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Cover Crop Frequency and Compost Effects on a Legume–Rye Cover Crop During Eight Years of Organic Vegetables

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ABSTRACT

The long-term impacts of adding organic matter to the soil using cover crops (CC) and compost are poorly understood in high-value, tillage-intensive vegetable systems. Therefore, we evaluated the effects of CC frequency (annually vs. every fourth winter) and yard-waste compost (0 vs. 15.2 Mg dry matter ha^{-1} annually) on the performance of a legume–rye (*Secale cereale* L.) CC in three systems during Years 4 and 8 of the Salinas Organic Cropping Systems experiment in Salinas, CA. Other inputs during the 8 yr of commercial-scale vegetable production were identical across systems. The CC were planted at 420 kg ha^{-1} and we measured soil organic carbon (SOC), soil NO_3, CC population density, and CC shoots (biomass, N accumulation, N concentration, and C/N). At the beginning of Year 4, the systems receiving compost had higher SOC, and by Year 8 the system with frequent CC had higher soil NO_3. Total CC biomass and N accumulation did not differ markedly between systems, although legumes were less variable and somewhat more productive in the systems with infrequent CC, regardless of compost. Rye and total CC residue were generally higher quality (lower C/N) in the system with frequent CC. Despite large differences in rainfall between years (234 vs. 123 mm), CC performance was relatively stable across years, although the percentage of legume biomass declined more during the drier year. We conclude that cover cropping frequency and compost have relatively subtle effects on legume–rye growth in intensive, high-value, organic vegetable production.

Core Ideas

- Cover crops and compost are common inputs in high-value, organic vegetables.
- Cover crop frequency and compost effects on a legume–rye mixture were evaluated over 8 yr.
- Yard-waste compost additions increased soil organic C in vegetable systems.
- Frequent cover cropping increased soil nitrate levels.
- Cover crop frequency and compost had subtle effect on legume–rye growth.

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California produces a large portion of the organic and conventional vegetables in the United States, and efficient management of soil and water resources is necessary to ensure the long-term agricultural productivity of this region. There are critical questions about the sustainability of common production practices in parts of California (i.e., Salinas Valley) where decades of intensive, high-input vegetable production have contaminated precious and dwindling ground water with nitrates, primarily from fertilizers (Brennan, 2017; Rosenstock et al., 2014); unlike many other regions of California, ground water is the sole source of irrigation and drinking water in the Salinas Valley. Rosenstock et al. (2014) concluded that "California agriculture cannot continue along its current nitrogen trajectory and still preserve ground water quality, thus placing Californians and the agricultural industry in precarious positions." Winter cover cropping has been suggested as a widely applicable best management practice to help to solve the nitrate problem in Salinas ground water (Brennan, 2017; Dzurella et al., 2012; Hartz, 2006; Jackson et al., 1993; Wyland et al., 1996). And over the past 15 yr in the Salinas Valley there has been considerable research on high biomass (typically 5 to 8 Mg oven-dry shoots ha^{-1}) winter cover crops (Boyd and Brennan, 2006; Boyd et al., 2009; Brennan and Smith, 2005; Brennan and Boyd, 2012a, 2012b; Brennan and Acosta-Martinez, 2017; Brennan et al., 2013, 2011a, 2011b; Ferris et al., 2012; Maltais-Landry et al., 2014, 2015) that can scavenge leftover N from previous cash crops and add large amounts of organic matter to the soil that can improve its physical, biological, and chemical characteristics (Fageria et al., 2005). Furthermore, California's recent drought has heightened awareness of the need to increase groundwater recharge from winter rainfall (Harter and Dahlke, 2014; O'Geen et al., 2015), and it is likely that standard cover crops (i.e., full season, ≈4–8 Mg ha^{-1} oven-dry shoots) and alternative, low-residue strategies (i.e., partial season, ≈1 Mg ha^{-1}) could help with this if they are managed to increase infiltration and terminated in a timely manner to conserve soil moisture during the latter part of the season (Brennan, 2017; Heinrich et al., 2014); growing cover crops in furrow bottoms of winter-fallow beds and killing them with an herbicide to create a low-residue layer of mulch is an example of alternative, and promising strategies (Brennan, 2017).

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Abbreviations: DM, dry matter; GDD, growing degree day; NHST, null-hypothesis significance testing; SOC, soil organic carbon; SOCS, Salinas Organic Cropping Systems.

