to 8 December (Table 2), cover crop population densities were determined by counting emerged cover crop plants in 50- or 100-cm sections of four rows from each plot and were converted to plants m⁻² based on six cover crop rows m⁻²; in most years, the four counted rows were not adjacent. In the rye monoculture systems, individual plants were differentiated from tillers by uprooting plants as needed. For the population densities of the mustard mixture we differentiated the two components species only during Years 5, 7, and 8. For population densities of the legume-rye mixture, we differentiated all species except the vetches. The expected percent emergence of each cover crop seed type was calculated based on 1000 seed weights and the proportion of seed of each component in the mixtures, assuming 100% germination and seed purity, and that 90% of the seed loaded into each cone was evenly distributed in the plot.

Shoot biomass of cover crops was sampled by harvesting one 50- by 100-cm quadrat oriented to include three adjacent rows for each plot at three (Years 1–3) or two (Years 4–8) sampling dates each winter (Table 2). Harvested cover crop biomass of the legume-rye mixture was separated in 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. The biomass sampling dates were chosen to track changes in cover crop DM over the season and to minimize sampling on rainy days.

Statistical Analysis

All data were analyzed using SAS ver.9.2 (SAS Institute, Cary, NC). The 95% confidence intervals (CI) of the cover crop 1000 seed weights, cover crop population densities, and

cover crop shoot DM were calculated using the CLM option with the MEANS procedure. Analyses of total cover crop population densities and cover crop DM were conducted with the MIXED procedure as a repeated measures model with year as the repeated effect, an autoregressive AR(1) covariance structure, and cover crop \times SR \times block as the SUBJECT option. In the ANOVA, cover crop, year, and SR were treated as fixed effects, and block and cover crop \times SR \times block were treated as random effects. The repeated measures approach also was used for the analysis of cover crop densities of the legume and rye components, and for analyses of the total legume vs. rye DM of the legume–rye mixture where year and SR were treated as fixed effects, and block and SR \times block were treated as random effects. Where necessary the data were transformed to meet the assumptions of ANOVA, but back-transformed means are presented. Natural log transformations were used for rye densities in the legume–rye mixture, and for total legume DM at season-end. Square root transformations were used for population densities of faba bean and pea. Pairwise comparisons were controlled at the familywise error rate of $p \leq 0.05$ using Bonferroni or Tukey–Kramer adjustments. Regression analysis using the REG procedure was used to determine the relationship between GDD and DM production throughout the season. Regression analysis was also used to identify

climatic variables associated with season-end DM production of the legume–rye components. Climatic variables investigated included GDD by season-end, GDD at 30 DAP, precipitation + irrigation over the season, and the number of days that reference evapotranspiration exceeded precipitation during the last 60 d of the season; we refer to the latter explanatory variable as days with deficit precipitation ($DDP_{last60d}$). The coefficient of variation (CV) was used to assess season-end cover crop DM yield variability across years as has been done with other crops (Smith and Gross, 2006; Grover et al., 2009). The CV were calculated for each cover crop by SR combination for each year, and were subjected to ANOVA using the MIXED procedure where cover crop and SR were fixed effects, and year and year \times cover crop \times SR were random effects.

RESULTS AND DISCUSSION

Climate

Average daily air temperatures during the cover cropping ranged from a high of 20.5°C in late October (Year 1) to a low of 1.3°C in January (Year 4), but typically were between 5 and 15°C (Fig. 1). Differences between years in planting date and subsequent air temperatures caused differences in accumulated GDD during the first 30 d after planting (DAP). For example, Years 4 and 7 had especially low GDD (273 and 252, respectively) compared with

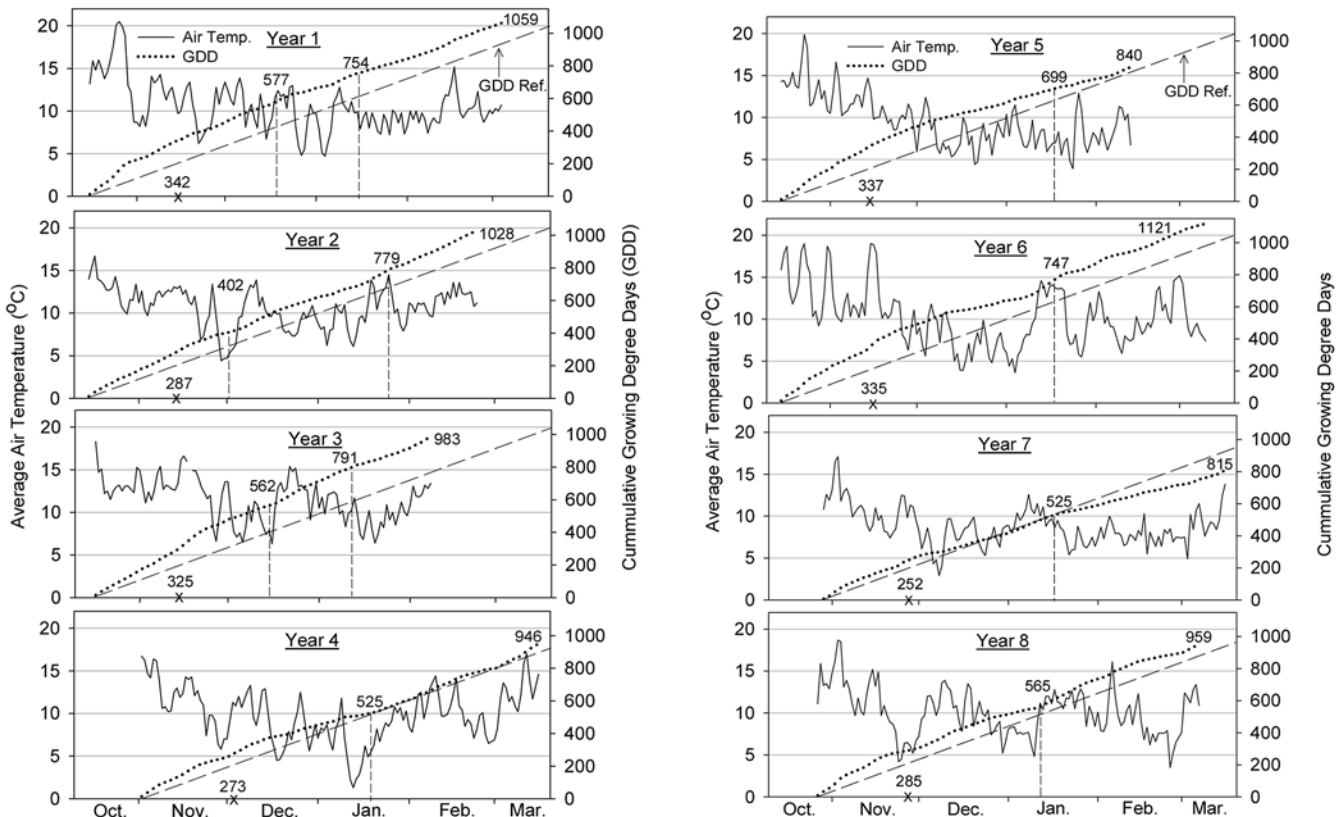


Fig. 1. Average daily air temperatures and cumulative growing degree days (GDD) during the cover cropping periods of 8 yr in Salinas, CA, from data at station no. 89 of the California Irrigation Management System (<http://www.cimis.water.ca.gov>). The GDD are calculated with the single sine method with a baseline threshold of 4°C using the online calculator at the University of California Statewide Integrated Pest Management (<http://www.ipm.ucdavis.edu>). Vertical dashed lines indicate the date of cover crop dry matter harvests prior to the final harvest with the GDD for these harvest above the dashed line; GDD for the final harvest are shown next to the upper end of the GDD curves. The diagonal dashed line adjacent to each GDD curve is a reference line for comparing the GDD curves across years; the reference begins at the planting date and has the same slope in each plot. The “x” on each x axis indicates the point that is 30 d after cover crop planting, and the number above the “x” is the number of GDD by this point in the season.

