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Comparison of Rye and Legume–Rye Cover Crop Mixtures for Vegetable Production in California

E. B. Brennan,* N. S. Boyd, R. F. Smith, and P. Foster

ABSTRACT

Rye (*Secale cereale* L.) is an important cover crop in high-value vegetable production in California. A 2-yr winter study on organic farms in Salinas and Hollister, CA evaluated cover crop population densities, ground cover, aboveground dry matter (DM), and N content of rye and five legume–rye mixtures. Mixtures had 60 or 90% legumes by seed weight and included two or more of the following legumes: faba bean (*Vicia faba* L.), vetches (*V. benghalensis* L., *V. dasycarpa* Ten., *V. sativa* L.), and pea (*Pisum sativum* L.). Seeding rates were 90 (rye) and 140 (mixtures) kg ha^{-1}, and densities were 142 to 441 plants m^{-2}. Early-season ground cover was usually greater in monoculture rye and the 60% legume mixtures than the 90% legume mixtures. Total DM, and legume and rye DM in mixtures differed by year, site, harvest, and cover crop. Total DM was usually at least two times higher at season end than mid-season. The 90% legume mixtures generally produced more legume DM than the 60% legume mixtures, but legume DM usually declined after mid-season. Rye DM increased with rye density. Total cover crop N uptake was greater in Hollister than Salinas; however, legume DM and legume N uptake were greater in Salinas. Interactions between site, year, cover crop, and harvest illustrate the complex growth dynamics of legume–rye mixtures. The 90% legume mixtures appear most suitable for vegetable production in California because they had a better balance of legume and rye DM at season end.

Winter cover cropping can help improve soil properties by adding organic matter, and scavenging and cycling nutrients (Fageria et al., 2005; Hartz, 2006). Rye is an important winter cover crop in vegetable rotations on the central coast of California, especially on conventional and large-scale organic farms. Cover crop mixtures have received less research attention than single species cover crops. Legumes are commonly included in winter cover crop mixtures in California and include erect species such as a small seed type of faba bean, and climbing species such as vetches and pea. Hairy vetch (*V. villosa* Roth) is a legume that is commonly mixed with rye in winter cover crops in other regions of the United States (Kuo and Jellum, 2002; Ruffo and Bollero, 2003; Sainju et al., 2005; Teasdale et al., 2008). Several legume–oat (*Avena sativa* L.) cover crop seed mixtures are sold extensively in California, but legume–rye seed mixtures are less common. The limited research on legume–rye mixtures in California investigated weed control with a rotary hoe (Boyd and Brennan, 2006) and a no tillage system for processing tomatoes (*Lycopersicon esculentum* Mill.) (Herrero et al., 2001). In contrast, considerable research on legume–rye cover-crop mixtures has occurred in other regions of the United States (Ranells and Wagger, 1996; Creamer et al., 1997; Griffin et al., 2000; Sainju et al., 2005; Clark et al., 2007a; Delate et al., 2008; Teasdale et al., 2008; Zotarelli et al., 2009). Basic information on aboveground DM production potential, ground cover, N content, and weed suppression in legume–rye cover crops for organic, high-value vegetable production in California is needed. To better understand the complex competition dynamics between the cover crop mixture components and develop better mixtures and seeding rate recommendations we need more information on the population densities of the mixture components.

Legume–rye mixtures combine the N fixing abilities of legumes with the N scavenging ability of rye (Ranells and Wagger, 1997). Ding et al. (2006) reported differences in the chemical and structural composition of soil organic matter in systems with a rye–hairy vetch mixture vs. rye over several years. Studies with winter cover crops incorporated into the soil before vegetable crops (Burket et al., 1997; Griffin et al., 2000) reported higher crop yields following legume–rye mixtures vs. rye. The effects of cereals vs. legume–cereal mixtures on high-value, and high-input organic vegetable systems in the central coast of California are not known.

Cover crop residue management can be a major challenge in tillage-intensive vegetable rotations and can delay planting while the residue decomposes sufficiently. Winter cover crops in the central coast of California are typically mowed and incorporated into the soil between January and April to allow time for residue decomposition and bed preparation for subsequent vegetable plantings that typically occur 4 to 6 wk after incorporation. Rosecrance et al. (2000) reported C/N of 15 in a rye–vetch mixture vs. 21 in monoculture rye, and also found net mineralization with surface applied rye–vetch residue, but net immobilization with rye residue. In a no-tillage system, the rate of N release was greater for cover crop residue from a vetch–rye mixture than rye

E.B. Brennan, USDA-ARS, 1636 East Alisal St., Salinas, CA 93905; N.S. Boyd, Dep. of Environmental Sci., P.O. Box 550, Nova Scotia Agricultural College, Truro, NS, Canada B2N5E3; R.F. Smith, Univ. of California Cooperative Extension, 1432 Abbott St., Salinas, CA 93901; P. Foster, Phil Foster Ranches, P.O. Box 249, San Juan Bautista, CA 95045. Received 2 Apr. 2010. *Corresponding author (eric.brennan@ars.usda.gov).

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Abbreviations: DM, dry matter.

Table 1. Cover crop descriptions and seed costs.

Cover crop	Mixture type	1000-seed weight†	Composition‡						Seed cost§	
			Faba bean	Pea	Com. vetch	Purp. vetch	Wollyp. vetch	Rye		
		g	%						$ kg^{-1}¶	$ ha^{-1}
Mix 1	90% legume: 10% rye	76.0, 65.2	35	25	15	15	–	10	1.35 (1.27)	189
Mix 2	90% legume: 10% rye	36.7, 30.0	–	–	45	45	–	10	1.67 (1.59)	234
Mix 3	90% legume: 10% rye	56.3, 47.3	23	17	10	10	30	10	1.59 (1.50)	223
Mix 4	60% legume: 40% rye	41.8, 32.9	23	17	10	10	–	40	1.20 (0.84)	167
Mix 5	60% legume: 40% rye	36.2, 23.6	–	–	30	30	–	40	1.41 (1.06)	197
Rye								100	0.88	79

† 1000-seed weight of each mixture for Year 1 (2003–2004) and 2 (2004–2005), respectively. 1000-seed weights of mixture components for Year 1 and Year 2, respectively, are in parentheses. Rye, *Secale cereale* 'Merced' (22.0, 16.5); Common (Com.) vetch, *Vicia sativa* (54.3, 54.8); Purple (Purp.) vetch, *Vicia benghalensis*, (37.9, 32.2);Woolypod (Woolyp.) vetch, *Vicia dasycarpa* 'Lana' (40.1, 33.8); Faba bean, *Vicia faba*, small-seeded type known as 'bell bean' (417.4, 436.0); Pea, *Pisum sativum* 'Magnus', (238.7, 231).

‡ Percent by seed weight.

§ Costs ($ kg^{-1}) of mixture components in March 2009 were: *S. cereale* (0.44), *V. sativa* (0.70), *V. benghalensis* (0.90), *V. dasycarpa* (1.00), *V. faba* (0.57), *P. sativum* (0.54). Seed costs per ha were based on seeding rates of 140 kg ha^{-1} for mixtures and the sole rye at 90 kg ha^{-1}.

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

monoculture (Ranells and Wagger, 1996). Crop residue decomposition rates increase with tillage (Burgess et al., 2002). Thus, we expect that in the tillage-intensive systems in the central coast of California it may be easier to prepare fields for vegetable production following a legume–rye mixture than rye monoculture because the legume–rye residue would decompose more rapidly. To achieve a lower C/N in a legume–rye mixture, the legume component needs to compete effectively with rye and produce adequate legume biomass at season end when it is incorporated into the soil. However, it is not known whether farmers could save time during field preparation for subsequent vegetable production following a cover crop with a high vs. low C/N.

Weed suppression in winter cover crops in this region is important, because many weed species occur year round and the seed they produce during cover cropping will likely increase weed management costs in subsequent vegetable crops. Previous studies with winter cover crops in California reported that weed suppression is influenced by ground cover and that cover crops that closed their canopy early in the season were better at suppressing weeds (Brennan and Smith, 2005; Boyd et al., 2009).

In our study, we compared a winter cover crop of rye and five legume–rye mixtures on two certified organic farms. The mixtures were designed based on commercially available legume–oat mixtures in California that typically contain between 60 and 90% legumes by seed weight. The mixtures also differed in the proportion of larger seeded legumes (i.e., faba bean and pea), vs. smaller seeded vetch species. Our objectives were to evaluate (i) cover crop population densities, (ii) early-season cover crop ground cover, (iii) DM production of the total cover crop and of the rye and legume components at mid-season and season end, and (iv) C and N content of the cover crop at season end before soil incorporation.

MATERIALS AND METHODS

The study was conducted during two consecutive winters (November–April) from 2003 to 2005 on certified organic sites in Hollister (36°50′ N, –121°18′ W) and Salinas (36°37′ N, –121°32′ W), CA. Year 1 refers to the winter of 2003 to 2004, and Year 2 refers to the winter of 2004 to 2005. The Hollister site is a diversified organic vegetable and fruit farm and the soil is a Clear Lake clay (fine, smectitic, thermic Xeric Endoaquerts). The Salinas site is the USDA-ARS organic research farm and the soil is a Chualar loamy sand (fine-loamy, mixed, superactive, thermic Typic Argixerol). The study was conducted on different fields at each site each winter. Bulb onions (*Allium cepa* L.) and cucurbits [melons (*Cucumus melo* L.) and squash (*Cucurbita* sp.)] were grown in 2003 and 2004, respectively, before the research at Hollister. Buckwheat (*Fagapyrum esculentum* Moench) cover crop and baby leaf spinach (*Spinacia oleracea* L.) were grown in 2003 and 2004, respectively, before the research at Salinas.

A randomized complete block design with four blocks was used at each site. Six cover crops were evaluated including 'Merced' rye (*Secale cereale* L.) and five legume–rye mixtures. The legumes in the mixtures included the small seed type of faba bean that is often referred to as 'bell bean', 'Magnus' pea (*Pisum sativum* L.), common vetch, 'Lana' woolypod vetch, and purple vetch. All seed were obtained from L.A. Hearne Company (King City, CA). The composition of the mixtures and the 1000-seed weights (g) of the mixtures and the components are listed in Table 1; 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. By seed weight, Mix 1, 2, and 3 contained 90% legumes and 10% rye, and are referred to as 90% legume mixtures. Mix 4 and 5 contained 60% legumes and 40% rye, and are referred to as the 60% legume mixtures. The mixtures can also be categorized by legume type, whereby Mix 1, 3, and 4 contained erect (faba bean) and climbing legumes (peas and vetches), whereas Mix 2 and 5 had only vetches. The plots were 2.1 m wide by 15 m long and included 14 rows at 15-cm spacing. Field preparation before cover crop seeding included disc harrowing (John Deere, Moline, IL; Case IH, Racine, WI), spring tooth harrowing (Case IH, Racine, WI), and ring rolling (T.G. Schmeiser Co., Inc., Fresno, CA) as necessary. Cover crops were planted with a 4.6 m wide grain drill Model 1500 (Great Plains Mfg., Salina, KS) in a single pass over each plot. 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 seeding rate in small plots. Two treatment plots were planted simultaneously with the drill with each pair of cones distributing seed over the 14 rows in each plot. Seed for each cover crop mixture was prepared by separately weighing the required proportions needed for the area covered by each cone in each treatment plot of each replicate and were then combined for planting in a single pass at a seeding rate of 140 kg ha^{-1}. This procedure mimicked how cover crop mixtures are planted in a single pass in this region and ensured that all mixture components were evenly distributed in each plot; cover crop seed mixtures in California are planted typically using a grain drill with a single planter box. Rye was seeded at 90 kg ha^{-1}. The legume cover crop seed was inoculated with Rhizo Stick *Rhizobium* innoculant (Urbana Laboratories, St. Joseph, MO). Planting dates were 3 and 8 November in Hollister, and 4 and 9 November in Salinas in 2003 and 2004, respectively. Sprinkler irrigation was used during the week following seeding to stimulate germination at both sites before the onset of winter rainfall. To extend the growth period of the cover crop by a few weeks, 0.6 cm of sprinkler irrigation was also applied on 17 March of Year 2 in Salinas.