While winter cover cropping is relatively uncommon in the Salinas Valley, increased oversight of fertilizer inputs and winter runoff from agricultural land through the Irrigated Lands Regulatory Program (California Environmental Protection Agency, 2011) and greater attention to the nitrate problem (Harter et al., 2012) will hopefully increase cover crop adoption. To facilitate this, farmers need reliable information on the short- and long-term impacts of cover cropping, and alternative approaches (i.e., compost additions) to add organic matter to the soil. There is relatively little published research on compost vs. cover crop use in California vegetable systems, however, a survey of 13 organic tomato (*Lycopersicon esculentum* Mill.) fields reported that compost or manure were the primary organic matter input in most fields, and that cover crops were used in only five fields (Bowles et al., 2014). Compost is a more convenient way than cover cropping to add organic matter to vegetable rotations because large amounts of compost (typically 10 oven-dry Mg ha^{-1}) can be rapidly broadcast over the surface and easily incorporated during bed preparation without delaying subsequent vegetable plantings. There is surprisingly little research on the combined effects of compost and cover crops in California's high-value production systems for crops like lettuce (*Lactuca sativa* L.) and broccoli (*Brassica oleracea*). A 2-yr study (Jackson et al., 2004) in the Salinas Valley found that adding compost and rye cover crops improved soil quality, increased vegetable yields and reduced disease in some cases. The only other known study on compost and cover crop effects on high-value vegetables in Salinas Valley is the ongoing Salinas Organic Cropping Systems (SOCS) experiment that began in 2003. The SOCS experiment has shown that cover cropping has more beneficial effects than yard-waste compost on soil quality or health (Brennan and Acosta-Martinez, 2017; Ferris et al., 2012). While this research occurs in an organic context, it's findings are equally relevant to conventional systems that represent roughly 95% of the production in Monterey County (Monterey County Agricultural Commissioner, 2013).

In this paper we report on (i) biomass production, N accumulation, and residue quality (N concentration and C/N ratio) of a legume–rye cover crop mixture grown at a high seeding rate during the winters of Years 4 and 8 in three of eight systems in the SOCS experiment, and (ii) soil organic matter and soil nitrate changes in these contrasting systems. The three systems differed markedly in compost inputs and winter cover cropping frequency during the first 8 yr of the experiment and represent three radically different approaches to organic management that are all acceptable under the USDA National Organic Program regulations. This paper complements our previous reports on cover crop biomass, N accumulation, and residue quality for six systems that annually received cover crops and compost during the first 8 yr of the experiment (Brennan and Boyd, 2012a, 2012b; Brennan et al., 2013). The present paper and previous published research from the experiment provide a foundation to understand other aspects (i.e., cash crop yields, soil quality, weeds, etc.) that will be described in future papers. The objective here is to describe how the legume–rye cover crop mixture responded to the different soil organic matter inputs from cover crop and compost that occurred during the first several years of the commercial-scale vegetable production phase of the experiment.

MATERIALS AND METHODS

Site Description, Cropping Sequence, and Experimental Design

The ongoing SOCS experiment began in October 2003 and is located at the USDA-ARS organic research farm in Salinas, CA (36°37′ N, –121°32′ W). This study site has been certified organic under the USDA National Organic Program by California Certified Organic Farmers since 1999. This online video (Brennan, 2015) provides a visual overview of the research farm where the study occurs. Prior to certification, the site was used for conventional, winter oat (*Avena sativa* L.) hay production, with frequent fallow periods and occasional organic vegetables and cover crops with minimal inputs. Additional details on the history of the site and cropping sequence and management are provided in Brennan and Boyd (2012a). The soil is a Chualar loamy sand (fine-loamy, mixed, thermic Typic Argixerol) with 77% sand, 15% silt, and 8% clay with a relatively low organic matter content (i.e., ≈1–1.5%). The 1 ha field where the experiment occurred has an approximate slope of 1% and was laser-leveled to a uniform slope prior to the experiment.

The experimental design is a randomized complete block with eight systems in four replicates. This article focuses on cover crop performance during Year 4 (November 2006–March 2007) and Year 8 (October 2010–March 2011) of the trial in three systems that all received the same legume–rye cover crop mixture (Table 1) that was planted at a relatively high seeding rate (420 kg ha^{-1}). By seed weight the mixture included 10% cv. Merced rye, 35% faba bean (*Vicia faba* L.; small-seeded type known as "bell bean"), 25% cv. Magnus pea (*Pisum sativum* L.), 15% common vetch (*V. sativa* L.), and 15% purple vetch (*V. benghalensis* L.). Based on the 1000 kernel weights of seed (Brennan and Boyd, 2012a), the approximate number of seeds m^{-2} for Years 4 and 8 respectively were rye (210, 247), faba bean (34, 42), pea (52, 54), purple vetch (180, 150), common vetch (105, 93), all legumes (371, 339), and total (581, 586). The three systems differed in how often they received a winter cover crop (annually vs. every 4 yr) and whether urban yard-waste compost (C/N ≈22) was applied annually during the first 8 yr of the vegetable production at a rate of 7.6 Mg ha^{-1} (oven-dry basis) before each of vegetable crop (described below). All other management aspects during the vegetable rotation (i.e., irrigation, tillage, pest management, supplemental fertilizer inputs, and vegetable rotation) were identical. Systems 1 and 2 that were fallow during six of the eight winters were maintained weed-free with shallow tillage with a rototiller and hand weeding or flaming as needed during the winter periods when System 3 was being cover cropped. Winter bare fallowing is the most common way that fields without winter cash crops in this region are managed and usually these bare fallows have peaked beds to facilitate shallow cultivation with a rolling cultivator. However, our winter bare fallows were flat (i.e., not in peaked beds) because flat plots were easier to manage weed-free, primarily by hand, than with a rolling cultivator; furthermore, having peaked winter fallowed bed plots interspersed between flat winter cover cropped plots would have complicated winter field preparation and potentially have channeled winter rainfall runoff from fallow plots to cover cropped plots.