Year 1, 3, 5, and 6 with more than 320 GDD during the first 30 DAP. These differences in the daily rate of GDD during the first 30 DAP helped to explain differences in cover crop DM production discussed below. The differences in the GDD accumulation rate between years are apparent by comparing the slope of the GDD curves each year with the slope of the GDD reference line. For example, the daily GDD accumulation rate was usually greater than the reference line slope and for a longer period when the cover crops were planted earlier (i.e., mid-October). Furthermore, the GDD accumulation rate during the first 30 DAP was greater than 11 GDD DAP⁻¹ (i.e., ≥335 GDD/30 DAP) for Years 1, 5, and 6 with warmer early-season conditions compared with Year 7 that was markedly cooler with a GDD accumulation rate of only 8.4 GDD DAP⁻¹ (i.e., 252 GDD/30 DAP). Year 7 had the lowest GDD accumulation rate through the season because the late October planting was followed by relatively cool air temperatures (i.e., <10°C) through most of the season. Furthermore, Years 5 and 7 with the fewest total GDD had relatively long periods where slope of the GDD was less than the slope of the reference line particularly during January and February.

The amount and frequency of winter rainfall during the cover cropping periods varied considerably between years ranging

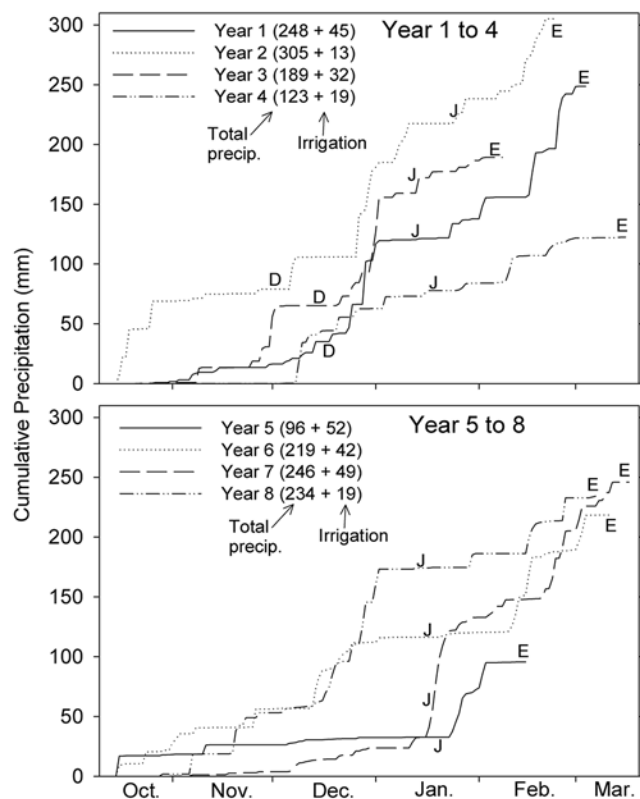


Fig. 2. Cumulative precipitation during the cover cropping period of 8 yr from data at station no. 89 in Salinas, CA, of the California Irrigation Management System (<http://www.cimis.water.ca.gov>). Numbers in parenthesis are total precipitation during the cover cropping period plus applied irrigation at the beginning of the season to establish the cover crops before adequate winter rainfall; applications occurred on 6 d for Year 1, 2 d for Year 2, 3 d for Years 3, 7, and 8, 1 d for Year 4, 7 d for Year 5, and 5 d for Year 6. The last irrigation was in November annually except during Year 5 when it was in early December. The dates of the dry matter harvests in December, January, and season-end are indicated on each curve with letters D, J, and E, respectively.

from 96 mm (Year 5) to 305 mm (Year 2) with an average (\pm 95% CI) across years of 208 \pm 58 mm (Fig. 2). The periods of November through January were relatively dry during Years 4 and 5 compared with the other years; these 2 yr also were considered drier than normal in this region. For example, rainfall from October through March of Years 4 and 5 was <50% of the average rainfall of 313 mm from October through March of 1994 to 2011. Irrigation to germinate and maintain the cover crops before the onset of consistent winter rainfall accounted for 4 to 17% of the total water (including precipitation) that the cover crops received during most years, with exception of Year 5 when irrigation accounted for 35% of the water received with the last irrigation in December (Fig. 2, Table 2).

Cover Crop Population Densities

There were significant differences in total cover crop densities between cover crop, year, and SR, and a significant interaction (cover crop \times year) (Table 4). The interaction occurred because averaged across SR, densities of the legume-rye mixture were less variable than those of rye and mustard, and because the changes in density between years were inconsistent across cover crops (Fig. 3). For example, from Year 4 to 5, the density of the rye monoculture treatments increased, whereas the cover crop density decreased in mustard and the legume-rye mixture. The lower variability in the population density of the legume-rye mixture compared with rye and mustard across years was most likely because the density of the legume-rye mixture included a diversity of components that each made small contributions to the overall density.

The effects of cover crop and SR on total population densities were expected because of the differences in cover crop seed size and SR. Averaged across years, densities were greatest for rye (320–854), followed by mustard (182–492), and then legume-rye (131–343) for the 1x and 3x SR, respectively. Although SR within each cover crop differed by three fold, the resulting densities differed by approximately 2.7-fold, indicating that the percent emergence of cover crop seed or seedling survival were greater in the 1x than 3x SR. Averaged across years, the

Table 4. Significance of tests of fixed effects and interactions on total cover crop density, and total shoot dry matter of cover crop at three harvest periods during 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA.

Effect	Total cover crop density	Dry matter harvest period		
		Dec.†	Jan.	Feb./Mar.
Cover crop‡	***	***	***	***
Seeding rate§	***	***	**	ns¶
Year	***	***	***	***
Cover crop \times seeding rate	ns	**	ns	ns
Cover crops \times year	***	***	***	***
Seeding rate \times year	ns	ns	ns	ns
Cover crop \times seeding rate \times year	ns	ns	ns	***

** Significant at the $p \leq 0.01$ level.

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

† December harvest only occurred during the first 3 yr of the trial.

‡ Cover crops include rye, a legume-rye mixture, and mustard.

§ Seeding rates in kg ha⁻¹ were rye (90, 270), legume-rye (140, 420), and mustard (11, 33).

¶ ns, not significant.

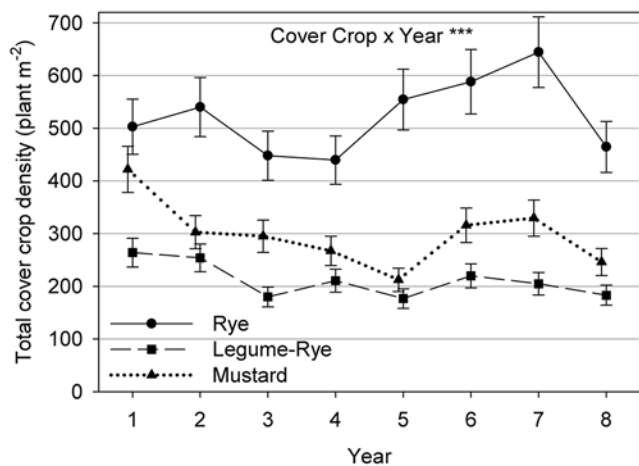


Fig. 3. Cover crop × year interaction for total cover crop population densities of three cover crop averaged across two seeding rates during 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA. Points are back-transformed means ± 95% confidence intervals; means are offset to differentiate confidence intervals within year. Seeding rates in kg ha⁻¹ were rye (90, 270), legume-rye (140, 420), and mustard (11, 33). *** Indicates the significance of the interaction ($p \leq 0.001$).