Cover crop population density was determined by counting the number of individual cover crop plants in three rows in two 50- by 50-cm quadrats at 24 and 29 days after planting (DAP) in Hollister, and at 22 and 27 DAP in Salinas in Year 1 and 2, respectively. Ground cover by the cover crops was measured by holding a 30- by 30-cm quadrat by hand with 64 cross grids approximately 50 cm above the ground and counting the number of grid crosses directly above cover crop vegetation at 42, 57, and 70 DAP (Hollister) and at 43, 57, and 70 DAP (Salinas) in Year 1, and at 35, 66, and 80 DAP (Hollister), and at 35, 64, and 77 DAP (Salinas) in Year 2. Two quadrats were counted at each date and the average of these values were converted to percent ground cover. Mid-season, aboveground DM of cover crops was determined by harvesting one 50- by 50-cm quadrat from each plot covering three rows at 86 to 87 DAP, and 84 to 85 DAP in Hollister, and 83 to 87 DAP, and 85 to 86 DAP in Salinas, in Year 1 and 2, respectively. Aboveground DM of cover crops at season end was determined by harvesting two 1-m rows of cover crops from each plot at 147 DAP and 150 to 154 DAP in Hollister, and three 1-m rows at 140 to 141 DAP, and 141 to 142 DAP in Salinas, in Year 1 and 2, respectively. There was no evidence of greater variability of season end DM in Hollister due to the smaller sampling area. Cover crop DM in the mixtures was separated into legume and rye components for each harvest. To minimize edge effects, DM harvests always occurred at least three rows (45 cm) from the edge of each plot. Season end harvests occurred after cover crop flowering began, but before viable cover crop seed production; this is the typical stage that cover crops are terminated in the central coast of California. Cover crop DM was oven-dried at 65°C for at least 48 h. Legume and rye DM samples from season end were ground to pass through a 0.250-mm screen and a 10-mg subsample was analyzed with a combustion gas analyzer method for total C and N at the Agriculture and Natural Resources Analytical Laboratory at the University of California (http://groups.ucanr.org/danranlab/Plant_Analysis_2/520.htm). The reported concentrations of C and N from the laboratory analyses are on a 100% DM basis from drying samples to 105°C. However, to calculate kg N ha^{-1} the N concentration was adjusted, because the DM values reported here are based on 93% DM of the samples dried at 65°C.

Statistical Analysis

All data were analyzed using SAS ver. 9.2 (SAS Inst. Cary, NC) with the MIXED procedure. The 95% confidence intervals (CI) of the cover crop population densities and total cover crop DM were calculated using the MEANS procedure with the CLM option. Analyses of total cover crop density and cover crop ground cover indicated significant year, site, and cover crop interactions; therefore, separate analyses were performed for each year and site. The ground cover analyses were only conducted on the earliest ground measurements taken at 35 to 43 DAP. The site, year, harvest, and cover crop were treated as fixed effects and block (site), cover crop × block (site), and year × cover crop block (site) were treated as random effects. These data were analyzed as a split-split plot in a randomized complete block design, where years and harvests were the main plots and subplots, respectively. Where necessary, data were transformed to meet the assumptions of ANOVA, but back-transformed means are presented; natural log transformations were used for total cover crop DM, total cover crop density, and N uptake by total cover crop DM, rye DM, and legume DM. A square root transformation was used for legume and rye DM. Pairwise comparisons among cover crops were controlled at the experimental error rate of $p \le 0.05$ with a Bonferroni correction. SAS/INSIGHT and SigmaPlot (version 11.0) software were used to fit the polynomial response curves of rye DM to rye density.

RESULTS AND DISCUSSION

Climate

Winter rainfall was greater in Year 2 than Year 1 at both sites although this was most apparent in Salinas (Fig. 1). Cumulative monthly winter rainfall in this region often peaks at approximately 85 mm in January, but was less than half of this amount in Year 1. Precipitation was below the 13-yr average at both sites in Year 1 and also in Year 2 in Hollister. March was markedly drier and warmer at both sites during Year 1 than 2. Variability in rainfall and temperatures between years may have contributed to the seasonal differences in cover crop growth.

Cover Crop Population Densities

There were significant differences in total cover crop densities between cover crops and years, and significant two-way interactions (site × year, site × cover crop, year × cover crop) (Table 2, Fig. 2). The significant site × year interaction occurred because total densities were higher in Hollister (242 plants m^{-2}) than Salinas (211 plants m^{-2}) in Year 1, whereas these densities were higher in Salinas (308 plants m^{-2}) than Hollister (285 plants m^{-2}) in Year 2. There was a significant site × cover crop interaction, due to higher differences between cover crops in Salinas than Hollister (Fig. 2A). For example, the density of Mix 3 and 4 did not differ in Hollister, whereas Mix 3 had a lower density than Mix 4 in Salinas. The factors affecting the emergence of some cover crops were not investigated, but could be due to differences in climatic or soil conditions, or pests between sites.

The significant effect of year on cover crop densities was due to differences in the 1000 seed weight of the cover crop components and resulting mixtures between years. For example, the 1000 seed weights of most components (rye, purple vetch, wooly pod vetch, and pea) were higher in Year 1, compared with faba bean that was higher in Year 2, and common vetch that differed little between years. The year × cover crop interaction (Fig. 2B) occurred because despite the 1000 seed weight differences of some components between years, the mixtures were based on fixed percentages of seed by weight, as is typical for commercially

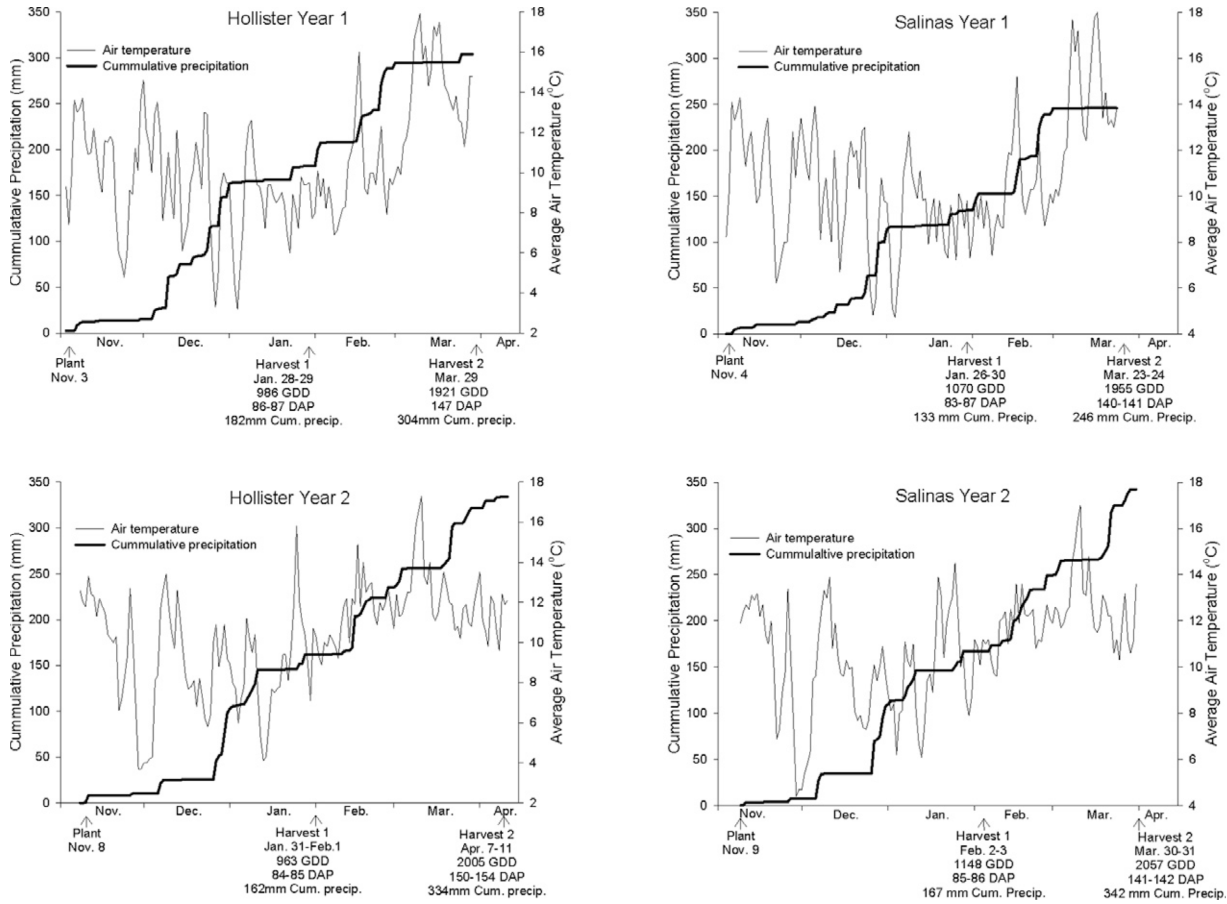

Fig. 1. Cumulative precipitation, air temperature, and growing degree days (GDD) from data from the California Irrigation Management Information System (CIMIS) (http://wwwcimis.water.ca.gov) in Year 1 (2003–2004) and Year 2 (2004–2005) at Hollister (CIMIS station no. 126) and Salinas (CIMIS station no. 89). The 13-yr average rainfall between November and April (1993–2007) was 395 mm (Hollister) and 346 mm (Salinas). 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).

Table 2. Significance of tests of fixed effects and interactions on total cover crop density, cover crop ground cover, and aboveground dry matter (DM) of total cover crop (rye + legume), rye and legume in Salinas and Hollister, CA.

Effect	Total cover crop density†	Cover crop ground cover ‡	DM type		
			Rye + legume	Rye	Legume
Site	ns§	***	***	***	***
Year	***	***	***	ns	***
Cover crop	***	***	**	***	***
Harvest¶	–	–	***	***	*
Site × year	**	***	***	***	**
Site × harvest	–	–	***	***	***
Year × harvest	–	–	***	***	***
Site × cover crop	*	***	ns	ns	ns
Year × cover crop	**	ns	**	***	**
Cover crop × harvest	–	–	*	ns	***
Site × year × cover crop	ns	***	***	*	ns
Site × year × harvest	–	–	ns	**	ns
Site × cover crop × harvest	–	–	ns	ns	ns
Year × cover crop × harvest	–	–	**	ns	ns
Site × year × cover crop × harvest	–	–	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.

† Cover crop densities were determined at 22 to 29 days after planting (DAP).

‡ Cover crop ground cover was measured at 35 to 80 DAP; however, the statistical analysis of ground cover was conducted only on ground cover from 35 to 43 DAP.

§ ns, not significant.

¶ Mid-season harvest was at 28–29 Jan. 2004, (86–87 days after planting, DAP), and Jan 31 Jan.–1 Feb. 2005 (84–85 DAP), in Hollister, and 26–30 Jan. 2004 (83–87 DAP), and 2–3 Feb. 2005 (85–86 DAP) in Salinas. Season end harvests were at 29 Mar. 2004 (147 DAP), and 7–11 May 2005 (150–154 DAP) in Hollister, and at 23–24 Mar. 2004 (140–141 DAP), and 30–31 Mar. 2005 (141–142 DAP) in Salinas.

available mixtures in California. As a result, the relative number of seed of each component within each mixture varied between years. The effect of the 1000 seed weight on cover crop densities between years was most apparent with monoculture rye and Mixtures 4 and 5 that contained more rye seed (Fig. 2B). This illustrates the problem with basing cover crop mixture composition on fixed percentages of component by seed weight, without considering potential differences in the 1000 seed weight between years. Using the fixed percentage of each component by seed weight may be the most convenient way to create a mixture; however, to minimize year to year variation it would be preferable to vary the percentage of seed of each mixture component to achieve optimal population densities of each component based on the 1000 seed weight, germination rate, and expected emergence. This approach would be consistent with planting recommendations for single species agronomic crops where seeding rates are varied to achieve an optimal plant population density.