The system plots are 12.2 m wide by 19.5 m long, and are arranged in a grid of four plots wide by eight plots long within a 0.9 ha field. The annual rotation in the three systems of interest included either winter fallow or cover crops from October or

Table 1. Details of the three systems in the Salinas Organic Cropping Systems experiment in Salinas, CA.

System no.	System label†	Annual compost rate	Cover crop frequency
		Mg ha^{-1}	
1	Fal-Leg-Rye-NoCp	0	Every fourth winter
2	Fal-Leg-Rye	15.2	Every fourth winter
3	Leg-Rye	15.2	Every winter

† Labels indicate if the system was fallow (Fal) for three winters, and received no compost (NoCp).

November to February or March, followed by romaine lettuce (*L. sativa* L. var. *longifolia* Lam.) from May to June or July each year, and was followed by baby leaf spinach (*Spinacia oleraceae* L., July–September, Year 1) or broccoli (*B. oleraceae* L. var *italica* Plenck., July or August to September or October, Years 2–7). The cover crops were planted on 2 Nov. 2006 and 27 Oct. 2010 that corresponded the beginning of Years 4 and 8 of the experiment; additional details on cover crop performance in System 3 during the intervening years (1–3, and 5–7) were reported previously (Brennan and Boyd, 2012a, 2012b; Brennan et al., 2013). The cover crop seed mixture was inoculated with appropriate Rhizobium inoculants and planted in a single pass with the grain drill with 15 cm spacing between seed lines.

Data Collection

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 rows m^{-2}. Emerged cover crops were categorized as either rye, pea, faba bean, or vetch. Cover crop shoot biomass was sampled by hand-clipping in one 50- by 100- cm quadrat oriented to include three adjacent rows for each plot at 18 to 20 Jan. and 15 to 16 Mar. 2007, and 12 to 14 Jan. and 7 to 9 Mar. 2011 during Years 4 and 8, respectively. Given the uniform planting of the cover crop mixture with a grain drill, this size quadrat was large enough to provide a representative sample of biomass of the legume and rye components. Harvested cover crop biomass from the January and March harvests was separated into the legume and rye components and oven-dried at 65°C for at least 48 h until the weight had stabilized. The biomass sampling dates were chosen to track changes in cover crop dry matter (DM) over the season and to minimize sampling on rainy days. Soil sampling occurred on 1 Nov. 2006 and 25 Oct. 2010 which was 1 to 2 d before cover crop planting; these soil sampling dates were 1 and 12 d after the previous broccoli crop residue was incorporated into the soil with a soil spader for 2006 and 2010, respectively. Therefore, Systems 1 and 2 would show no effect of cover cropping at the 2006 soil sampling that occurred at the end of Year 3 and the impact of only one cover crop growth period (3 yr prior) when sampled in 2010. Soil sampling was done with a soil probe to a depth of 30 cm in an "x" pattern across the plot to obtain 20 samples per plot that were mixed together.