estimated emergence was 84 and 73% for the legume-rye, 77 and 69% for mustard, and 82 and 73% for rye for the 1x and 3x SR, respectively. Previous studies have also reported reduced percent emergence with higher SR for a variety of small grains and cover crops, however, the causes have not been investigated (Juskiw et al., 2000; Whaley et al., 2000; Zhao et al., 2007; Boyd et al., 2009; Brennan et al., 2009; Brennan, 2011). The lowest percent emergence occurred with mustard at the 3x SR during Year 5 when only 43% of the expected seed emerged. Several factors may have contributed to the lower than expected population densities including the germination rate of the seed, seedling vigor, predation, and seed bed differences between years. Of the three cover crops, mustard was the most difficult to achieve a uniform stand due to its small seed size, particularly the smaller seeded species (*S. alba*). The density of larger seeded *B. juncea* vs. the smaller seeded *S. alba* was determined only during 3 yr (Years 5, 7, 8) and indicated slightly greater emergence of the larger seeded mustard; *B. juncea* comprised 56% of the emerged mustard plants even though the proportion of seed of the each species in the mustard mixture was approximately equal on a seed count basis. Achieving the optimal seeding depth for the diversity of cover crops used in the trial was challenging because of the large range in seed sizes (i.e., approximately 2–400 g/1000 seed) (Table 3).

The 1000 seed weights of the cover crops varied considerably between years with the greatest variation in rye (CV = 0.15) and the least variation in *B. juncea* (CV = 0.06) across 8 yr (Table 3). Seed size variability between years theoretically could have influenced the cover crop density because the SR (kg ha⁻¹) were stable across years. However, within a cover crop, there was no evidence of a correlation between 1000 seed weight and cover crop densities for rye ($r^2 = 0.39, p = 0.1$), mustard ($r^2 = 0.20, p = 0.5$), and the legume-rye mixture ($r^2 = 0.01, p = 0.8$). Cover crop seed bag labels in this region do not typically contain information on 1000 seed weight, and although such information may be useful in adjusting SR to achieve a target population density, the data from the current study suggest that year-to-year variation in seed

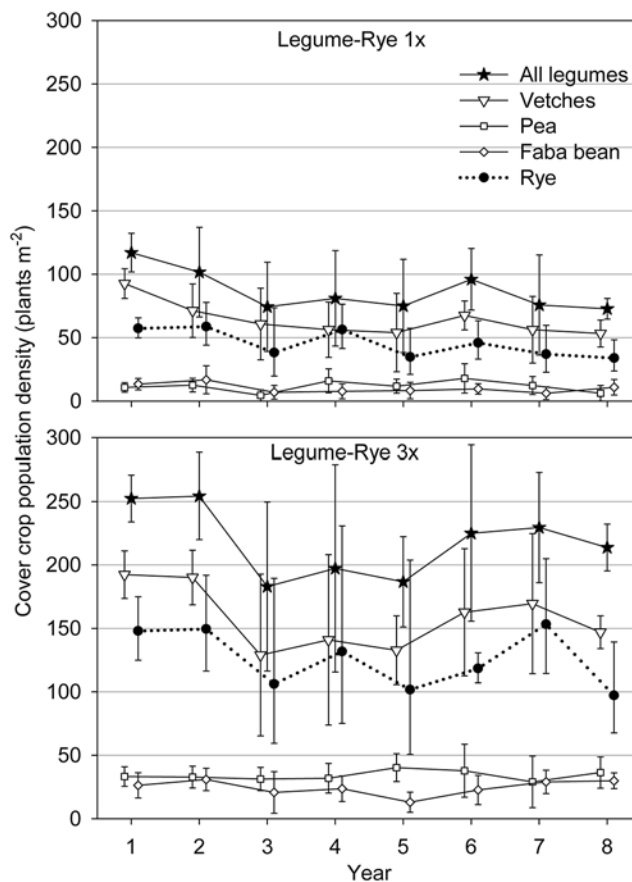


Fig. 4. Population densities of all legumes, legume components, and rye in the legume-rye mixture planted at two seeding rates during 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA. Points are means or back-transformed means (rye) ± 95% confidence intervals; means are offset to differentiate confidence intervals within year. Seeding rates were 140 and 420 kg ha⁻¹ for 1x and 3x, respectively. Averaged across years, densities were 1x (45 rye, 64 vetches, 11 pea, 10 faba bean) and 3x (126 rye, 158 vetches, 34 pea, 24 faba bean).

size had relatively little effect on plant density at the SR evaluated. Other factors such as germination rate and seed vigor were not recorded but could help to explain the observed variation in cover crop densities across years.

The legume-rye mixture contained 90% legume seed and 10% rye seed as a percentage of seed weight, however, the resulting population densities contained only 65 and 63% legume plants in the 1x and 3x densities respectively, because the legume seed had a larger 1000 seed weights than rye. As expected, legume density increased with SR (Fig. 4). Total legume density and the density of all legume components except for pea were significantly affected by year (Table 5). Vetches were the smallest seeded legume components and comprised the largest proportion (73%) of legume plants in the mixture, followed by pea (14%) and faba bean (11%) averaged across SR and years. The variability in the 1000 seed weights of the legume components between years were not correlated with the variability in the population densities of these components (data not shown).

Total Cover Crop Dry Matter Production

There were significant two-way interactions for total cover crop DM production at all harvest dates, and also a significant

Table 5. Significance of tests of fixed effects and their interaction on the density of legumes and rye components in a legume–rye cover crop planted at two seeding rates over 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA.

Effect	All legumes	Rye	Vetches†	Pea	Faba bean
Seeding rate‡	***	***	***	***	***
Year	***	***	***	ns§	*
Seeding rate × year	ns	ns	ns	ns	ns

* Significant at the $p \leq 0.05$ level.

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

† Vetches included equal proportions of common vetch and purple vetch by seed weight.

‡ Seeding rates were 140 and 420 kg ha⁻¹.

§ ns, not significant.

three-way interaction for total DM at season-end (February/March) (Table 4). The three-way interaction of cover crop × SR × year at season-end occurred because SR only affected total DM with the legume–rye mixture during Year 7 when the 3x SR produced more DM than the 1x SR (Fig. 5). In contrast, averaged across years and cover crop, total DM increased with SR in December and January, although the cover crop × SR interaction during December indicates that SR had a greater effect on the DM of the legume–rye mixture than the other cover crops (Fig. 6A, 6B). Furthermore, the significant cover crop × year interaction illustrates that the total DM varied by year and cover crop through the season (Fig. 7). For example, during December, rye produced more total DM than the legume–rye mixture during Year 1, whereas, mustard produced more total DM than the legume–rye mixture during Year 3 (Fig. 7A). There were significant differences in total DM in January during 5 of 8 yr with the greater DM in rye and legume–rye than mustard during Years 2, 5, and 6 (Fig. 7B). At season-end there were differences in total DM during 4 of the 8 yr, with rye and legume–rye producing more DM than mustard (Fig. 7C).

Averaged across SR, GDD from December to season-end explained more than 80% of the year-to-year variability in DM production of rye and legume–rye and nearly 70% of the variability in mustard yields (Fig. 8). The rate of DM accumulation per GDD expressed in kg ha⁻¹ GDD⁻¹ was for rye (9) and legume–rye (9–11) than for mustard (7) indicating that rye and legume–rye were the most efficient cover crops in terms of DM production per GDD. The lower DM production efficiency of mustard vs. the other cover crops is well-illustrated during Year 5 when mustard produced 3.4 Mg ha⁻¹ compared with more than 6.7 Mg ha⁻¹ by rye and legume–rye. (Fig. 7C, 8). We speculate that the low rainfall during Year 5 increased moisture stress particularly in mustard which shortened its vegetative growth period and thus reduced mustard DM.