Total cover crop densities ranged from 145 to 322 m^{-2} in Year 1, and 142 to 441 m^{-2} in Year 2, were lowest in Mix 1 and highest in Mix 5 and monoculture rye (Table 3). The type of legume used in each mixture had a significant effect on total density and tended to be highest in Mix 2 and 5 which contained more vetch. Due to the differences between years in the 1000 seed weights (especially of rye), total population densities were often higher in Year 2 (Table 3, Fig. 2B). The density differences between years were most apparent with monoculture rye and Mix 4 and 5 that contained 40% rye seed, than in Mix 1, 2, and 3 that contained 10% rye seed. For example in Salinas, the rye density of Mix 1 differed only by 19 plants m^{-2} compared with 92 plants m^{-2} in Mix 4 and 170 plants m^{-2} in monoculture rye between years (Table 3). As expected, average rye densities across years and sites in 60% legume mixtures were approximately four times higher (202 plants m^{-2}) than in the 90% legume mixtures (50 plants m^{-2}). As a percentage of planted seed, total cover crop emergence across sites was 69% for both years. Averaged across sites and cover crops, emergence of the cover crop components was 88 and 75% for faba bean, 86 and 73% for pea, 69 and 68% for vetch, and 67 and 68% for rye, in Year 1 and 2, respectively. Legume densities as a percentage of total cover crop densities ranged from 59 to 87% in the 90% legume mixtures, compared with 19 to 55% in the 60% legume mixtures.

Relative to the mean, the legume population densities were more variable for larger seeded legumes (faba bean and peas) than the smaller seeded and more numerous vetches. For example during Year 1 in Salinas, Mix 1 had a mean of 9 and 95% CI of 9 faba bean plants m^{-2}, whereas vetches had a mean of 71 and 95% CI of 13 plants m^{-2} (Table 3). Thus vetch plant density was more consistent than faba bean plant density in Mix 1. It is not known how the spatial variability of mixture components affects their growth or ability to suppress weeds. Increasing spatial uniformity by planting wheat in two perpendicular passes improved yield and weed suppression (Weiner et al., 2001), but research in California found no consistent differences in yield or weed suppression in cover crops of rye, or a legume–oat mixture planted in two perpendicular passes (Boyd et al., 2009; Brennan et al., 2009).

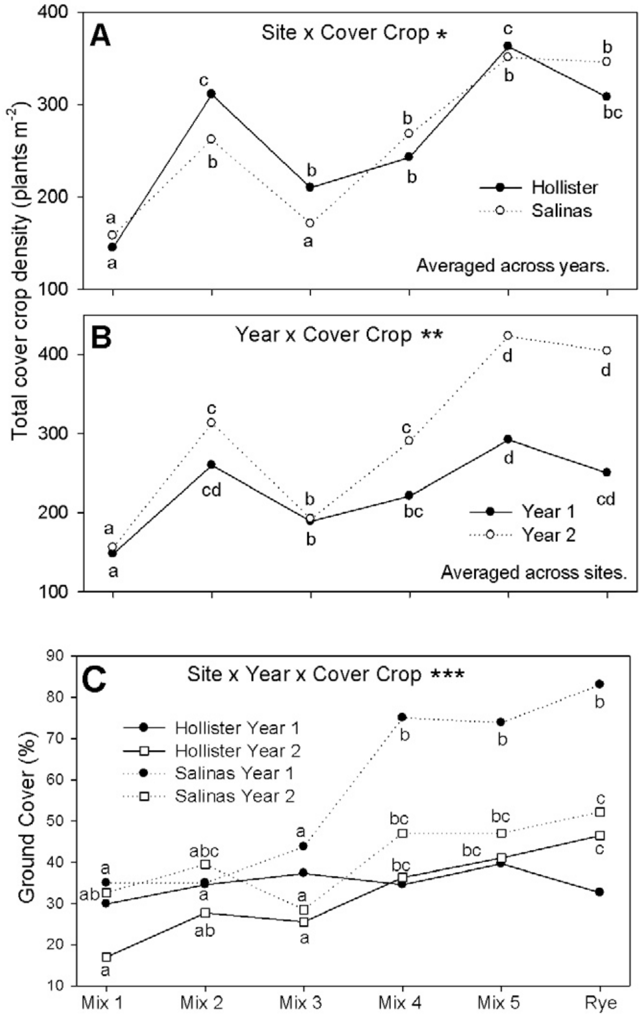

Fig. 2. Significant interaction plots of site × cover crop and year × cover crop for total cover crop densities (A, B), and site year × cover crop for ground cover (C) of five legume–rye mixtures and rye in Hollister and Salinas, CA during 2 yr. Densities were determined at 22 to 29 d after planting (DAP) and ground cover was determined at 35 to 43 DAP. The significance level of each interaction is shown next to title where *, **, and * are significant at the $p \leq 0.05$, 0.01, and 0.001 levels, respectively. Within each plot, least square means adjacent to symbols within a line that have different lowercase letters are significantly different at an experiment-wise error rate of $p \leq 0.05$ based on a Bonferroni correction; significance letters are only shown for lines with significant differences. By seed weight, Mix 1, 2, 3 contained 90% legume seed and Mix 4 and 5 contained 60% legume seed. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), Mix 3 (23% F, 17% P, 10% CV, 10% PV, 30% WV, 10% R), Mix 4 (23% F, 17% P, 10% CV, 10% PV, 40% R), and Mix 5 (30% CV, 30% PV, 40% R).**

Percent Ground Cover

Ground cover at 35 to 43 DAP was significantly affected by site, year, and cover crop, and all interactions were significant except year × cover crop (Table 2). The site × year × cover crop interaction (Fig. 2C) illustrates that the early season ground cover by the cover crops was more consistent across years in Salinas than in Hollister. For example, ground cover was usually greater in rye and the 60% legume mixtures than in the 90% legume mixtures in Salinas; however, this pattern only occurred during Year 2 in Hollister. Furthermore, the site × cover crop interaction is also

Table 3. Population densities of cover crop components, total cover crop, and legumes in five legume–rye cover crop mixtures and rye at Salinas and Hollister, CA, during Year 1 (2003–2004) and Year 2 (2004–2005).

Cover crop‡	Cover crop component (plants m^{-2})†					Leg. density, %¶
	Faba bean	Pea	Vetches	Rye	Total§	
			Hollister			
			Year 1			
Mix 1	10 ± 7#	12 ± 12	71 ± 30	56 ± 35	145 ± 46b	64
Mix 2	–	–	258 ± 43	48 ± 14	305 ± 46a	85
Mix 3	9 ± 4	12 ± 9	141 ± 90	56 ± 15	212 ± 72ab	77
Mix 4	8 ± 8	4 ± 7	29 ± 27	181 ± 53	218 ± 64ab	19
Mix 5	–	–	155 ± 18	167 ± 14	322 ± 12a	48
Rye	–	–		239 ± 64	236 ± 59a	0
			Year 2			
Mix 1	5 ± 8	14 ± 7	72 ± 23	52 ± 26	142 ± 39e	63
Mix 2	–	–	272 ± 45	45 ± 19	317 ± 63bc	86
Mix 3	8 ± 4	9 ± 8	147 ± 29	40 ± 21	203 ± 38de	81
Mix 4	6 ± 9	5 ± 3	43 ± 23	211 ± 32	264 ± 31cd	20
Mix 5	–	–	164 ± 32	242 ± 41	405 ± 55a	40
Rye	–	–		377 ± 62	377 ± 62ab	0
			Salinas			
			Year 1			
Mix 1	9 ± 9	17 ± 5	71 ± 13	50 ± 33	145 ± 37b	67
Mix 2	–	–	183 ± 64	32 ± 13	211 ± 59ab	87
Mix 3	8 ± 9	4 ± 6	110 ± 7	39 ± 34	159 ± 36b	76
Mix 4	4 ± 6	12 ± 7	45 ± 18	160 ± 76	215 ± 74ab	28
Mix 5	–	–	143 ± 34	119 ± 26	261 ± 38a	55
Rye	–	–	–	261 ± 110	254 ± 89 a	0
			Year 2			
Mix 1	9 ± 2	13 ± 11	78 ± 16	69 ± 29	169 ± 49c	59
Mix 2	–	–	243 ± 34	66 ± 22	309 ± 50b	79
Mix 3	7 ± 9	5 ± 5	119 ± 37	51 ± 22	181 ± 64c	72
Mix 4	5 ± 5	9 ± 8	50 ± 18	252 ± 125	315 ± 143b	20
Mix 5	–	–	160 ± 26	281 ± 57	441 ± 79a	36
Rye	–	–	–	431 ± 37	431 ± 37a	0

† Faba bean (*Vicia faba*), pea (*Pisum sativum*), vetches (Common vetch, *V. sativa*; Purple vetch, *V. benghalensis*; Wollypod vetch, *V. dasycarpa*) and rye (*Secale cereale*).

‡ By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R):
Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R),
Mix 2 (45% CV, 45% PV, 10% R),
Mix 3 (23% F, 17% P, 10% CV, 10% PV, 30% WV, 10% R),
Mix 4 (23% F, 17% P, 10% CV, 10% PV, 40% R),
Mix 5 (30% CV, 30% PV, 40% R).

§ With site, and year, total densities followed by different lowercase letters are significantly different at $p \leq 0.05$, based on a Tukey–Kramer experiment-wise error rate. Total densities in Year 1 may not equal the sum of the individual components within each cover crop because the total densities are back transformed means.

¶ Percentage of legume density of total cover crop density.

Expected densities assuming 100% emergence and based on 1000 seed weight and percentage of faba bean (F), pea (P), vetches (V), rye (*R*), and total (T) in Year 1 and 2, respectively, were:
Mix 1 (12F, 15P, 94V, 64R, 185T and 11F, 15P, 104V, 85R, 215T),
Mix 2 (324V, 64R, 388T, and 383V, 85R, 468T),
Mix 3 (8F, 10P, 168V, 64R, 250T, and 7F, 10P, 194V, 85R, 296T),
Mix 4 (8F, 10P, 63V, 255R, 336T, and 7F, 10P, 69V, 340R, 426T),
Mix 5 (216V, 255R, 471T and 256V, 340R, 596T),
Rye (409T, and 545T).

Means ± 95% confidence intervals determined with the CI option in the MEANS procedure.

evident in Fig. 2C with the greater differences by the 60% legume mixtures and rye vs. the 90% legume mixtures in Salinas than in Hollister. The significant site × year interaction occurred because ground cover at 35 to 43 DAP averaged across cover crops did not differ between years in Hollister (32–35%), but was greater during Year 1 (58%) than Year 2 (41%) in Salinas.