Soil and Plant Analysis

Soil and cover crop shoot analyses were conducted at the Agriculture and Natural Resources Analytical Laboratory at the University of California in Davis. Cover crop dry matter (DM) samples were ground to pass through a 0.250 mm screen, and a subsample was analyzed with a combustion gas analyzer method (AOAC, 2006) for total C and N at the University of California Davis Analytical Laboratory (http://anlab.ucdavis.edu/using-the-lab/analysis/plant/522) using a TruSpec CN analyzer (LECO Corp., St. Joseph, MI). The reported concentrations of C and N of the cover crops shoots from these analyses were on a 100% DM basis from drying samples to 105°C. However, to calculate N accumulation in kg N ha^{-1} the N concentrations were adjusted, because DM ha^{-1} was on 98% DM basis from drying at 65°C. The legume and rye components of the cover crop mixture were analyzed separately. We did not determine N accumulation in the legume component due to scavenging vs. biological N fixation. The soil samples taken prior to cover crop planting were analyzed for NO_3 N using the flow injection analyzer method (http://anlab.ucdavis.edu/using-the-lab/analysis/soils/312). Total soil C was determined by the combustion method (http://anlab.ucdavis.edu/using-the-lab/analysis/soils/320) and inorganic C by titration with 0.025N H_2SO_4 of carbonate and bicarbonate in a saturated paste extract (http://anlab.ucdavis.edu/using-the-lab/analysis/soils/220). Soil organic C was estimated by subtracting inorganic C from total soil C (Nelson and Sommers, 1982).

Statistical Analysis

All data were analyzed using SAS ver.9.2 (SAS Inst., Cary, NC). As suggested by Drummond and Vowler (2011), we presented the raw data and their 95% confidence interval (CI) to illustrate the data's variability, skewness, and scatter, and to provide a transparent and visual method to help us and readers make practical inferences about the results and their reproducibility (Cumming, 2012; Kirk, 1996); when CI are reported in the text they are within square brackets [ ]. Confidence intervals (95%) of paired differences (i.e., effect sizes) from Years 4 to 8, within systems, were calculated to evaluate the evidence of the magnitude of change in SOC and soil nitrate between years; the difference within each replication was calculated, followed by CI of the mean paired difference. Similarly, 95% CI of paired differences were calculated to compare changes from January to March in cover crop shoot biomass (DM, N accumulation, residue quality). Considering the criticisms of the null-hypothesis significance testing (NHST) that often encourage dichotomous (i.e., black and white) approaches to statistical analysis and can lead to misinterpretation of results (Anderson et al., 2000; Campbell et al., 2015; Carver, 1978; Cohen, 1994; Fidler et al., 2006; Hubbard and Lindsay, 2008; Lambdin, 2012; Nakagawa and Cuthill, 2007; Shrout, 1997) we chose to use CI as a standalone approach to statistical analysis. Confidence intervals are relatively uncommon in the agronomy literature (Campbell et al., 2015) but provide more reliable information about the replicability of experimental results than *P* values and NHST (Cumming, 2008), and encourage meta-analytical thinking (Cumming and Finch, 2001) that is increasingly being used to answer questions in a variety of scientific fields. The overlap between CI of independent groups (i.e., systems in our study) can be used as a robust graphical approach to compare group means using the "rule of eye" method (Cumming et al., 2007), whereby the smaller the overlap between CI, the stronger the evidence of a true difference. Using this method, 95% CI of independent groups can overlap considerably and still be considered different. For example, where $n \geq 10$, intervals that overlap by half of a CI arm (or one margin of error, MOE) are different at $P \approx 0.05$, and where $n = 3$ (less than in our study), $P \approx 0.05$ if CI of two groups overlap by one MOE (Cumming et al., 2007); in other words, $P \approx 0.05$ when MOEs completely overlap and the means are just touching the end of the CI where $n = 3$. In cases where the MOE differ for two groups being compared, their average MOE can be used to determine the overlap (Cumming et al., 2007); readers that are interested in learning more about this method are encouraged to use the free, interactive ESCI software (Cumming, 2012) to explore how sample size and variability affect the degree of overlap between two CI. We mention the relationship between CI and P values simply as a point of reference because unfortunately agricultural researchers are often more familiar with using P values than CI to make inferences about data. Furthermore, to help evaluate our data we encourage readers to view CI as "cat's eyes" (Supplemental Fig. S1) whereby the "fatness" of the cat's eye represents the plausibility of values at various points on the CI (Brielmann and Stolarova, 2015; Cumming, 2012). For example, with a 95% CI the cat's eye is fattest at the center of the CI indicating that values near the center of the CI are approximately seven times as plausible as those values at the far ends of the CI where the cat's eye narrows (Cumming, 2012). When viewing CI it is also helpful to keep in mind that "a 95% CI will on average capture 83.4% of future replication means" (Cumming et al., 2004). This CI comparison method is not adjusted to control the family-wise error rate.

We recognize that some readers may like to see an analysis of our data using a more traditional statistical approach, and therefore we have provided this in the supplemental information (Supplemental Fig. S3–S10). However, our discussion of the results will not be based on this more traditional NHST. In this analysis we used the MIXED procedure in SAS with year and system as fixed effects, block and block × system as random effects for the following response variables: cover crop shoot dry matter, N accumulation, N concentration, and C/N ratio. In these analyses the data were checked to meet the assumptions of ANOVA. For the analysis of the rye shoot C/N ratios for January we used the "group =" option in the random statement in the MIXED procedure to model a heterogeneous variance model for the year effect. The "lsmestimate" statement was used in these analyses to make comparisons between the three systems within each year. The P values of these multiple comparisons are reported with a comparision-wise (i.e., unadjusted) error rate and a Bonferroni adjusted family-wise error rate. Where the System effect was statistically significant at $P \leq 0.05$ and the System × Year interaction was not significant, multiple comparisons across years are presented.