Yield variability of total DM at season-end based on CV did not differ significantly between cover crop or SR. However, the CV (\pm 95% CI) suggest greater variability with mustard (1x SR 21 \pm 5%, 3x SR 21 \pm 7%) than the legume–rye mixture (1x SR 18 \pm 7%, 3x SR 13 \pm 4), and rye (1x SR 16 \pm 5, 3x SR 19 \pm 8).

Averaged across years and SR, cover crop shoot DM ranged from 2 to 2.4 Mg ha⁻¹ in December, 3.5 to 4.7 Mg ha⁻¹ in January, and 5.6 to 7.2 Mg ha⁻¹ at season-end in February or March (Fig. 9). These yields were comparable to yields in previous reports for rye, legume–rye mixtures, and mustards in Salinas (Brennan and Smith, 2005; Boyd and Brennan, 2006; Boyd

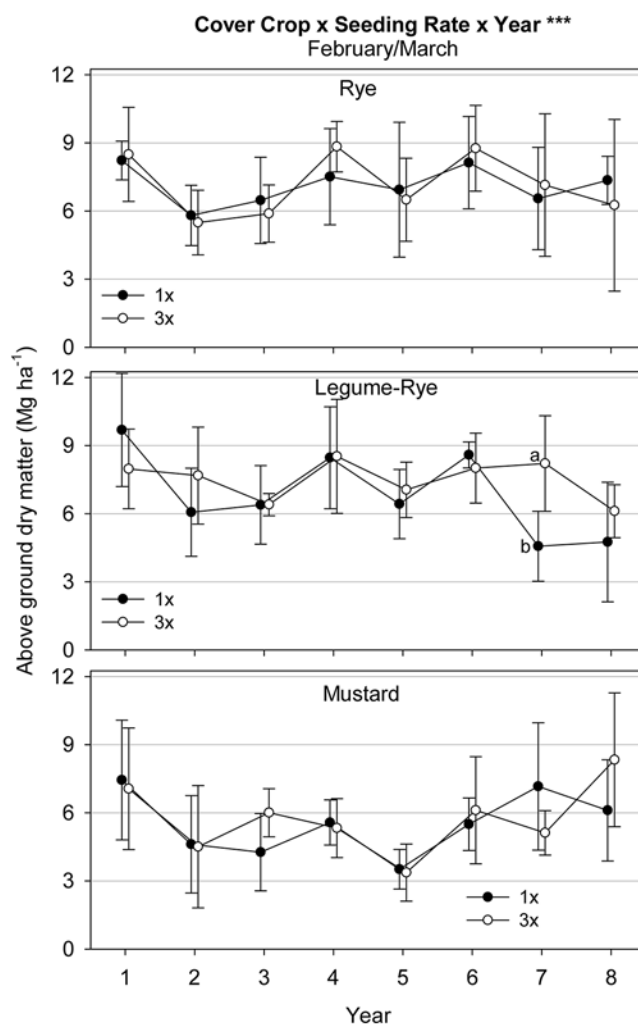


Fig. 5. Cover crop × seeding rate × year interaction for total cover crop dry matter at the final harvest in February/March during 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA. * Indicates the significance of the interaction ($p \leq 0.001$). Seeding rates for the 1x and 3x rates (respectively) in kg ha⁻¹ were rye (90, 270), legume–rye (140, 420), and mustard (11, 33). Points are means \pm 95% confidence intervals; means are offset to differentiate confidence intervals within year. Means adjacent to different letters are significantly different within cover crop and year based on a Bonferroni family-wise error rate of $p \leq 0.05$; the only difference occurred during Year 7 with the legume–rye mixture.**

et al., 2009; Brennan et al., 2011a); however, yields of rye and legume–rye mixtures >10 Mg ha⁻¹ have been reported at another higher fertility site (Hollister, CA) in this region during some years (Brennan et al., 2011a). All three cover crops produced final shoot DM levels greater than the 5 Mg ha⁻¹ minimum suggested for maintaining adequate SOM (Larson et al., 1972; Rasmussen et al., 1980). Rye and mustard were more productive than the legume–rye mixture during approximately the first third of the season; however, DM production by the legume–rye mixture exceeded that of mustard by January, and was equivalent to rye by season-end (Fig. 9). Furthermore, averaged across years and cover crops, higher SR increased cover crop DM production from planting through January but not at season-end (Table 4, Fig. 6). The lack of difference in season-end DM production by rye vs. the legume–rye mixture indicate cover crop DM production was not N limited. Previous studies from other regions reported

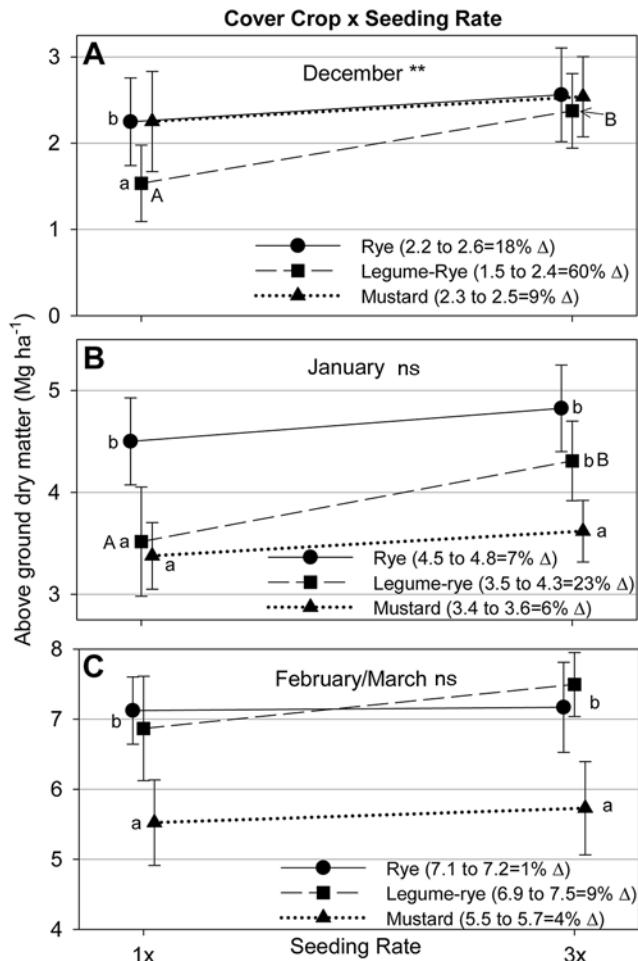


Fig. 6. Cover crop × seeding rate interactions for total cover crop dry matter (DM) at the December harvest during 3 yr, and January and February/March harvests during 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA. Seeding rates for the 1x and 3x rates (respectively) in kg ha⁻¹ were rye (90, 270), legume-rye (140, 420), and mustard (11, 33). Points are means ± 95% confidence intervals; means are offset to differentiate confidence intervals within seeding rate. Means are averaged across years. Within harvest and rate, means adjacent to different lower case letters are significantly different; within harvest and cover crop, 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 $p \leq 0.01$ and NS indicates a nonsignificant interaction. The lines for rye and mustard are difficult to differentiate from each other during December (Fig. 8A) because of they overlap. The numbers in parentheses following the legends are the DM levels for the 1x to 3x seeding rates and the percent change.

considerable variability, between sites and years, in whether rye or hairy vetch-rye mixtures produced more shoot DM (Ranells and Waggoner, 1996; Teasdale and Abdul-Baki, 1998; Griffin et al., 2000; Kuo and Jellum, 2002; Ruffo and Bollero, 2003; Sainju et al., 2005; Clark et al., 2007). Our current study and previous work here provides no evidence of differences in final DM production by rye vs. the legume-rye mixtures. Recent work with wheat-pea intercropping found that the intercrop produced more DM in systems with lower N availability (Bedouss and Justes, 2010). It would be useful to know if there are soil N thresholds below which legume-cereal mixtures would be more