Ground cover provided by the cover crops increased rapidly during the first 60 DAP and usually reached 100% by 80 DAP (Fig. 3). Averaged across cover crops, early-season ground cover was greater in Salinas than Hollister, and was also greater during Year 1 than 2 (Fig. 2C), probably because fall temperatures were higher in Salinas than Hollister and were also higher during Year 1 than 2 (Fig. 1). Averaged across sites and years, ground cover between 35 and 43 DAP was in order of rye (54%) = Mix 5 (50%) = Mix 4 (48%) > Mix 3 (34%) = Mix 2 (34%) = Mix 1 (29%). This ranking also usually occurred within sites and years with exception Hollister during Year 1, when ground cover did not differ significantly. These trends indicate that early-season

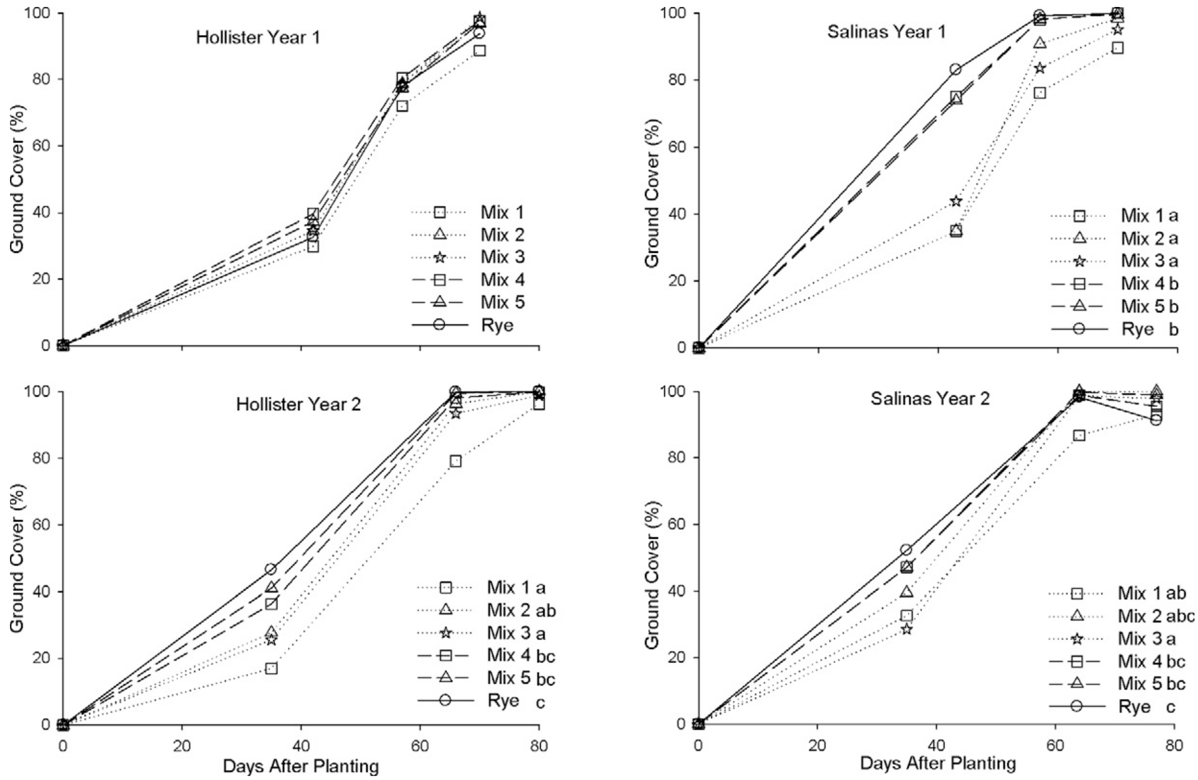

Fig. 3. Mean percentage of ground cover by five legume–rye cover crop mixtures and rye cover crop at three dates in Hollister and Salinas, CA during Year 1 (2003–2004) and Year 2 (2004–2005). Within each site and year, crops with significantly different ground cover at this date have different letter following the cover crop label within each year with an experiment-wise error rate of $p \leq 0.05$ based on a Bonferroni correction; significance letters are not listed for Hollister Year 1 because there were no differences. By seed weight, mixtures with 90% legumes have dotted lines, mixtures with 60% legumes have dashed lines, and monoculture rye has a solid line. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), Mix 3 (23% F, 17% P, 10% CV, 10% PV, 30% WV, 10% R), Mix 4 (23% F, 17% P, 10% CV, 10% PV, 40% R), and Mix 5 (30% CV, 30% PV, 40% R).

ground cover increased with rye density and suggests that weed suppression would be in order of rye >60% legume mixtures >90% legume mixtures. We would also expect that within the 90% legume mixtures, weed growth would be greatest in Mix 1 which often had the least canopy closure.

Comparisons of the year x cover crop interaction for cover crop density (Fig. 2B) and the significant year effect for cover crop ground cover indicates that ground cover was not affected by differences between years and sites in cover crop density. For example, total cover crop densities were higher during Year 2 than 1; however, cover crop ground cover was higher during Year 1 than 2. Furthermore within the 90% legume mixtures (Mixes 1, 2, 3), ground cover often increased as the density of small seeded legumes (vetches) increased, although this was never significant.

Total Cover Crop Dry Matter Production

Total DM production (rye + legume) of cover crops at season end ranged from 8.1 to 14.6 Mg ha^{-1} and 4.7 to 9.3 Mg at Hollister and Salinas, respectively (Fig. 4), and were similar to previous reports of winter cover crops at these sites (Brennan and Smith, 2005; Boyd and Brennan, 2006; Boyd et al., 2009; Brennan et al., 2009). For example, a legume–oat mixture produced total DM of 5 to 12 Mg ha^{-1} in Hollister and 5 to 9 Mg ha^{-1} in Salinas during the same period (Brennan et al., 2009). These yields at season end were considerably higher than those reported for rye or legume–rye mixtures in other regions of the United States which were usually below 6 Mg ha^{-1} (Ranells and Wagger, 1996; Griffin et al., 2000; Kuo and Jellum, 2002; Ruffo and Bollero, 2003; Sainju et al., 2005), but occasionally >6 Mg ha^{-1} (Teasdale and Abdul-Baki, 1998; Clark et al., 2007b; Teasdale et al., 2008).

Significant two- and three-way interactions were observed for total cover crop DM (Table 2). Averaged across harvests, total DM did not differ between cover crops in Salinas either year or in Hollister during Year 1, however, rye and Mix 5 produced more DM than Mixes 1 and 3 during Year 2 in Hollister, which explains the significant site × year × cover crop interaction (Fig. 5A). There was a significant year × cover crop × harvest interaction because total DM did not differ between cover crops, except at mid-season in Year 2 when Mixes 2, 4, 5, and rye produced more total DM than Mixes 1 and 3 (Fig. 5B); this figure also shows the year × harvest interaction where DM increased more from mid-season to season end during Year 1 than Year 2. Total cover crop DM from Year 1 to 2 increased in Hollister, but decreased in Salinas which explains the site × year interaction (Fig. 5A). Averaged across years and cover crops, total cover crop DM from mid-season to season end increased from 3.6 to 10.1 Mg ha in Hollister, compared with 3.2 to 6.8 in Salinas which explains the significant site × harvest interaction. The lower total DM production by Mix 1 compared with the other cover crops at mid-season averaged across years and sites, and averaged across sites and harvests during Year 2, explains the significant cover crop × harvest and cover crop × year interactions.

There were significant differences in total cover crop DM production between sites, years, cover crops, and harvests (Table 2).

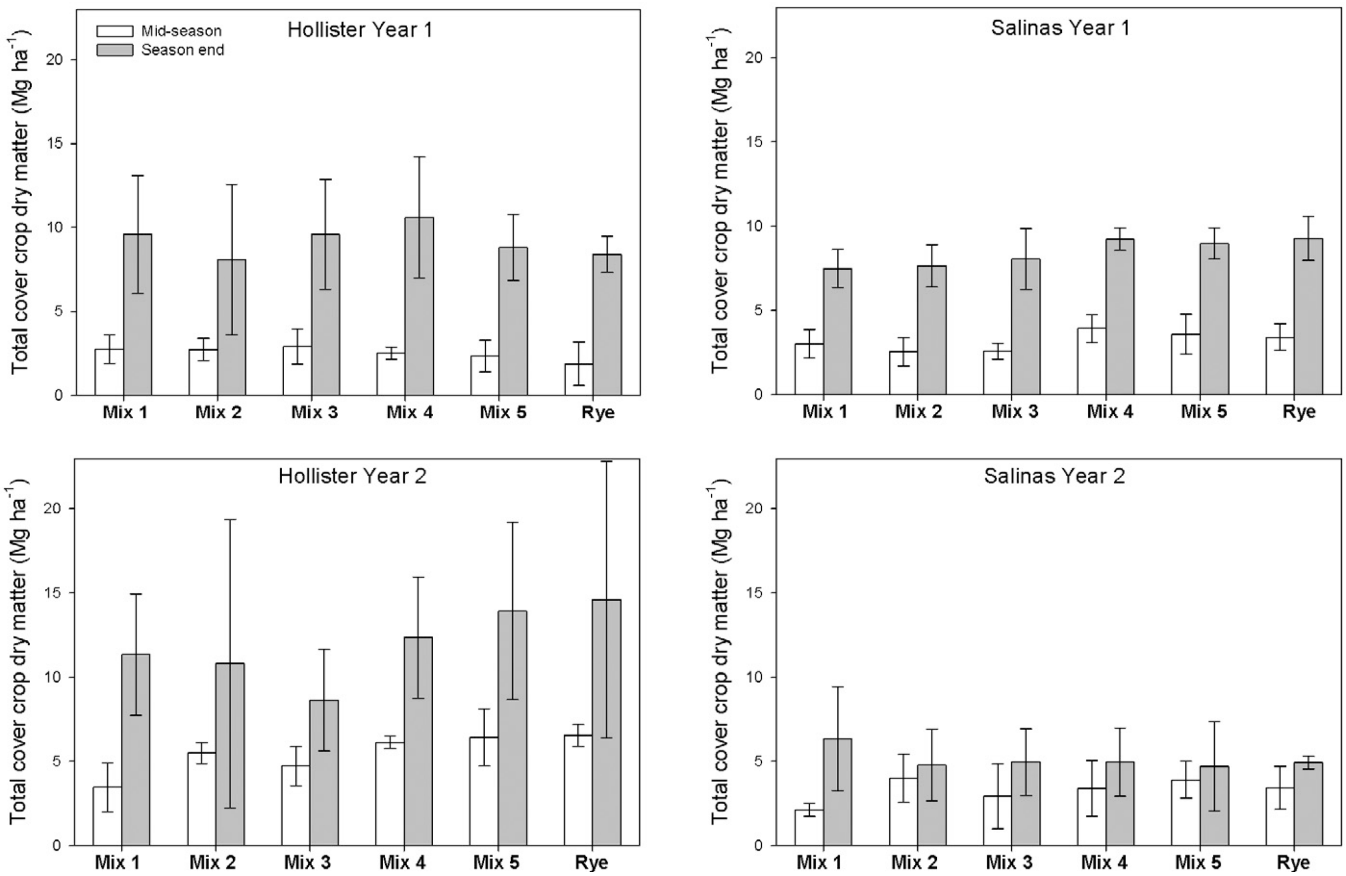

Fig. 4. Total aboveground cover crop dry matter (DM) of five legume–rye cover crop mixtures and rye at mid-season and season end during Year 1 (2003–2004) and Year 2 (2004–2005) in Hollister and Salinas, CA. The mid-season harvests occurred at 84 to 85 d after planting (DAP), and 84 to 85 DAP in Hollister, and at 83 to 87 DAP, and 85 to 86 DAP in Salinas, in Year 1 and 2, respectively. Season end harvests occurred at 147 DAP, and 150 to 154 DAP in Hollister, and at 140 to 141 DAP, and 141 to 142 DAP in Salinas, in Year 1 and 2, respectively. Bars are mean ± 95% confidence intervals. By seed weight, Mix 1, 2, and 3 contained 90% legumes, while Mix 2 and 4 contained 60% legumes. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), Mix 3 (23% F, 17% P, 10% CV, 10% PV, 30% WV, 10% R), Mix 4 (23% F, 17% P, 10% CV, 10% PV, 40% R), and Mix 5 (30% CV, 30% PV, 40% R).

Averaged across cover crops, years, and harvests, total cover crop DM was also significantly greater in Hollister (6.0 Mg ha^{-1}) than Salinas (4.5 Mg ha^{-1}). Furthermore, total DM production averaged across cover crops, sites, years and harvests was significantly lower in Year 1 (4.9 Mg ha^{-1}) than Year 2 (5.5 Mg ha^{-1}). Harvest had a significant affect on total DM because averaged across cover crops, site and years, total DM increased from 3.3 Mg ha^{-1} at mid-season to 8.1 Mg ha-1 at season end.