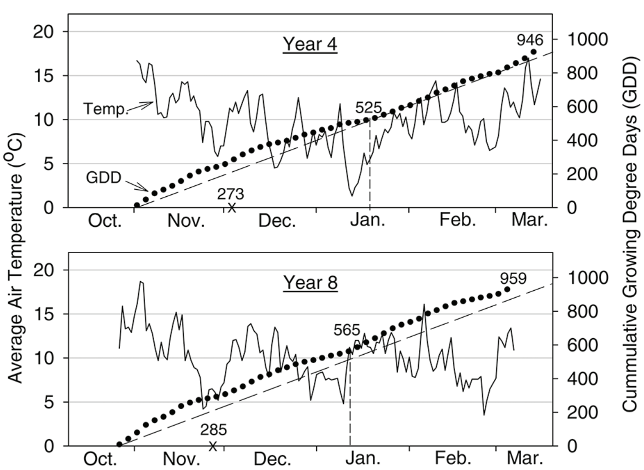

Fig. 1. Average air temperatures and growing degree days (GDD) during the cover cropping periods for Years 4 and 8 in Salinas, CA, from data at station no. 89 of the California Irrigation Management Information System (http://www.cimis.ca.gov). The GDD are calculated with the single sine method with 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 "×" on each x axis indicates the point that is 30 d after cover crop planting, and the number above the "×" is the number of GDD by this point in the season.

RESULTS AND DISCUSSION

Climate

Climatic differences across the first 8 yr of the experiment were presented previously (Brennan and Boyd, 2012a) and are only discussed briefly here for Years 4 and 8. Average daily air temperatures during cover cropping ranged from a high of 18.7°C in early November (Year 8) to a low of 1.3°C in January (Year 4), but typically were between 5 and 15°C (Fig. 1). Growing degree day (GDD) accumulation at 30 d after planting and at the January and March harvests showed that Year 4 was cooler overall than Year 8 (Fig. 1). For example, by the January harvest, cover crops had 40 fewer GDD in Year 4 than Year 8, although by the final harvest this difference was only 13 GDD. Cumulative rainfall during cover cropping was considerably less during Year 4 (123 mm) than Year 8 (234 mm) mainly due to a wetter period with more than 100 mm of rain from mid- to late December of Year 8 (Fig. 2). The cumulative monthly rainfall for the typical winter cover cropping period in this region (October–March) was 135 mm (Year 4) and 313 mm (Year 8); in comparison, average cumulative rainfall from October through March from 1994 to 2011 for this site was 313 mm indicating that Year 4 was much drier than normal.

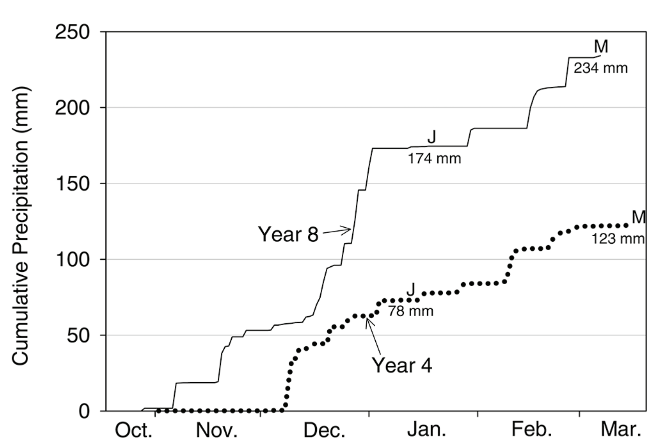

Fig. 2. Cumulative precipitation during the cover cropping periods for Years 4 and 8 in Salinas, CA. Data are from station no. 89 of the California Irrigation Management Information System (http://www.cimis.ca.gov). Both cover crops received 19 mm of irrigation to establish them after seeding. The "J" and "M" on the curves indicate the point of the biomass harvests in January and March.