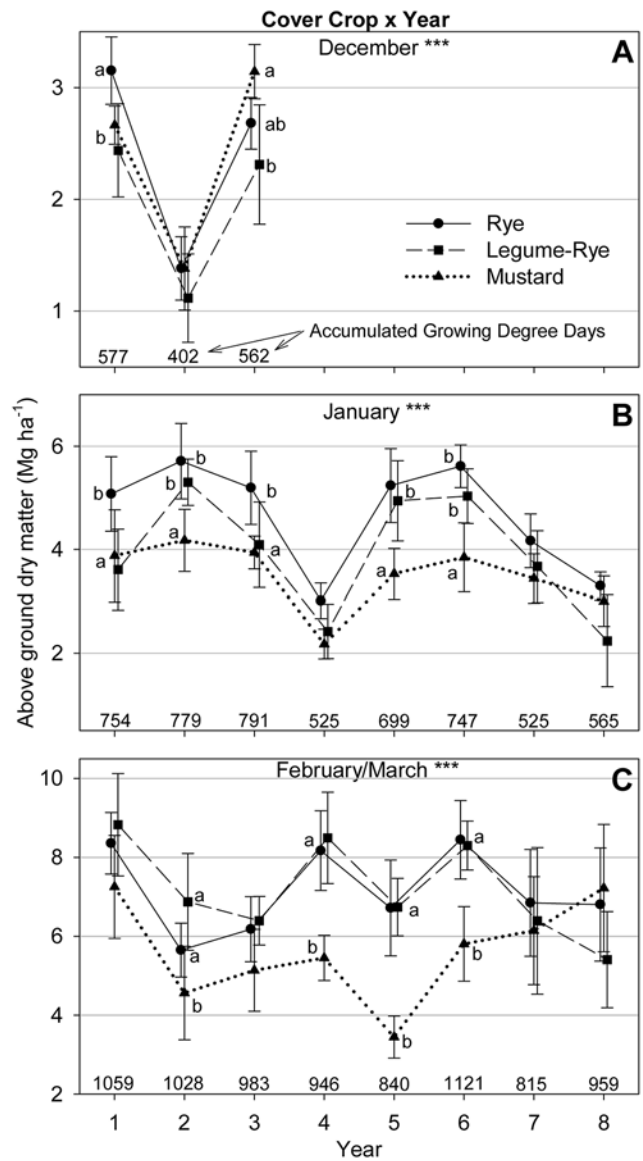


Fig. 7. Cover crop × year interactions for total shoot cover crop dry matter at December, January, and February/March harvests during 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA. *** Indicates the significance of the interaction ($p \leq 0.001$). The points are means ± 95% confidence intervals averaged across seeding rates for each cover crop; means are offset to differentiate confidence intervals within year. Within year and harvest, means adjacent to different letters are significantly different based on a Bonferroni family-wise error rate of $p \leq 0.05$. The numbers above the × axis are the accumulated growing degree days by the harvest for each year.

beneficial than nonlegumes in the relatively high-input organic cropping systems in California.

The results of the present study that higher SR can increase winter cover crop DM of up to mid-season agree with previous studies from this region (Boyd et al., 2009; Brennan et al., 2009). We speculate that SR had a greater effect on early-season DM production of the legume-rye mixture than other cover crops because the population density of the 1x SR for the legume-rye mixture (131 plants m⁻²) was markedly lower than the 1x SR for mustard (182 plants m⁻²) or rye (320 plants m⁻²), and because on a per plant basis, rye and mustard may be more competitive than the legumes that comprised the majority of

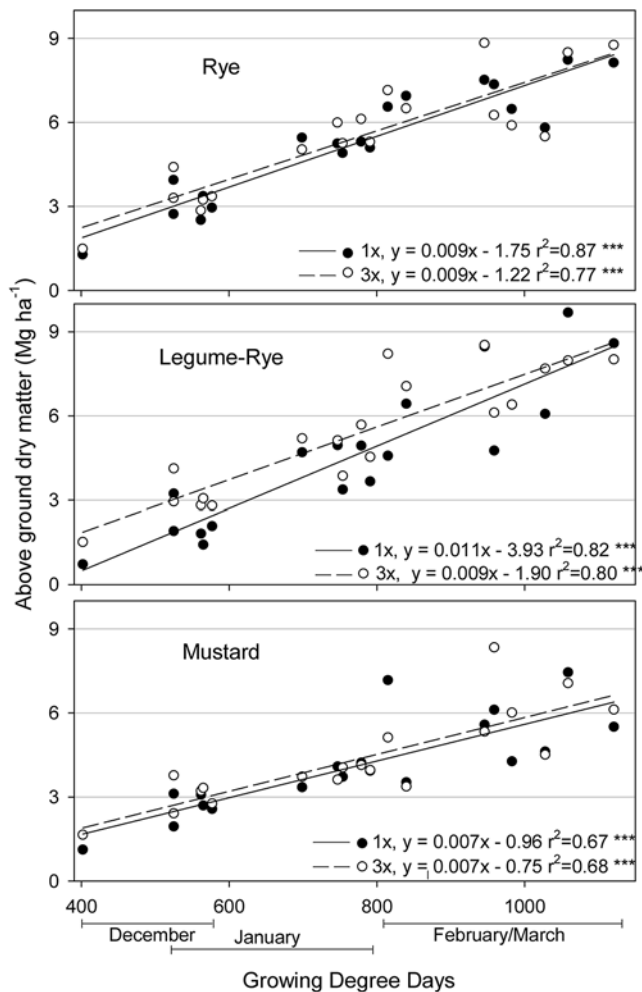


Fig. 8. Relationship between accumulated growing degree days (GDD) through the cover cropping season and shoot dry matter of rye, legume-rye, and mustard cover crops over 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA. December harvests occurred during the first 3 yr of the trial, and the January and February/March harvests occurred over all 8 yr. The horizontal lines below the x axis indicate the range of GDD for each harvest. Due to year-to-year variability in GDD accumulation, there was overlap in December and January GDD range during some years. Cover crops were planted at 1x and 3x seeding rates that in kg ha^{-1} were 90 and 270 for rye, 140 and 420 for the legume-rye mixture, and 11 and 33 for mustard. *** Indicate the significance levels of the linear regression equations at $p \leq 0.001$.

the plants in the legume-rye mixture. The greater effect of SR on the legume-rye mixture suggests that the legume-rye 1x was less efficient at capturing limited resources (light, nutrients, water) than the 1x SR of rye and mustard.

Legume and Rye Dry Matter Production in the Legume-Rye Mixture

Within the legume-rye mixture, DM of the rye and legume components was significantly affected by SR and years (Table 6). Seeding rate increased DM production of the legume and rye components in December and January, but not at season-end (Table 6, Fig. 10). Furthermore, SR had a proportionally greater effect on legume than rye DM as is well-illustrated in December, where legume DM increased by 100% (i.e., from 0.4 to 0.8 Mg ha^{-1}) compared with only a 36% increase (i.e., from

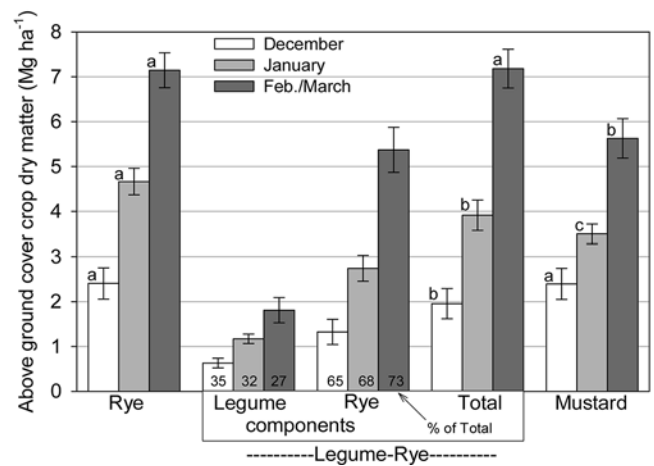


Fig. 9. Shoot cover crop dry matter (DM) during three harvests during 8 yr and averaged across two seeding rates in the Salinas Organic Cropping Systems trial at Salinas, CA; seeding rates in kg ha^{-1} were 90 and 270 for rye, 140 and 420 for the legume-rye mixture, and 11 and 33 for mustard. December harvests were during Years 1 to 3, while other harvests were all 8 yr. Bars are means \pm 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 DM are shown above the x axis. Mean total DM production in Mg ha^{-1} were rye (2.4, 4.7, 7.1), legume-rye (2.0, 3.9, 7.2), and mustard (2.3, 3.5, 5.6) for the December, January, and final harvests, respectively.