The greater total DM production in Hollister than Salinas may be due to soil quality differences between the sites. The clay soil at the Hollister farm contained 3 to 5% soil organic matter (OM) and has been in intensive organic vegetable production with regular inputs of cover crops, compost, and supplemental organic fertilizers for more than 10 yr, whereas the sandy soil at the Salinas site had only 1.2% OM and received relatively few soil amendments over the past 10 yr. Furthermore, the field in Hollister had 5.1% soil OM during Year 2 and tended to be more productive than the field with 3.6% soil OM used in Year 1.

Research in other regions of the United States reported considerable variability between sites and years in whether rye or hairy vetch–rye mixtures produced more total aboveground DM as winter cover crops (Ranells and Wagger, 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., 2007a). In our study, no differences were recorded for total DM by rye vs. the vetch–rye mixtures (2 and 5) averaged across harvests or at mid-season or season end (Fig. 5A, 5B).

Rye Dry Matter Production

There were significant two- and three-way interactions for rye DM production (Table 2). Averaged across cover crops, rye DM ranged from 2 to 4 Mg ha^{-1} at mid-season and increased markedly both years in Hollister, but only during Year 1 in Salinas, which explains the significant site × year ×harvest interaction (Fig. 5C); this figure also illustrates the site × year and site × harvest interactions for rye DM. For example, site × year was significant because rye DM yield was higher in Salinas during Year 1, whereas it was higher in Hollister during Year 2. Furthermore, averaged across years, rye DM increased more from mid-season to final season in Hollister than Salinas, which explains the significant site × harvest interaction. The other significant interactions for rye DM (site × year × cover crop, site × cover crop, and year × cover crop) occurred mainly because of difference in rye DM production between monoculture rye and the 60% legume mixtures vs. the 90% legume mixtures (Fig. 5D). For example, monoculture rye and the 60% legume mixtures had more rye DM than the 90% legume mixtures at both sites during Year 2, compared with Year 1 where there were no differences in Hollister and only one

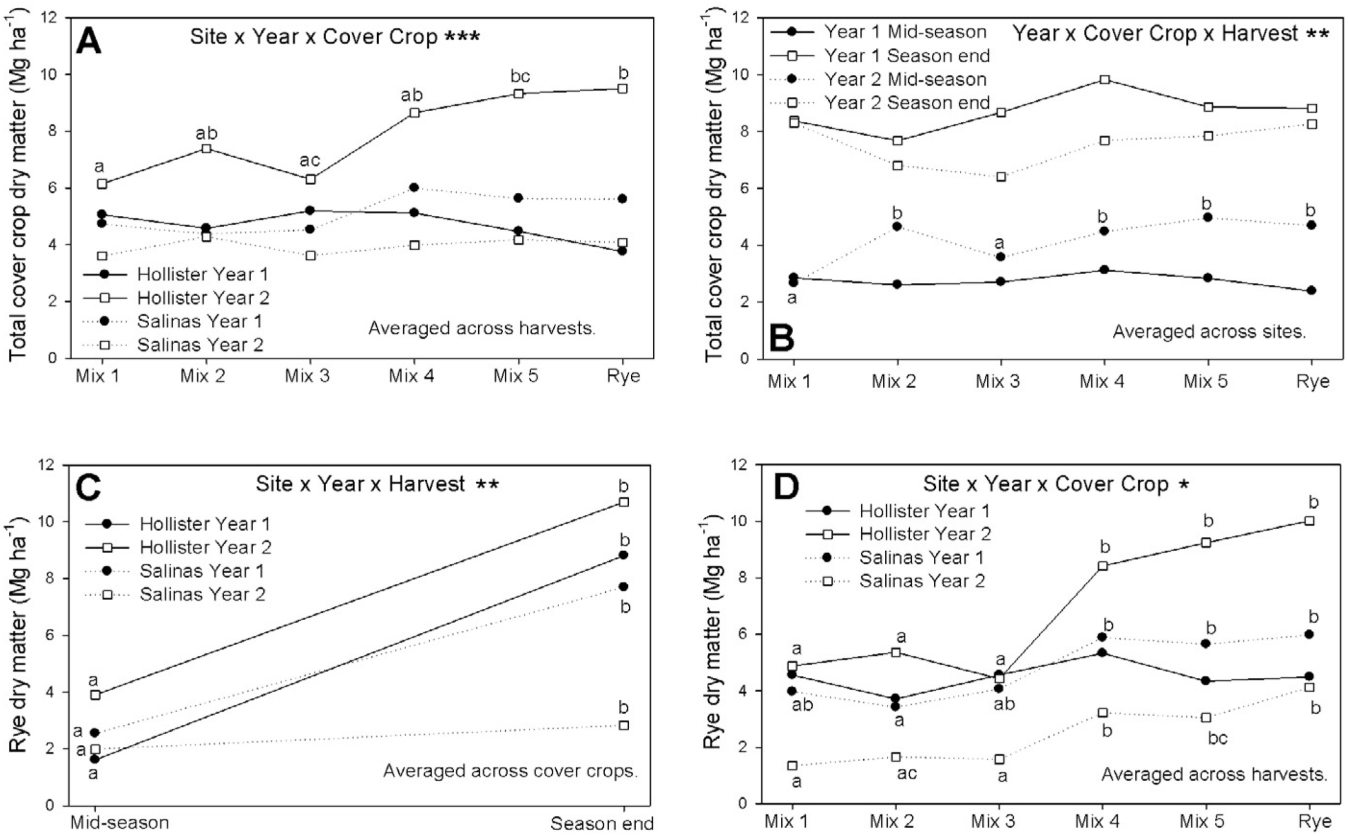

Fig. 5. Significant three-way interaction plots for total above ground cover crop dry matter (legume + rye) (A, B), rye dry matter (C, D) of five legume–rye mixtures and rye in Hollister and Salinas California during 2 yr. The significance level of each interaction shown next to title where *, **, and * are significant at the $p \leq 0.05$, 0.01, and 0.001 levels, respectively. Within each plot, least square means adjacent to symbols within a line that have different lowercase letters are significantly different based on an experiment-wise error rate of $p \leq 0.05$ based on a Bonferroni correction; significance letters are only shown for lines with significant differences. By seed weight, Mix 1, 2, 3 contained 90% legume seed and Mix 4 and 5 contained 60% legume seed. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), Mix 3 (23% F, 17% P, 10% CV, 10% PV, 30% WV, 10% R), Mix 4 (23% F, 17% P, 10% CV, 10% PV, 40% R), and Mix 5 (30% CV, 30% PV, 40% R).**

difference (Mix 2) in Salinas. All main effects were significant for rye DM production except for year (Table 2). Averaged across cover crops and harvests, the higher rye DM yield in Hollister (6.4 Mg ha^{-1}) than Salinas (3.9 Mg ha^{-1}) was likely due to the soil fertility differences noted above.

There was a significant, positive, linear or quadratic relationship between rye density and rye DM at both harvests in Salinas during both years, and in Hollister during Year 2 (Fig. 6). This trend indicates that rye DM production was usually limited by rye density especially in the 90% legume mixtures that had densities of 32 to 69 plants m^{-2}. We speculate that rye compensated for the lower plant densities in the mixtures by producing more tillers as in previous studies with rye in this region (Boyd et al., 2009).

Legume Dry Matter Production

Significant two-way interaction occurred for legume DM production in the mixtures (Table 2, Fig. 7). Averaged across cover crop mixtures and harvests, legume DM was greater during Year 2 than 1 at both sites; however, the difference was larger in Salinas than in Hollister which explains the site × year interaction (Fig. 7A). The significant site × harvest interaction occurred because averaged across mixtures and years, legume DM increased from mid-season to season end in Salinas, but decreased in Hollister (Fig. 7B). The year × harvest interaction illustrates that averaged across sites and cover crops, legume DM from mid-season to season end declined in Year 1 but did change in Year 2 (Fig. 7C). The interactions of year x cover crop, and cover crop x harvest, illustrate the different legume growth dynamics in the 90 vs. 60% legume mixtures between years and harvests (Fig. 7D, 7E). For example, averaged across sites and harvests, there were few differences between the 90% vs. 60% legume mixtures during Year 1, whereas all 90% legume mixtures produced more legume DM than the 60% legume mixtures during Year 2 (Fig. 7D). Furthermore, the cover crop × harvest interaction indicates legume DM at mid-season and season end were related to the percentage of legume (i.e., 90 vs. 60%) and the species of legume (i.e., faba bean, pea, and vetch) in the mixtures (Fig. 7E). For example, legume DM was greatest at mid-season in Mix 2 that contained only vetch, but was greatest at season end in Mix 1 that contained faba bean, vetch, and peas. Similarly, among the 60% legume mixtures, Mix 4 that contained all legume types had more legume DM at season end than Mix 5 that only contained vetches. These patterns suggest that the vetches contributed the most legume DM to mixtures up to mid-season, while other components such as faba bean contributed more legume DM latter in the season.

All main effects (site, year, cover crop, and harvest) had a significant affect on legume DM production (Table 2). Averaged