Soil Organic Carbon and Nitrates Prior to Years 4 and 8 Cover Crops

Prior to planting the cover crops in the fall of Year 4, SOC in the top 30 cm of soil was approximately 2 g kg^{-1} higher in Systems 2 and 3 that had received compost annually compared to System 1 that never received compost (Fig. 3A, Supplemental Fig. S2). While there is a slight overlap in the CI of System 3 and the mean of System 1 at Year 4 that was due to the relatively low value for replicate 4 of System 3, the three other replicates in System 3 had higher SOC than all replicates in System 1 that year. The overlap in the CI of SOC in Systems 2 and 3 at the beginning of Year 4, where the means are approximately the same, is strong evidence of no practical difference in SOC between these systems at this time, and suggests that the higher average SOC in Systems 2 and 3 than System 1 were due primarily to the 15.2 Mg ha^{-1} yr^{-1} of compost added in Systems 2 and 3. It is interesting and somewhat surprising that the additional 22.1 Mg ha^{-1} from cover crop shoot DM (Brennan and Boyd, 2012a) in System 3 than in System 1 or 2 during the first 3 yr, and root C inputs (not measured) had no apparent effect on SOC by the beginning of Year 4. However, the SOC levels by the beginning of Year 8, after Systems 1 and 2 had been cover cropped one winter, and System 3 had been cover cropped seven consecutive winters, provide some evidence (despite the overlapping CI of System 2 with the means of Systems 1 and 3) that both compost and cover crops increased SOC because on average they were lowest in System 1, intermediate in System 2, and highest in System 3. This increasing pattern from Systems 1 to 2 to 3 at Year 8 occurred in all replicates except for replicate 2 where there was a slight decline (from 7.9 to 7.7 g kg^{-1}) in SOC from System 2 to 3 (Supplemental Figure S2). Across all systems, there was more variability in the SOC at Year 8 than Year 4 (Fig. 3A) which resulted in wider CI for SOC differences between years in all systems and considerable overlap between all means and CI (Fig. 3B).

Soil nitrates prior to planting the cover crops during Year 4 averaged 7 mg NO_3–N kg^{-1} dry soil in Systems 1 and 2 vs. 10 mg in System 3 (Fig. 4A, Supplemental Fig. S4). In contrast, prior to cover crop planting in Year 8, nitrate levels in Systems 1 and 2 were still relatively low (approximately 5–10 mg NO_3–N kg^{-1} dry soil), compared with an average of 22 mg in System 3. The clear increase in soil nitrate between years in System 3 but not in Systems 1 and 2 (Fig. 4B), may be related to the more frequent cover cropping in System 3 which provided more opportunity for N cycling from decomposing broccoli residue and biological N fixation from the legumes in the cover crop mixture. The levels of soil nitrate for these three systems in the present paper and other systems in this trial (Brennan and Boyd, 2012b) prior to cover cropping, were still relatively low compared with those in a conventional vegetable field in Salinas (67–83 mg NO_3–N kg of dry soil) at winter cover crop planting (Jackson et al., 1993). Furthermore, differences in soil nitrates in the three systems do not appear to be related to the productivity of the previous broccoli crop that were lower in Systems 1 and 2 than System 3 during 2006 (just prior to Year 4 cover cropping), but were relatively equivalent among systems during 2010 (prior to Year 8 cover cropping) (Brennan, unpublished data, 2010).

Cover Crop Population Densities

Cover crop densities were more variable during Year 4 than Year 8, but otherwise did not appear to differ between systems or years (Fig. 5A, 5B). Total cover crop densities averaged across all systems and years were 321 plants m^{-2} [95% CI, 302,340], and there were nearly twice as many legumes (mean = 209 m^{-2}, [196, 222]) as rye plants (mean = 111 m^{-2}, [98, 124]). The higher density of legume than rye plants was expected given that seeding density averaged across years was higher for the legumes (355 seed m^{-2}) than for rye (229 seed m^{-2}). Estimated emergence