Table 6. Significance of tests of fixed effects and their interaction on legume and rye shoot dry matter of the legume-rye mixture at three harvest periods during 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA.

Effect	Harvest period					
	Dec.†		Jan.		Feb./Mar.	
	Legume	Rye	Legume	Rye	Legume	Rye
Seeding rate‡	***	*	***	*	ns§	ns
Year	*	***	***	***	***	***
Seeding rate \times year	ns	ns	ns	ns	ns	ns

* Significant at the $p \leq 0.05$ level.

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

† December harvest only occurred during the first 3 yr of the trial.

‡ Seeding rates were 140 and 420 kg ha^{-1} .

§ ns, not significant.

1.1 to 1.5 Mg ha^{-1}) in rye DM by tripling the SR (Fig. 10A, 10B). In contrast, the higher SR in monoculture rye only increased rye DM by 18% in December, presumably because the rye 1x monoculture densities (320 plants m^{-2}) were seven times higher than rye in the 1x legume-rye mixture (45 plants m^{-2}). Rye and other cereals are well-known for their ability to compensate for lower seeding densities by producing more tillers (Boyd et al., 2009), and this is most likely how rye in the mixture was remarkably able to produce more than 50% of the monoculture rye DM in December and January, and 74% of the monoculture rye DM by season end (Fig. 9, 10). The positive effect of SR on DM production of the mixture components in the present study generally

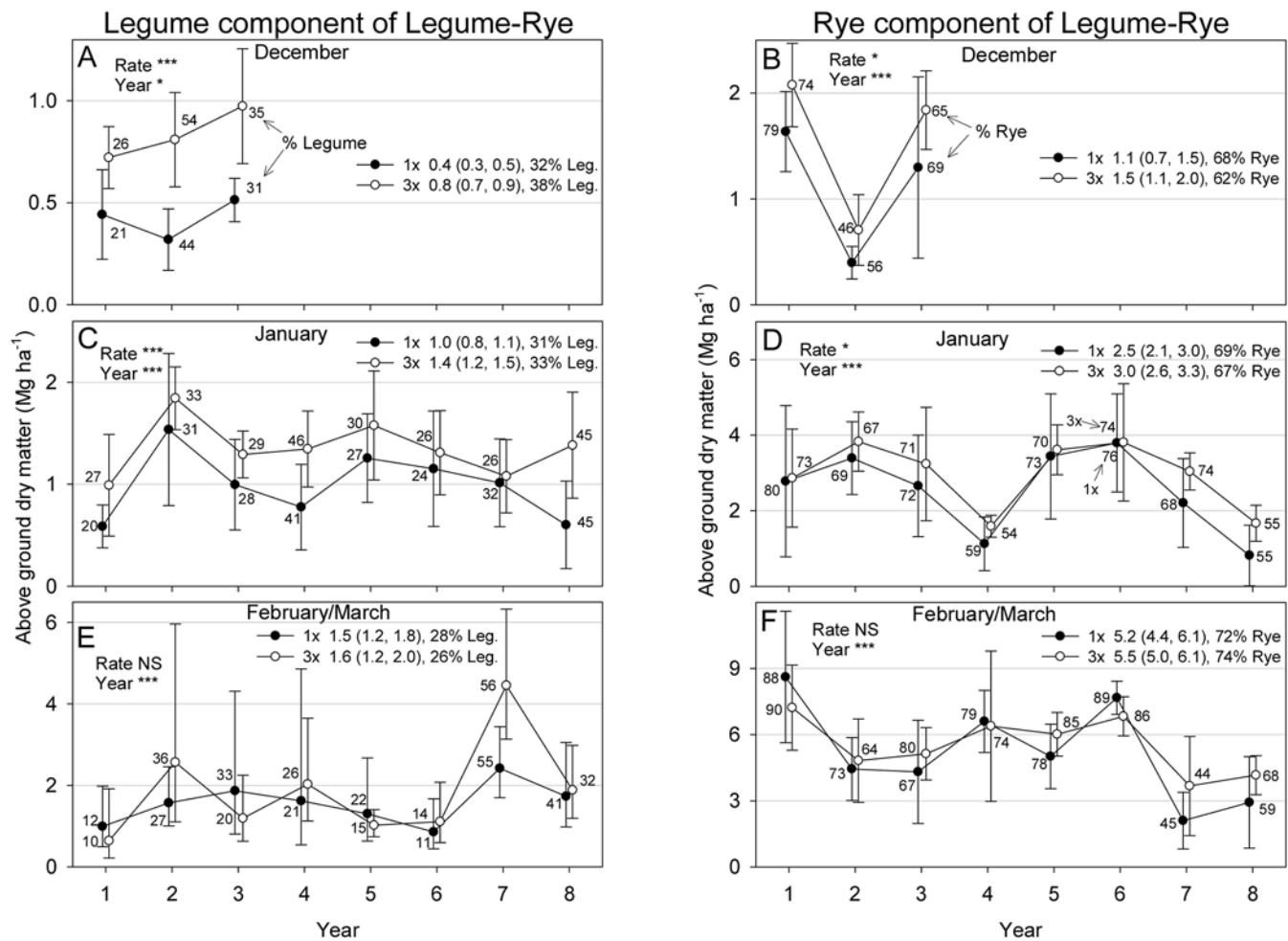


Fig. 10. Effect of seeding rate and year on shoot dry matter (DM) of the legume (A, C, E) and rye (B, D, F) components of the legume-rye mixture during three harvests over 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA. * and *** indicate the significance of the effects at the $p \leq 0.05$ and 0.001 levels, respectively; NS is not significant. Points are means or back-transformed means (legume in February/March) \pm 95% confidence intervals; means are offset to differentiate confidence intervals within year. The numbers adjacent to each point are the % legume or % rye DM of total cover crop DM. The 1x and 3x seeding rates were 140 and 420 kg ha⁻¹, respectively. The mean and 95% confidence intervals in parentheses and the percent of component DM, averaged across years, follow the seeding rate legends. Legume DM at season-end averaged across rates (1.55 Mg ha⁻¹) is slightly less than the amount shown in Fig. 9 because back-transformed means are presented here, whereas arithmetic means are presented in Fig. 9.

agree with the findings of a 2-yr study in this region with a legume-oat cover crop (Brennan et al., 2009). The effect of cover crop SR on DM production of the legume and rye components of the mixture was consistent across years in the present study as evidenced by the lack of significant SR \times year interactions (Table 6).

The amount and percentage of DM production by the legume-rye components across all harvests varied by year (Fig. 10). The amount of legume DM increased through the season, although averaged across years and SR, the percentage of the legume DM component of the legume-rye mixture declined gradually from 35% in December to 32% in January to 27% at season-end (Fig. 9). This general pattern occurred within both SR during most years although the percentage of legume DM in December was considerably higher (44–54%) during Year 2 (Fig. 10A). A markedly different pattern occurred during Year 7 where the percentage of legume DM, averaged across SR, nearly doubled from January to season-end (Fig. 10C, 10E). Year 7 also had the most legume DM production over the 8-yr period with 4.5 Mg ha⁻¹ in the 3x SR at season-end. Furthermore, the

quantity and percentage of rye DM at both SR was least during Year 7 which was the only time legume DM was the dominant component at season-end (Fig. 10E, 10F).