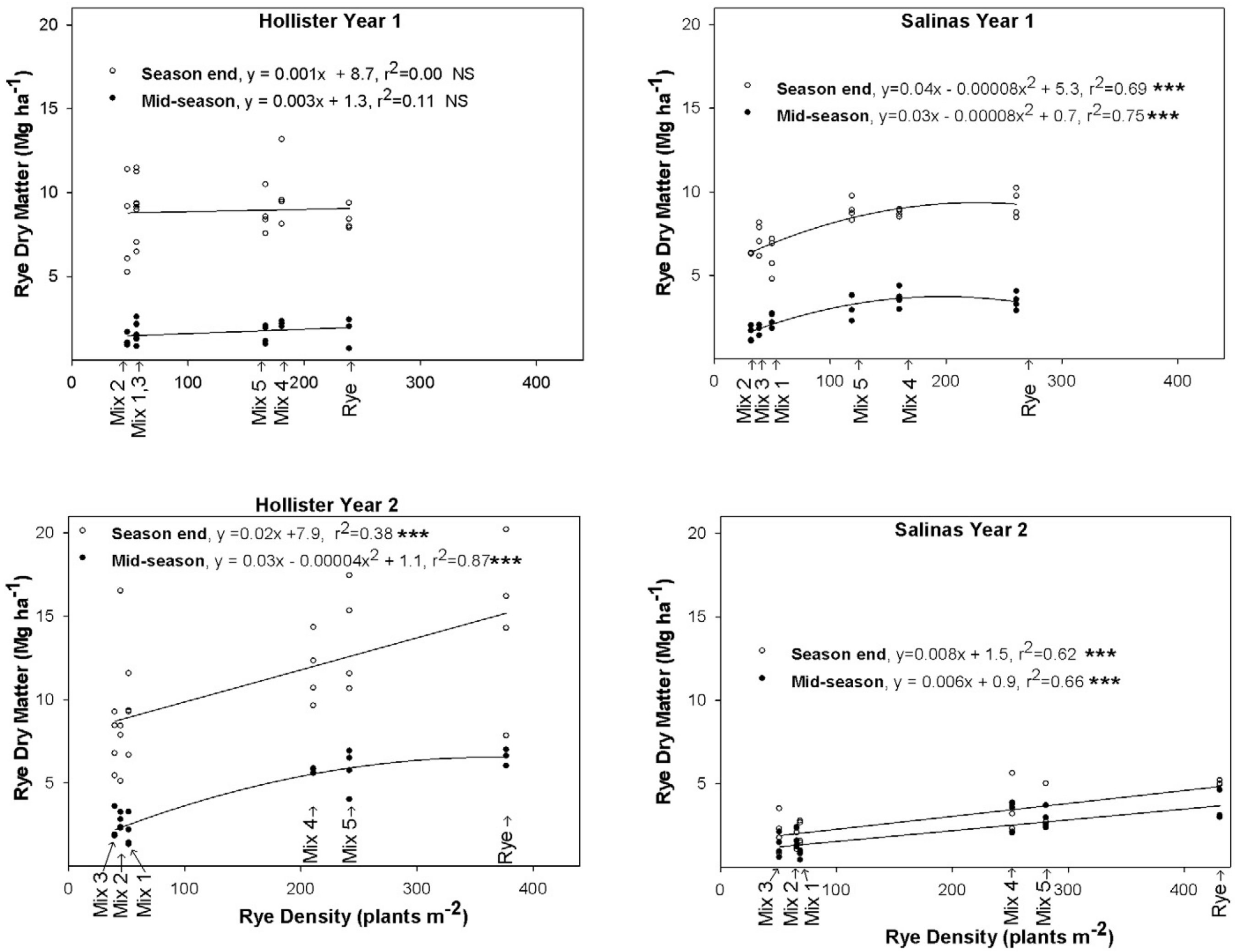

Fig. 6. Response of rye dry matter (DM) at mid-season (83–87 d after planting) and season end (141–154 d after planting) to rye densities in five legume–rye cover crop mixtures and monoculture rye in Hollister and Salinas, CA during Year 1 (2003–2004) and Year 2 (2004–2005). The mixture number for each cluster of data is shown with an arrow above or below the *x* axes. By seed weight, Mix 1, 2, 3 contained 90% legume seed and Mix 4 and 5 contained 60% legume seed. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), Mix 3 (23% F, 17% P, 10% CV, 10% PV, 30% WV, 10% R), Mix 4 (23% F, 17% P, 10% CV, 10% PV, 40% R), and Mix 5 (30% CV, 30% PV, 40% R). Fitted curves are based on raw data where *n* = 4 for each cover crop. * is significant at *p* < 0.001 and NS is not significant.**

across years, cover crop mixtures, and harvests, legume DM yield was greater in Salinas (1.1 Mg ha^{-1}) than Hollister (0.8 Mg ha^{-1}). Furthermore, averaged across sites, cover crop mixtures, and harvests, legume DM yield was also greater during Year 2 (1.4 Mg ha^{-1}) than Year 1 (0.6 Mg ha^{-1}). In contrast to total cover crop DM and rye DM, legume DM averaged across sites, years, and mixtures, declined from mid-season (1.0 Mg ha^{-1}) to season end (0.9 Mg ha^{-1}).

The percentage of rye or legume component of the total cover crop DM differed considerably by mixture, site, harvest, and year (Fig. 8). For example, averaged across years and sites, legume DM comprised 47% of total cover crop DM in the 90% legume mixtures vs. 16% in the 60% legume mixtures at mid-season. Furthermore, the percentage of legume DM of total DM in the 90% legume mixtures averaged across sites was nearly two times greater during Year 2 than Year 1. We speculate that the more frequent rainfall in Year 2 and greater rainfall later in the season that year reduced moisture competition between the legumes and rye and increased legume DM. In cereal–legume intercropping, legume yields are typically reduced by cereals, and the more extensive root systems of cereals provides a competitive advantage for soil moisture extraction (Ofori and Stern, 1987). Biological N-fixation improves legume competitive ability, but fixation declines as moisture stress increases (Ledgard and Steele, 1992).

Legume DM, as a percentage of total cover crop DM, declined by several fold in most cases in Hollister after mid-season. This decline in legume DM in Hollister was probably influenced by increased competition from rye as the season progressed and was most apparent in Mix 2, 3, and 5 that contained more vetch plants (Fig. 8). A study with a legume–oat mixture that occurred simultaneously at the same site in Hollister reported that legume DM declined more as the mixture seeding rate increased (Brennan et al., 2009). The N-fixation was not quantified; however, these differences in legume DM between sites and years suggest that more N was fixed by the legumes in the mixtures in Salinas than Hollister, particularly during Year 2. Nitrogen fixation in grass legume mixtures is highly

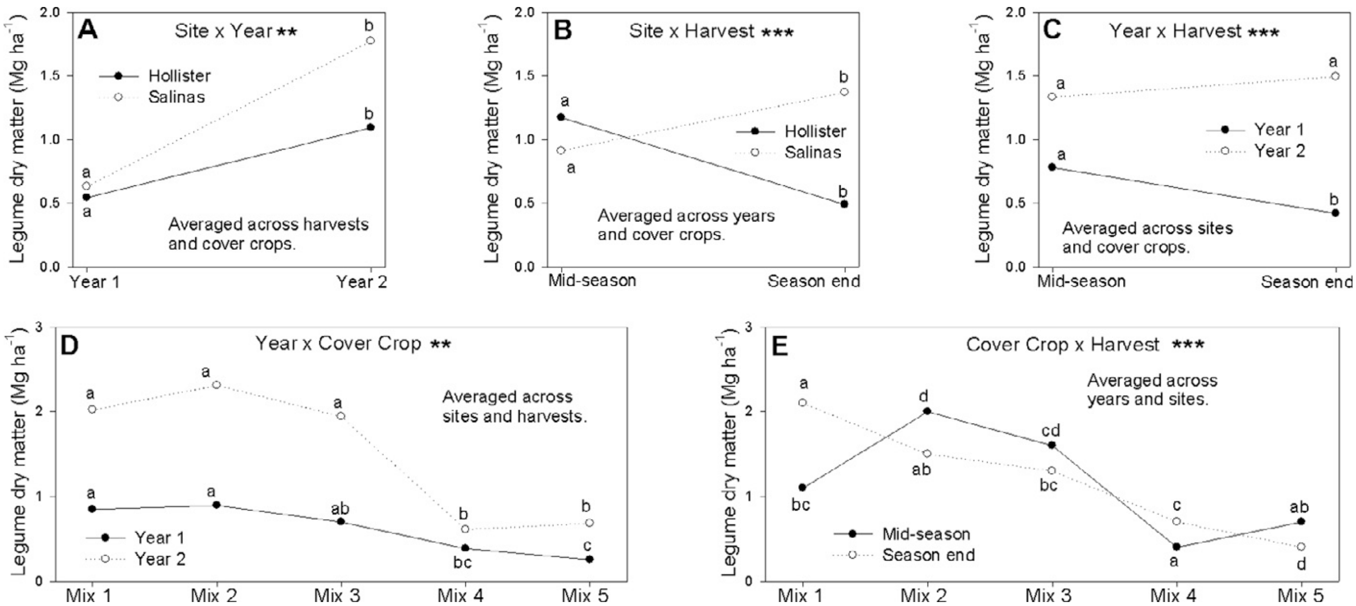

Fig 7. Significant two-way and three-way interaction plots for legume dry matter of five legume-rye in Hollister and Salinas, CA during two years. The significance level of each interaction is shown in each plot. Within each plot, least square means adjacent to symbols within a line that have different lower case letters are significantly different at an experiment-wise error rate of p≤0.05 based on a Bonferroni correction. By seed weight, Mix 1, 2, 3 contained 90% legume seed and Mix 4 and 5 contained 60% legume seed. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), Mix 3 (23% F, 17% P, 10% CV, 10% PV, 30% WV, 10% R), Mix 4 (23% F, 17% P, 10% CV, 10% PV, 40% R), and Mix 5 (30% CV, 30% PV, 40% R).

correlated with legume DM production (Carlsson and Huss-Danell, 2003; Hogh-Jensen et al., 2004; Carlsson et al., 2009).

Previous work with rye mixed with other species including legumes found that rye is highly competitive in mixtures and usually dominated DM at season end (Creamer et al., 1997; Karpenstein-Machan and Stuelpnagel, 2000; Ruffo and Bollero, 2003); however, other studies have also shown that legume DM can be the dominant component in many cases (Teasdale and Abdul-Baki, 1998). Our study illustrates that under relatively mild winter conditions in the central coast of California, rye can dominate a mixture even when the mixture only contains 10% rye seed with relatively low rye plant densities (i.e., 32–56 plants m^{-2}). Studies with rye–vetch mixtures as winter cover crops in colder regions of the United States used mixtures containing 50% or more rye seed with the rye component of the mixture seeded at 40 to 134 kg ha^{-1} with an average across studies of 58 kg ha^{-1} (Ranells and Wagger, 1997; Teasdale and Abdul-Baki, 1998; Griffin et al., 2000; Kuo and Jellum, 2002; Ruffo and Bollero, 2003; Sainju et al., 2005; Clark et al., 2007a; Delate et al., 2008; Teasdale et al., 2008). Unfortunately, none of these studies reported the resulting population densities of rye and vetch, which we believe is critical information to help understand the competition dynamics between mixture components and to make comparisons within and between studies.

Cover Crop Nitrogen Concentration, Nitrogen Uptake, and Carbon/Nitrogen

The legume DM of Mix 1, 2, and 5 had an average N concentration of 34 g kg^{-1} and did not differ between cover crops, sites, or years (Table 4). In contrast, there were significant interactions for the N concentration of the rye DM (Table 4). The site × year interaction for rye N concentration occurred because rye N concentration averaged across cover crops did not change between years in Hollister (19 g kg^{-1}), but in Salinas it declined from 19 g kg^{-1} in Year 1 to 14 g kg^{-1} in Year 2. Averaged across sites, rye N concentration did not differ between cover crops in Year 1, but was higher in Mix 2 during Year 2, which explains the year × cover crop interaction (Fig. 9A). The higher N concentration of rye DM in Mix 2 suggests that N may have been transferred from the legumes to rye during Year 2. Transfer of N from legumes to associated intercrops has been documented (Ledgard and Steele, 1992; Stern, 1993; Hauggaard-Nielsen and Jensen, 2005). Significant effects of site and year occurred for rye N concentration, which was higher in Year 1 (18 g kg^{-1}) than 2 (17 g kg^{-1}), and was also higher in Hollister (19 g kg^{-1}) than in Salinas (17 g kg^{-1}) (Table 4).

There were significant interactions for N uptake by the rye and legume components and total cover crop (Table 4). Legume N uptake by Mix 1 and 2 ranged from 40 to 110 kg ha^{-1} and exceeded N uptake by Mix 5 in Salinas; however, N uptake in Hollister was usually <40 kg ha^{-1} and did not differ between cover crops; hence the significant site × year × harvest interaction for legume N uptake (Fig. 9B). Averaged across cover crop and years, site was significant because legume N uptake was lower in Hollister (10 kg ha^{-1}) than in Salinas (35 kg ha^{-1}). Furthermore, averaged across cover crops and sites, year was significant for legume N uptake because legume N uptake was also lower during Year 1 (9 kg ha^{-1}) than 2 (39 kg ha^{-1}).