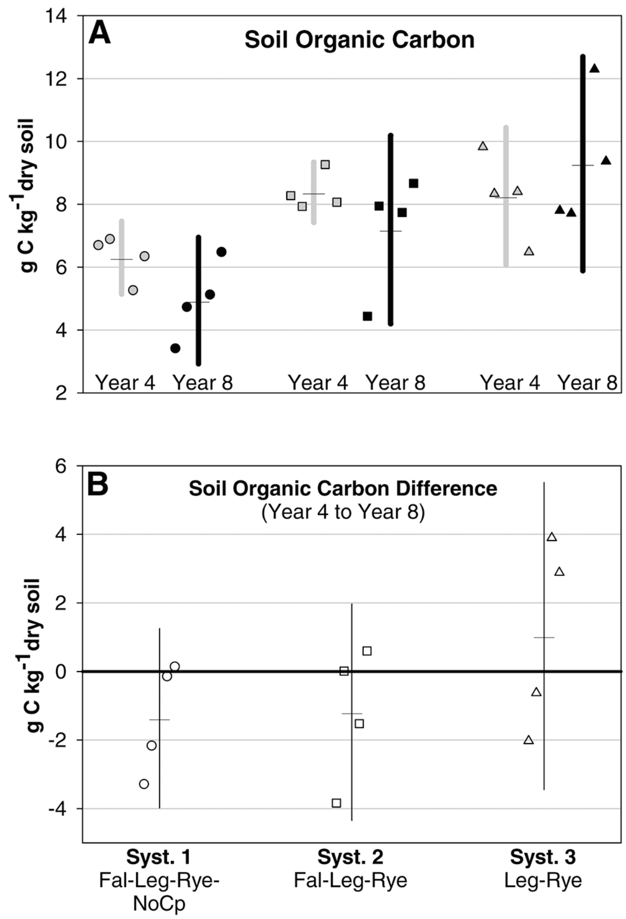

Fig. 3. (A) Soil organic carbon (SOC) in the top 30 cm of soil for three systems prior to planting cover crops during Years 4 and 8 and (B) the difference between years in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow ("Fal") for Years 1 to 3, and 5 to 7, cover cropped during Years 4 and 8, without compost ("NoCp"); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares or triangles and are in order of replicates 1 to 4 for each data cluster; the vertical bar within each data cluster is the 95% confidence interval (CI) with the mean at the central horizontal line on the bar. Means and CI in brackets [ ] of SOC for Systems 1, 2, and 3 were 6.3 [5.1, 7.5], 8.4 [7.4, 9.3], and 8.3 [6.1, 10.4] for Year 4, and 4.9 [2.9, 6.9], 7.2 [4.2, 10.2], 9.3 [5.9, 12.7] for Year 8. Mean and CI of SOC differences between years were –1.4 [–4.0, 1.3], –1.2 [–4.3, 2.0], and 1.0 [–3.4, 5.5] for Systems 1, 2, and 3, respectively. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

as a percentage of the planted seed, averaged across years and systems was 49% for rye, 59% for the legumes, and 55% total, indicating that considerable amounts of planted seed did not emerge. These emergence rates were lower than that of System 3 averaged across 8 yr where it was 73% or 342 total plants m^{-2} (Brennan and Boyd, 2012a). Several factors (germination rate, seedling vigor, predation, seed bed conditions) could have caused the lower than expected population densities. Within the legumes, densities averaged across years and systems were 150 vetch m^{-2} [139, 161], 34 pea m^{-2} [31, 37], and 25 faba bean m^{-2} [22, 28]. These relative proportions of the mixture are similar to those when this cover crop mixture was planted at a lower seeding rate (i.e., 140 kg ha^{-2}, 195 seed m^{-2}) in another system in the experiment (Brennan and Boyd, 2012a).