There was a positive exponential relationship between rye population density and the percentage of final (February/March) shoot rye DM produced by December and January in the legume-rye mixture and rye monoculture (Fig. 11). For example, rye at the highest monoculture density (854 plants m⁻²) produced 67% of its final DM by January, compared the lowest density rye component (45 plants m⁻² in the legume-rye 1x) that produced 48% of final rye DM. This illustrates the effect of rye density on the growth rate of rye in the monoculture and mixture.

Understanding the causes of the year-to-year variation in the growth of legume vs. cereal components of cover crop mixtures within and across sites has been a major weakness of short-term studies in this region (Boyd and Brennan, 2006; Brennan et al., 2009, 2011a). For example, results from a previous study suggested that more frequent rainfall and greater rainfall late in the season reduced moisture competition between legume and rye and increased legume DM in one of 2 yr (Brennan et al., 2011a).

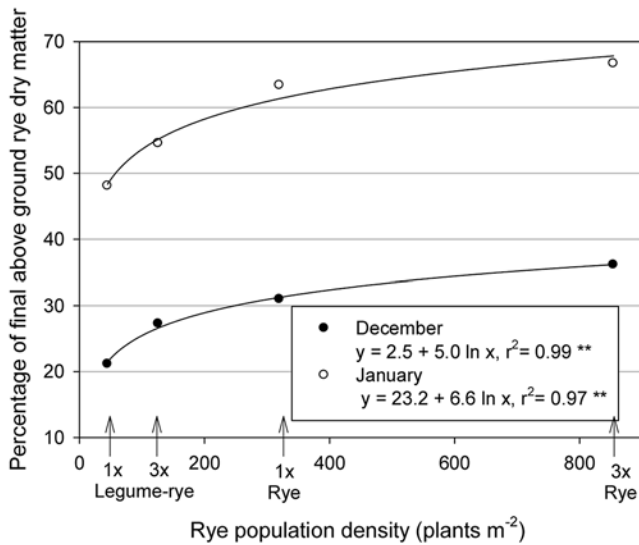


Fig. 11. Relationship between rye population density and the percentage of final (February/March) shoot rye dry matter produced by December and January in a legume-rye mixture and rye monoculture in the Salinas Organic Cropping Systems trial at Salinas, CA. The December data is averaged across 3 yr and the January data is averaged across 8 yr. Population densities were from counts made in November or December. Cover crops were planted at 1x and 3x seeding rates that in kg ha^{-1} were 140 and 420 for the legume-rye mixture and 90 and 270 for rye. ** indicates the significance of the relationship at $p \leq 0.01$.

The amount and percentage of legume DM production also tended to be lower in legume-cereal mixtures grown on higher fertility sites (Brennan et al., 2009, 2011a). The long-term data from the present study provide new insights into these dynamics and suggest that the legume vs. rye components responded differently to climatic differences between years. For example, during December of Year 2, there was a dramatic reduction in the quantity and percentage of rye DM production compared with December of Years 1 and 3 (Fig. 10B). The reduced production by rye was presumably because there were approximately 150 fewer GDD by the December harvest in Year 2 compared with Year 1 and 3 (Fig. 7A). However, legume DM levels during December of Year 2 did not show this sharp decline, suggesting that the effect of early season GDD accumulation differed by the cover crop components; competition for soil moisture between the rye and legume was not likely involved because there were relatively minimal differences in the amount of water received up to the December harvests (Year 1, 80 mm; Year 2, 92 mm; Year 3, 97 mm). The differential response of rye vs. legume DM in December during these 3 yr indicates that rye DM production was more sensitive than legume DM to lower air temperatures. Accumulated GDD during the first 30 DAP were markedly lower during Year 2 (287) than Year 1 (342) or Year 3 (325) (Fig. 1). We speculate that these early-season differences in GDD changed the competition dynamics between the legumes and rye in favor of the legume and explain why the legume DM was greater from January to season-end in Year 2 than Years 1 and 3. This reasoning is further supported by similar patterns during Years 4, 7, and 8 that also accumulated relatively few GDD during the first 30 DAP but had comparatively high percentages of legume DM during either January or season-end (Fig. 1, 10C, 10E). In contrast, during Years 1, 3, 5, and 6 where the rye component

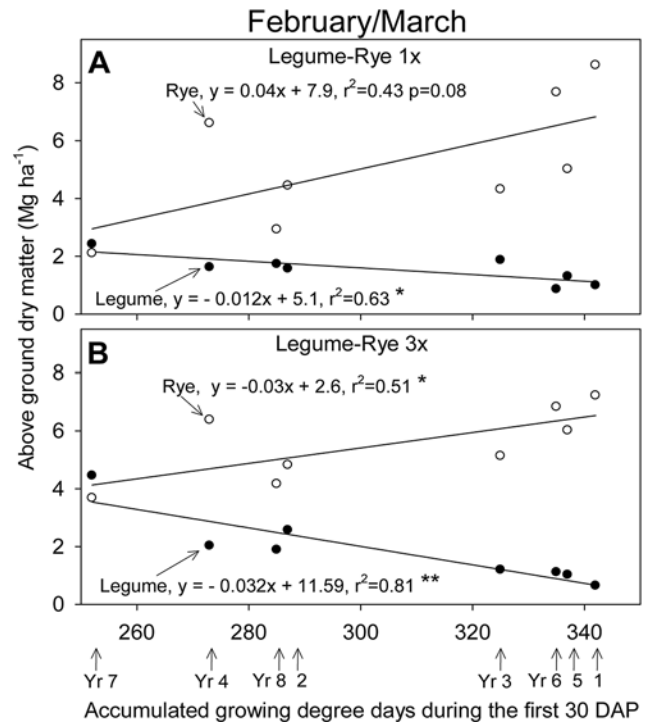


Fig. 12. Relationship between accumulated growing degree days during the first 30 days after planting (DAP) and shoot dry matter of rye and legume components in a legume-rye mixture planted at (A) 1x and (B) 3x seeding rates at season-end (February/March) over 8 yr in the Salinas Organic Cropping Systems trial at Salinas, CA. The 1x and 3x seeding rates were 140 and 420 kg ha^{-1} , respectively. * and ** indicate the significance levels of the linear regression equations at the $p \leq 0.05$ and 0.01, respectively; the p value is given for the regression equation where $0.05 > p < 0.10$. Each point is the mean of four replicates for each year and the labels with arrows below the x axis indicate year.

was more dominant at season-end, all cover crops accumulated at least 325 GDD during the first 30 DAP. The regression relationships between early season GDD and final DM production of the legume and rye components also support this reasoning (Fig. 12). This figure illustrates that for both SR, early-season GDD were negatively correlated with legume DM, but positively correlated with rye DM. We speculate that these trends were more significant in the higher SR because the higher density would cause competition between the legumes and rye earlier in the season. In addition to the early-season effect of GDD accumulation on legume DM, legume DM at season-end was highest during Year 7 (Fig. 10E) that had the most consistent rainfall during the last 60 d of the season (Fig. 1). Regression analysis revealed that for the legume-rye 3x SR, significantly more of the year-to-year variation in the season-end legume DM was explained by the model with two explanatory climatic variables (legume DM = $-0.027 \text{ GDD}_{30\text{DAP}} - 0.069 \text{ DDP}_{\text{last}60\text{d}} + 13.07$, $R^2 = 0.94$) than the single variable model (Fig. 12B, $r^2 = 0.81$). In contrast, $\text{DDP}_{\text{last}60\text{d}}$ was not a significant explanatory variable for legume DM at the 1x SR, or for the rye DM component at either SR.