There was a site × year interaction for rye N uptake, because N uptake, averaged across cover crops, increased from 139 kg ha^{-1} during Year 1 to 193 kg ha^{-1} during Year 2 in Hollister; however, it decreased from 129 to 36 kg ha^{-1} in Salinas from Year 1 to 2. The site × cover crop interaction for total cover crop N uptake shows that N uptake did not vary between cover crops in Hollister, compared with Salinas where it was greatest in the 90% legume mixtures (Mixes 1, 2), intermediate in the 60% legume mixture (Mix 5) and least in monoculture rye (Fig. 9C). Clark et al. (2007a) reported that N uptake by rye increased with fall soil residual N levels. Fall residual N was not measured in our study;

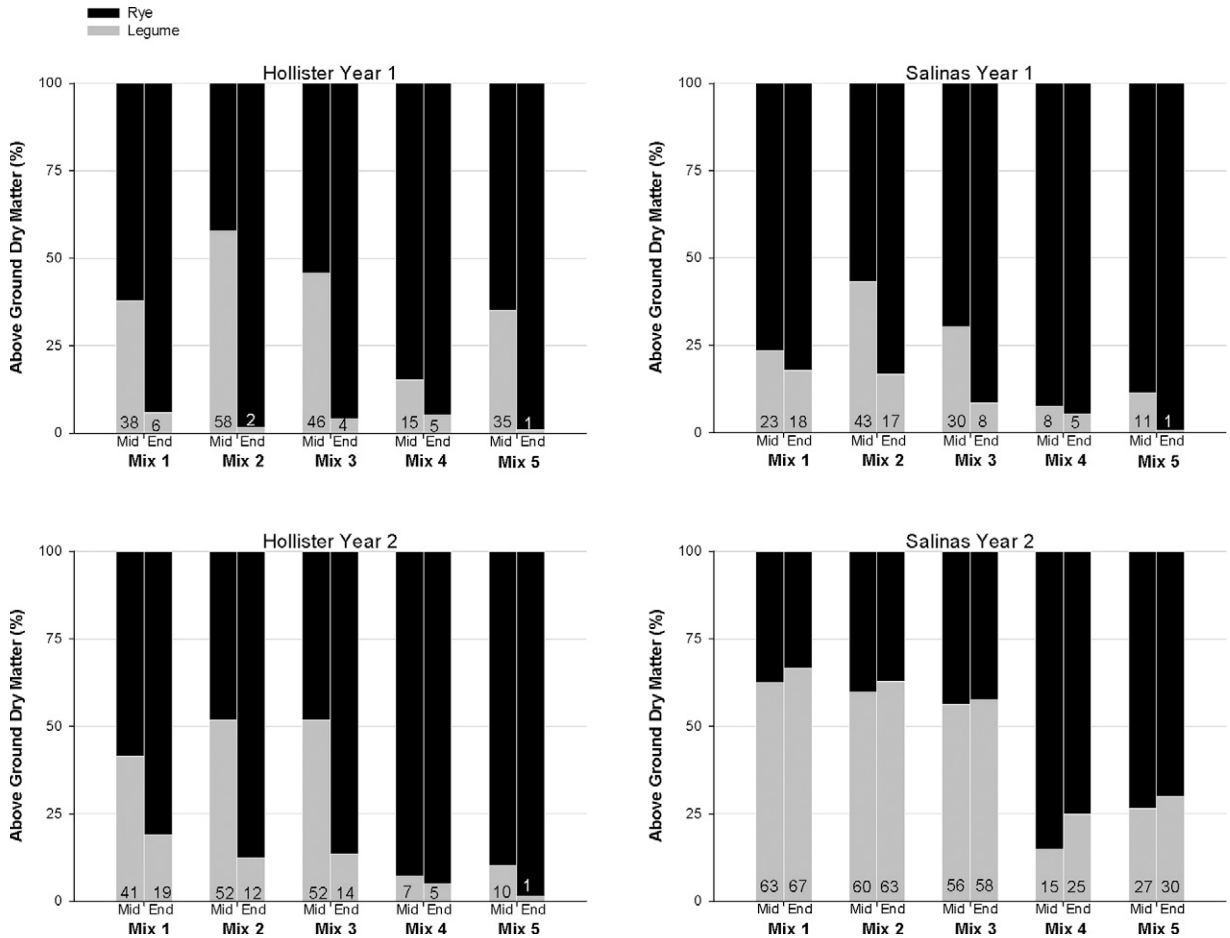

Fig. 8. Percentage of above ground dry matter (DM) from legumes and rye in five legume-rye cover crop mixtures at mid-season (Mid) and season end (End) in Hollister and Salinas, CA during Year 1 (2003-2004) and Year 2 (2004-2005). The mid-season harvests occurred at 84 to 85 days after planting (DAP), and 84 to 85 DAP in Hollister, and at 83 to 87 DAP, and 85-86 DAP in Salinas, in Year 1 and 2, respectively. Season end harvests occurred at 147 DAP, and 150 to 154 DAP in Hollister, and at 140 to 141 DAP, and 141 to 142 DAP in Salinas, in Year 1 and 2, respectively. The number in each bar is the legume percentage of total cover crop DM. By seed weight, Mix 1, 2, and 3 contained 90% legume seed and 10% rye, while Mix 2 and 4 contained 60% legume seed and 40% rye. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), Mix 3 (23% F, 17% P, 10% CV, 10% PV, 30% WV, 10% R), Mix 4 (23% F, 17% P, 10% CV, 10% PV, 40% R), and Mix 5 (30% CV, 30% PV, 40% R).

however, the N uptake by monoculture rye suggests that residual N was similar between sites in Year 1, but considerably higher in Hollister than Salinas in Year 2. These differences in N uptake help to explain differences in the DM production by the legume and rye components of the mixtures between sites and years.

Comparing legume N uptake (Fig. 9B) with total N uptake (Fig. 9C) indicates that the majority of the N in the mixtures at season end in Hollister was in the rye component. For example, averaged across years, rye in Mix 1 contained 14% (26/181 kg N ha^{-1}) of the N in Hollister, compared with 50% (76/152 kg N ha^{-1}) in Salinas.

The C/N of the aboveground cover crop DM ranged from 9 to 15 for the legumes, 20 to 29 for rye in the mixtures, 24 to 41 for monoculture rye, and 16 to 27 for the total cover crop DM of the mixtures. There were significant differences in the C/N of legume, rye, and total cover crop DM, and significant interactions (Table 4). Averaged across sites and years, the C/N of legume DM was significantly higher in Mix 1 (14), than in Mix 2 and 5 (12), probably because Mix 1 contained legumes with more lignified stems (faba bean) whereas Mix 2 and 5 only contained vetches. There was a significant site × year interaction for legume C/N, because it did not change between years in Hollister (13), but increased from Year 1 (11) to Year 2 (13) in Salinas. The C/N of rye DM averaged across cover crops increased in Salinas from 24 to 31 from Year 1 to 2, respectively, but decreased from 26 to 23 in Hollister, hence the significant site × year interaction for rye C/N. The interaction plots for rye C/N (Fig. 9D, 9E) and total cover crop C/N (Fig. 9F) revealed that most of the differences in the C/N between cover crops were due to the relatively high C/N of monoculture rye during Year 2 in Salinas. The lower C/N of rye DM in Mix 2 may be due to recycling of N from vetch DM that declined markedly from mid-season to season end (Fig. 7E). Our results agree with previous studies that reported lower C/N of legume–rye residue than pure rye residue (Ranells and Wagger, 1997; Teasdale and Abdul-Baki, 1998; Rosecrance et al., 2000; Kuo and Jellum, 2002; Sainju et al., 2005). However, our study also illustrates that the C/N of total cover crop residue from legume–rye mixtures can vary by cover crop mixture, site, and year (Table 4, Fig. 9E and 9F).

Economic Analysis of Cover Crop Dry Matter versus Seed Cost

The seed costs at the rates we used were more than two times higher for the mixtures than for monoculture rye, and an average

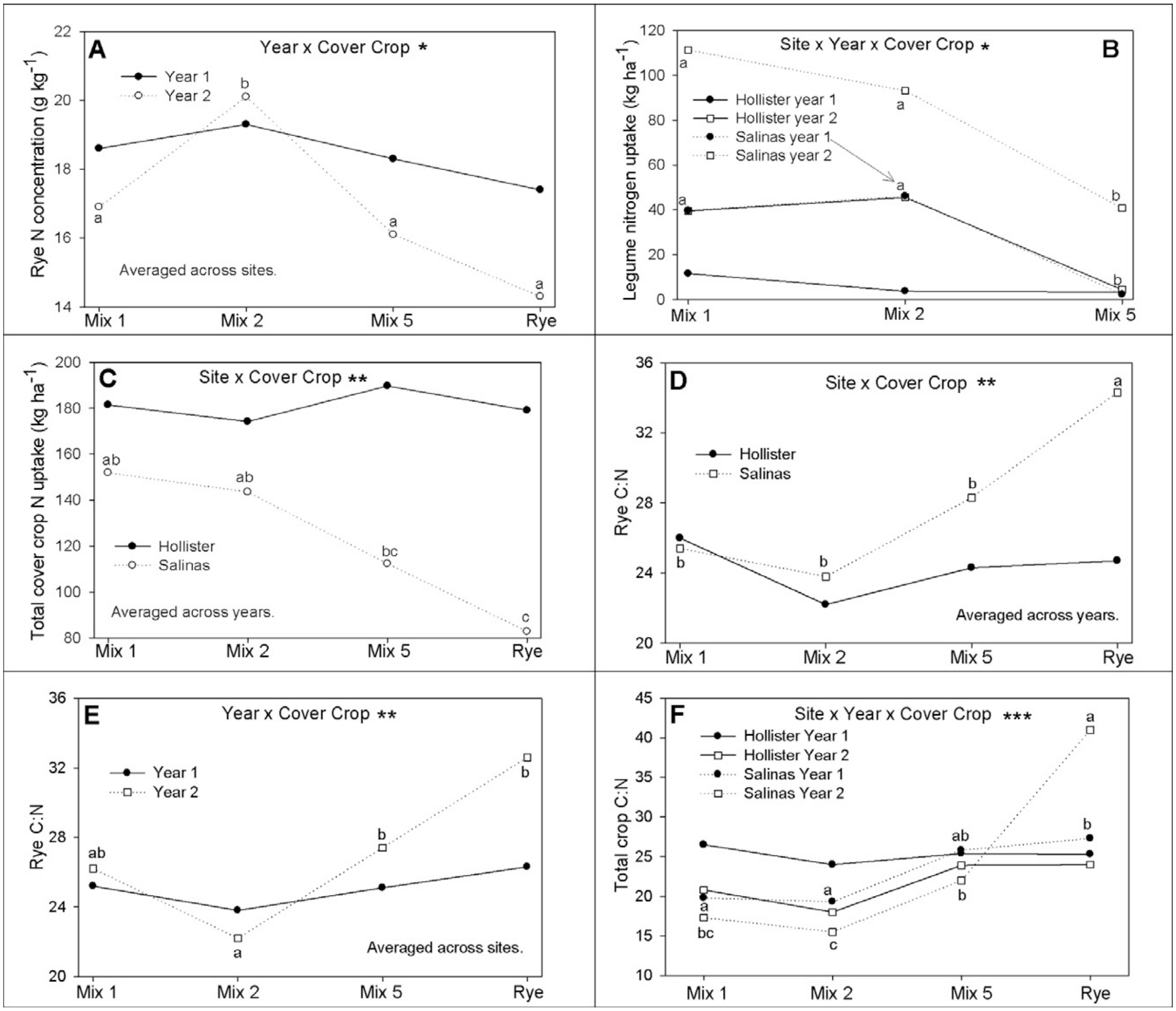

Fig. 9. Significant interaction plots for rye N concentration, N uptake by legumes and total cover crop, and C/N for of rye and total cover crop of three legume–rye mixtures and rye at season end in Hollister and Salinas, California during 2 yr. The significance level of each interaction is shown next to title where *, **, and * are significant at the $p \leq 0.05$, 0.01, and 0.001 levels, respectively. Within each plot, least square means adjacent to symbols within a line that have different lowercase letters are significantly different at an experiment-wise error rate of $p \leq 0.05$ based on a Bonferroni correction; significance letters are only shown for lines with significant differences. By seed weight, Mix 1 and 2 contained 90% legume seed, and Mix 5 contained 60% legume seed. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), and Mix 5 (30% CV, 30% PV, 40% R). The lines for Salinas during Year 1 and Hollister during Year 2 overlap in Fig. 9B, however, the significance difference letters are for Salinas during Year 1.**

Table 4. Significance of tests of fixed effects and interactions of N concentration, N uptake, and C/N ratios in aboveground dry matter of three legume–rye cover crop mixtures, and rye, at season end of the winter cover cropping periods in Year 1 (2003–2004), and Year 2 (2004–2005) in Hollister and Salinas, CA.

	N Concentration		N Uptake			C/N ratios		
Effect	Legume	Rye	Legume	Rye	Rye + legume	Legume	Rye	Rye + legume
Site	ns†	***	***	***	***	ns	**	ns
Year	ns	**	***	***	ns	ns	**	*
Cover crop‡	ns	***	***	**	*	**	***	***
Site × year	ns	***	ns	***	***	*	***	**
Site × cover crop	ns	ns	ns	ns	**	ns	**	***
Year × cover crop	ns	*	ns	ns	ns	ns	**	***
Site × year × cover crop	ns	ns	*	ns	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.

† ns, not significant.

‡ Cover crops included Mix 1, Mix 2, Mix 5 and monoculture rye. By seed weight, the mixtures contained the following percentages of faba bean (F), pea (P), common vetch (CV), purple vetch (PV), wollypod vetch (WV), and rye (R): Mix 1 (35% F, 25% P, 15% CV, 15% PV, 10% R), Mix 2 (45% CV, 45% PV, 10% R), and Mix 5 (30% CV, 30% PV, 40% R).

of 18% more for the 90% legume mixtures compared to the 60% legume mixtures (Table 1). The legume seed comprised an average of 95% of the seed cost for the 90% legume mixtures vs. 73% of the seed cost for the 60% legume mixtures. Rye was the most cost effective cover crop in terms of total DM production per unit seed cost. For example, averaged across sites and years, the cost of total cover crop DM was \$8 Mg^{-1} ha^{-1} for rye, \$22 Mg^{-1} ha^{-1} for the 60% legume mixtures, and \$24 Mg^{-1} ha^{-1} for the 90% legume mixtures. Legume DM costs per unit seed cost were several times higher than those of total cover crop DM. For example, even during Year 2 in Salinas when legume DM production was the highest at season end (i.e., 3.4 Mg ha^{-1} in the 90% legume mixtures and 1.3 Mg ha^{-1} in the 60% legume mixtures), the cost of legume DM was \$92 Mg^{-1} ha^{-1} for the 60% legume mixtures, and \$54 Mg^{-1} ha^{-1} for the 90% legume mixtures. These partial budget analyses do not account for the cost of cultural practices associated with growing a cover crop such as planting costs (other than seed), irrigation to germinate, mowing, and soil-incorporation of cover crop residue. These other costs typically comprise at least 80% of the cost of cover cropping in this area (Tourte et al., 2004) and are not thought to differ by cover crop. It is not known if the higher cost of DM from the legume mixtures provide an economic benefit to the farmer in terms of reduced fertilizer costs due to N fixation, or more rapid mineralization of cover crop residue in subsequent vegetable crops from a lower C/N of the legume component.

CONCLUSIONS

This is the first study in the central coast of California to compare several legume–rye mixtures. It provides important preliminary information on cover crop population densities, early-season ground cover, above ground DM production, and N content of a range of legume–rye mixtures and rye for potential use in vegetable production systems. The study illustrates that developing mixtures that have a desirable balance of rye and legume DM over a range of field and climatic conditions is difficult, because of the interactions between the mixture components, climate, and soil. Changing the proportion of rye to legume seed, and legume species in the mixtures affected the seed cost, cover crop population densities, early-season ground cover, N content, and the amount and proportions of legume to rye DM. With the five mixtures evaluated, the proportion of legume to rye seed in the mixture rather than the species of legume had a greater effect on the growth of the legume component. At a seeding rate of 140 kg ha^{-1}, the 60% legume mixtures provided more early-season ground cover than 90% legume mixtures indicating that 60% legume mixture may provide better weed suppression. Most mixtures produced the same amount of aboveground DM as monoculture rye at the middle and end of the cover cropping period, and rye was usually the dominant component of the mixtures at season end, especially with the 60% legume mixtures. The only case where legumes dominated total cover crop DM at season end occurred with the 90% legume mixes during Year 2 in Salinas, when DM of the rye monoculture was relatively low. Total cover crop N uptake was greater in Hollister than Salinas; however, legume DM and legume N uptake were greater in Salinas. Therefore, farmers may derive more benefits from legume–rye mixtures at lower fertility sites such as Salinas. Our data indicate that in the central coast of California, approximately 60 to 85% of the plants in the mixtures should be legumes to achieve adequate legume DM to justify the high cost of legume seed; this was usually the case the 90% legume mixtures. More research is needed to understand (i) the effect of seeding rate on DM production and weed suppressive ability of these legume-rye mixtures, (ii) the above and belowground DM contributions of individual legumes species in mixtures, (iii) nutrient cycling in legume–cereal mixtures due to senescence of the mixture components during the cover cropping period, and (iv) the economics of using legume–rye mixtures vs. monoculture rye in high-value vegetable production systems in California.

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ERRATA

Comparison of Rye and Legume–Rye Cover Crop Mixtures for Vegetable Production in California

Brennan, E. B., N. S. Boyd, R. F. Smith, and P. Foster

Agron. J. 103:449–463. doi:10.2134/agronj2010.0152.

Some incorrect values in Table 1 and Fig. 1 were unfortunately published in the article above.

The updated table is shown below. The corrected values in the § footnote are highlighted in boldface type. In the published version the values in the footnote were reported in $/lb rather than $/kg.

The growing degree day (GDD) shown in the original Fig. 1 were calculated in °F with a baseline threshold of 39°F. The corrected Fig. 1 here shows them calculated in °C 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).'

The authors regret the errors and apologize for any inconvenience this may have caused readers.

— Eric B. Brennan
eric.brennan@ars.usda.gov
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Table 1. Cover crop descriptions and seed costs.

Cover crop	Mixture type	1000-seed weight†	Composition‡ Faba bean	Pea	Com. vetch	Purp. vetch	Wollyp. vetch	Rye	Seed cost§ $ kg⁻¹¶	$ ha⁻¹
		g	%						$ kg^{-1}¶	$ ha^{-1}
Mix 1	90% legume: 10% rye	76.0, 65.2	35	25	15	15	–	10	1.35 (1.27)	189
Mix 2	90% legume: 10% rye	36.7, 30.0	–	–	45	45	–	10	1.67 (1.59)	234
Mix 3	90% legume: 10% rye	56.3, 47.3	23	17	10	10	30	10	1.59 (1.50)	223
Mix 4	60% legume: 40% rye	41.8, 32.9	23	17	10	10	–	40	1.20 (0.84)	167
Mix 5	60% legume: 40% rye	36.2, 23.6	–	–	30	30	–	40	1.41 (1.06)	197
Rye								100	0.88	79

† 1000-seed weight of each mixture for Year 1 (2003–2004) and 2 (2004–2005), respectively. 1000-seed weights of mixture components for Year 1 and Year 2, respectively, are in parentheses. Rye, *Secale cereale* 'Merced' (22.0, 16.5); Common (Com.) vetch, *Vicia sativa* (54.3, 54.8); Purple (Purp.) vetch, *Vicia benghalensis*, (37.9, 32.2);Woolypod (Woolyp.) vetch, *Vicia dasycarpa* 'Lana' (40.1, 33.8); Faba bean, *Vicia faba*, small-seeded type known as 'bell bean' (417.4, 436.0); Pea, *Pisum sativum* 'Magnus', (238.7, 231).

‡ Percent by seed weight.

§ Costs ($ kg^{-1}) of mixture components in March 2009 were: *S. cereale* (**0.88**), *V. sativa* (**1.54**), *V. benghalensis* (**1.98**), *V. dasycarpa* (**2.20**), *V. faba* (**1.26**), *P. sativum* (**1.19**). Seed costs per ha were based on seeding rates of 140 kg ha^{-1} for mixtures and the sole rye at 90 kg ha^{-1}.

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

(continued)

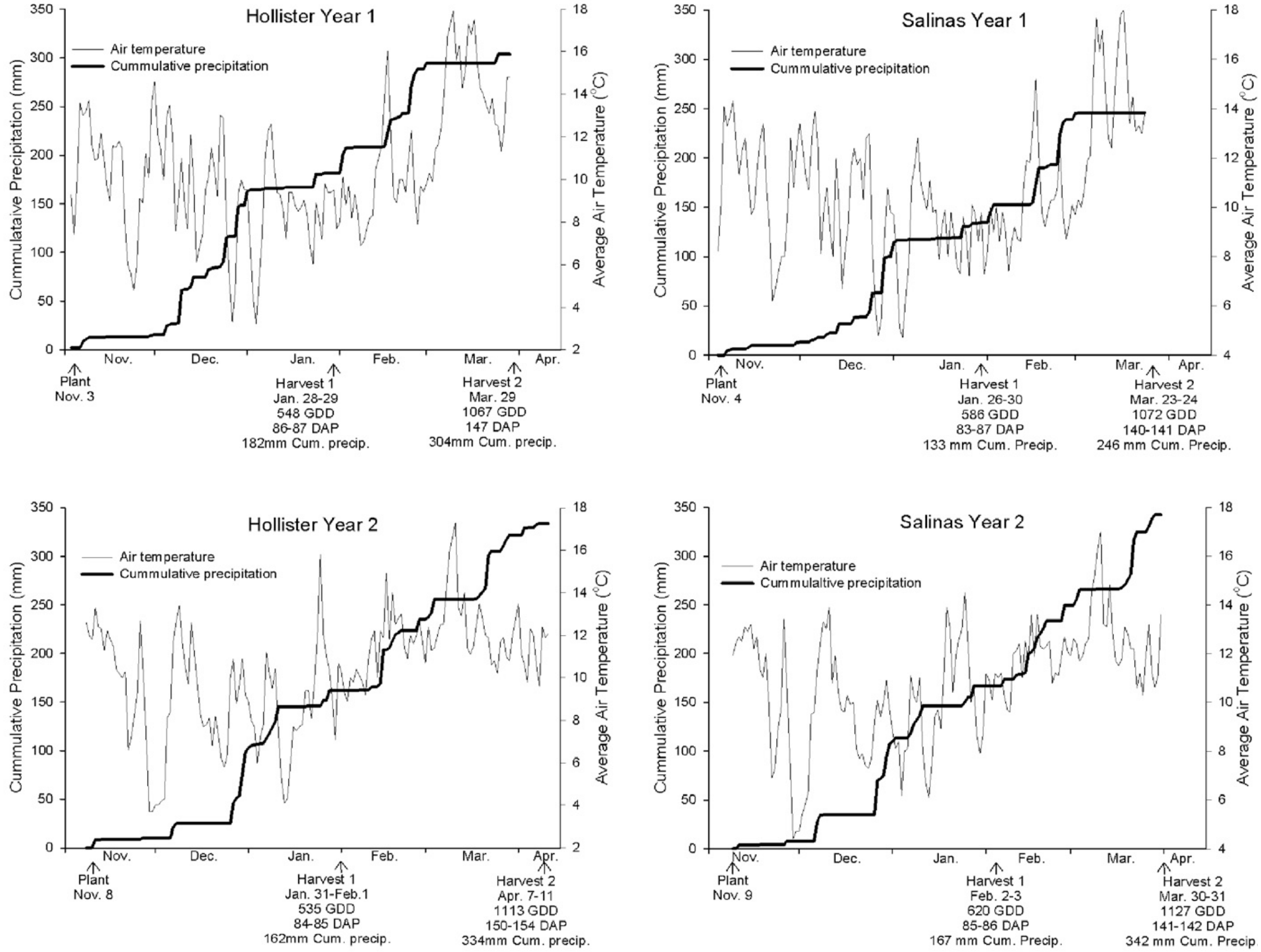

Fig. 1. Cumulative precipitation, air temperature, and growing degree days (GDD) from data from the California Irrigation Management Information System (CIMIS) (http://wwwcimis.water.ca.gov) in Year 1 (2003–2004) and Year 2 (2004–2005) at Hollister (CIMIS station no. 126) and Salinas (CIMIS station no. 89). The 13-yr average rainfall between November and April (1993–2007) was 395 mm (Hollister) and 346 mm (Salinas). 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).