The Value of Long-Term Cover Crop Systems Research

Long-term research is needed to develop practical and robust solutions to agricultural problems that help farmers develop more profitable, resilient, and ecologically-sound systems (Robertson

et al., 2008). This approach is pertinent to winter cover crops because their performance often varies considerably among years, as is shown here and in numerous studies in this region (Brennan and Smith, 2005; Brennan et al., 2009, 2011a) and elsewhere (Griffin et al., 2000; Sainju et al., 2005; Feaga et al., 2010). Furthermore, conducting long-term research in a production systems context that depends on the annual sale of crop yields to ensure research continuity, bolsters the legitimacy of the research among the local farming community and exposes researchers to the practical challenges that farmers may face if they adopted any of the systems. While short-term field studies (i.e., 2-yr) can provide useful information, they may lead to incorrect conclusions (Johnston, 1997; Drinkwater, 2002). This is clearly illustrated in the present study by comparing the results of two consecutive years vs. the results across 8 yr. For example, the January and season-end DM data for Years 7 and 8 of the SOCS trial indicate there were no differences between the three cover crops (Fig. 7B,7C). However, averaged across 8 yr, all cover crops differed in January, and mustard was the least productive at season-end (Fig. 9).

Practical Implications

Previous studies showed that early-season DM production by winter cover crops is a good indicator of their competitive ability with weeds (Brennan and Smith, 2005; Boyd et al., 2009; Brennan et al., 2009), and that reducing weed biomass in winter cover crops reduces weed seed production (Boyd and Brennan, 2006). Minimizing weed seed production in winter cover crops in this region is extremely important because many weeds occur year round and seed produced at any time may increase weed management costs in subsequent vegetable crops. The early-season DM data from the SOCS trial indicate that rye and mustard would be the most weed-suppressive cover crop at the 1x SR, and that the 3x SR would likely be most effective at improving weed suppression in the legume-rye mixture because the 3x SR produced 60% more DM than the 1x SR in December (Fig. 6A). Weed growth during the cover cropping phase of the SOCS trial and weed densities in the subsequent vegetable crops, indicated the 3x SR of the legume-rye mixture provided excellent weed suppression whereas the typical 1x SR did not (Brennan, unpublished data, 2003–2012). Based on these findings, current recommendations for legume-cereal mixtures to achieve adequate weed control are at least twice as high as the 1x SR used in the present study (Brennan et al., 2011b).

Increasing the cover crop SR by threefold increases the cost of cover cropping, but it would not triple the cost because cover crop seed typically accounts for only 20 to 30% of total cover cropping costs compared with labor costs to plant, irrigate and terminate the cover crop in high-value vegetable systems in California (Tourte et al., 2004a; Klonsky and Tourte, 2011). However, since the trial began in 2003, the seed proportion of cover cropping cost has increased dramatically. For example, from 2003 to 2010, conventional cover crop seed costs in the region increased by approximately 50% for rye and by more than 100% for many popular winter legumes such as faba bean. Increased costs for cover crop seed are even more significant for organic growers who face increasing pressure to use higher-priced, certified organic cover crop seed, when it is commercially available, rather than untreated conventionally grown seed that was previously allowable (OSA, 2011); organic cover crop seed in this region is often twice the price of conventional

seed. These changes could potentially cause organic growers to switch from the popular, yet higher priced legume-cereal mixtures that may require higher SR for adequate weed control, to lower priced nonlegume cover crops that suppress weeds adequately at lower SR. Snapp et al. (2005) highlighted biological trait differences (i.e., seed size, dispersal mechanism) between legumes and grasses that increase the seed and establishment cost legume cover crops.

Rye and the legume-rye mixture were approximately 20% more productive than mustard in terms of final shoot DM and therefore may be the best choices for vegetable growers to maximize cover crop DM production and add SOM. However, this does not account for root biomass production. Root biomass by winter cover crops in this region has only been studied for cover crops planted in 42-cm wide rows on beds and the researchers estimated that roots accounted for 10 to 28% of *Brassica* biomass, and 17% of rye biomass (Jackson et al., 1993). Studies elsewhere with SR that were more comparable to the present study, reported that roots accounted for 25 to 35% of total cover crop DM for *Brassica* spp., rye, and rye-vetch (Thorup-Kristensen, 2001; Snapp et al., 2007). Assuming that roots were 30% of total cover crop DM in the present study, we estimate that cover crop DM contributions to SOM were approximately 10Mg ha⁻¹ for the rye and legume-rye, vs. 8 Mg ha⁻¹ for mustard. Therefore all three cover crops produced more final DM than the annual 5 Mg ha⁻¹ minimum suggested for maintaining SOM (Larson et al., 1972; Rasmussen et al., 1980).

The most cost effective cover crops in terms of DM produced per seed costs were rye and mustard because they produced approximately three times more DM per unit of seed cost than the legume-rye mixture assuming 2010 seed costs (Table 1). For example, at the 1x SR, the seed cost for 1 Mg ha⁻¹ of total shoot DM at season-end was \$10 for rye, \$13 for mustard, and \$33 for the legume-rye mixture. Because the legume seed comprised 96% of the seed cost in the legume-rye mixture, the legume seed cost of 1 Mg ha⁻¹ of the legume biomass component was extremely high for both the 1x (\$145) and 3x (\$407) SR.

Planting date studies with winter cover crops have not been conducted in this region, however, 15 October is considered the optimal planting date to establish a uniform stand during the warmer period of the fall and before the onset of winter. However, the present study suggests that greater GDD accumulation during the first 30 DAP may be detrimental to the legume DM production due to increased suppression by the rye component. If this is true, growers may be able adjust planting dates for legume-cereal mixtures to avoid warmer fall temperatures that may suppress the more expensive legume component of the mixture. Furthermore, it may be possible to increase legume DM production at season-end by irrigating the cover crops, however this may be practically challenging because hand-move sprinkler pipe is usually removed earlier in the season before smothered by the cover crop, and because the typical nozzle height (60 cm) may not provide uniform irrigation in taller cover crops at season-end.

CONCLUSIONS

The first 8 yr of data from the ongoing SOCS trial provides the most comprehensive information on winter cover crop growth dynamics in California and highlights the effects of SR, and annual weather variation on rye, a mustard mixture,

and a legume–rye mixture in rotation with high-value organic vegetables. This study illustrates the value of long-term systems research that is needed to provide robust information to help organic and conventional farmers integrate cover crops into rotations. Such long-term efforts may be particularly critical to develop management scenarios that provide the most consistent benefits if climate change causes more variable weather patterns. Increasing SR from 1x to 3x resulted in approximately a 2.7-fold increase in cover crop densities, and the higher densities increased shoot DM production during December and January, but not at season-end in February or March. Seeding rate had the greatest effect on DM production of the legume–rye mixture, particularly the legume component, indicating that higher SR would be more justified with the legume–rye mixture than with the other cover crops. Year had a significant effect on DM production throughout the season and these differences were correlated by annual differences in early- and mid-season GDD accumulation. Across years and SR, mustard and rye were most productive early in the season (December) but by season-end (February/March), rye and the legume–rye were most productive. Due to the higher priced legume seed in the legume–rye mixture, rye and mustard were several times more cost-effective cover crops to maximize DM contributions to the SOM. The lack of difference in final shoot DM by the legume–rye mixture vs. rye suggests that N was not limiting in these systems and that biological N fixation by the legume component did not increase overall cover crop shoot DM production. Rye was the more dominant component of the legume–rye mixture, however, the results suggest that cooler early-season conditions and frequent season-end rainfall reduced growth of the rye but increased the percentage of legume DM. More research is needed to confirm this hypothesis and determine if growers can manipulate legume–cereal mixtures to obtain greater value from the more expensive legume seed by increasing legume DM production. Additional research is also needed to determine if legume–cereal mixtures can play a role in reducing the importation of off-farm sources of N fertilizers in high-value vegetable production systems.

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