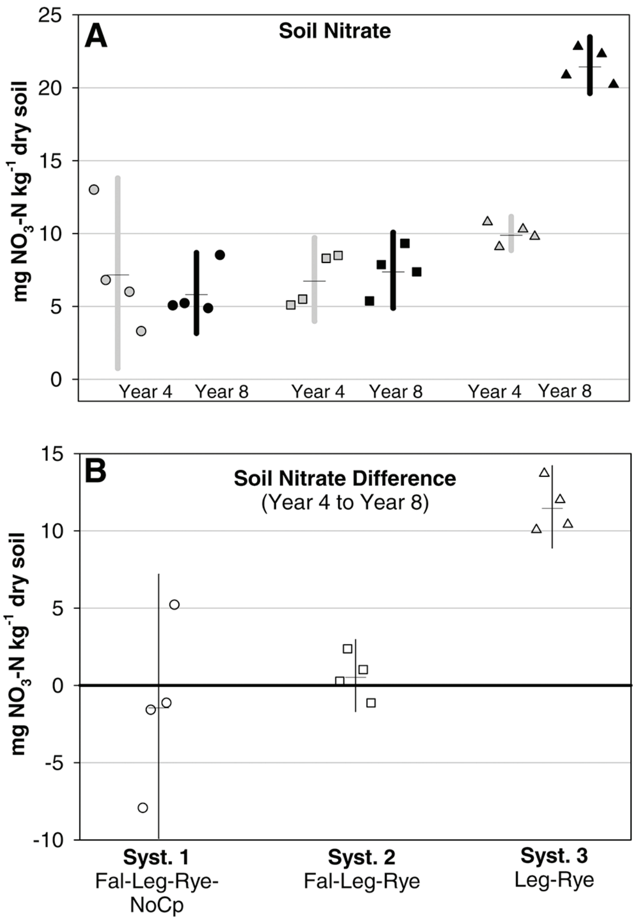

Fig. 4. (A) Soil nitrate concentrations in the top 30 cm of soil in three systems prior to planting cover crops during Years 4 and 8 and (B) the difference between years in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow ("Fal") for Years 1 to 3, and 5 to 7, cover cropped during Years 4 and 8, without compost ("NoCp"); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares, or triangles and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval (CI) with the mean at the central horizontal line on the bar. Means and CI in brackets [ ] of soil nitrate for Systems 1, 2, and 3, were 7.3 [0.8, 13.8], 6.9 [4.0, 9.7], and 10.0 [8.8, 11.2] for Year 4, and 5.9 [3.2, 8.7], 7.5 [4.9, 10.1], 21.6 [19.6, 23.5] for Year 8. Mean and CI of soil nitrate differences between years were –1.4 [–9.9, 7.2], 0.6 [–1.7, 3.0], and 11.6 [8.9, 14.2] for Systems 1, 2, and 3, respectively. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

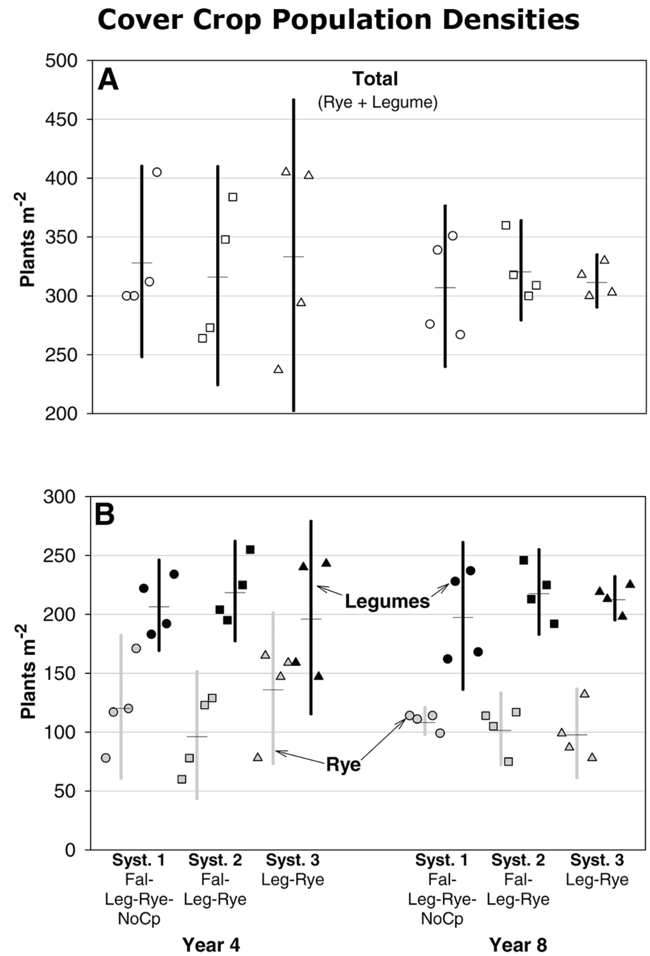

Fig. 5. Total, rye, and legume cover crop densities for three systems during Years 4 and 8 in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow ("Fal") for Years 1 to 3, and 5 to 7, cover cropped during Years 4 and 8, without compost ("NoCp"); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares, or triangles and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval (CI) with the mean at the central horizontal line on the bar. For Systems 1, 2, and 3, mean total densities and 95% CI in brackets [ ] were 329 [248, 410], 317 [224, 410], 335 [202, 467] for Year 4, and 308 [240, 376], 322 [280, 364], and 313 [291, 335] for Year 8. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

Cover Crop Shoot Biomass Production

Cover crops produced large amounts of biomass in all systems (Fig. 6, Supplemental Fig. S5 and S6). Total cover crop shoot biomass (Legume + Rye) by January averaged across systems ranged was 2.7 Mg ha^{-1} [2.5, 2.9] during Year 4, to slightly more (mean = 3.0 [2.7, 3.3]) during Year 8 (Fig. 7A). By season-end (March) both years, total biomass across systems had increased by an average of approximately 4 to 5 Mg ha^{-1} during Year 4, compared with approximately 3 to 4 Mg ha^{-1} during Year 8 (Fig. 6A, 6D). Despite the higher rainfall during Year 8 (Fig. 2), total cover crop biomass averaged across systems in March was 1.3 Mg ha^{-1} [0.3, 2.3] lower in Year 8 than in Year 4 (Fig. 7A); in contrast, there was some evidence of slightly more total biomass in January of Year 8 [−0.04, 0.6 Mg ha^{-1}] (Fig. 7A).

The overlap in CI and means of total cover crop shoot biomass between systems within harvest dates and years provides strong evidence that total biomass was unaffected by compost or winter cover cropping frequency (Fig. 6A). For example, while there was

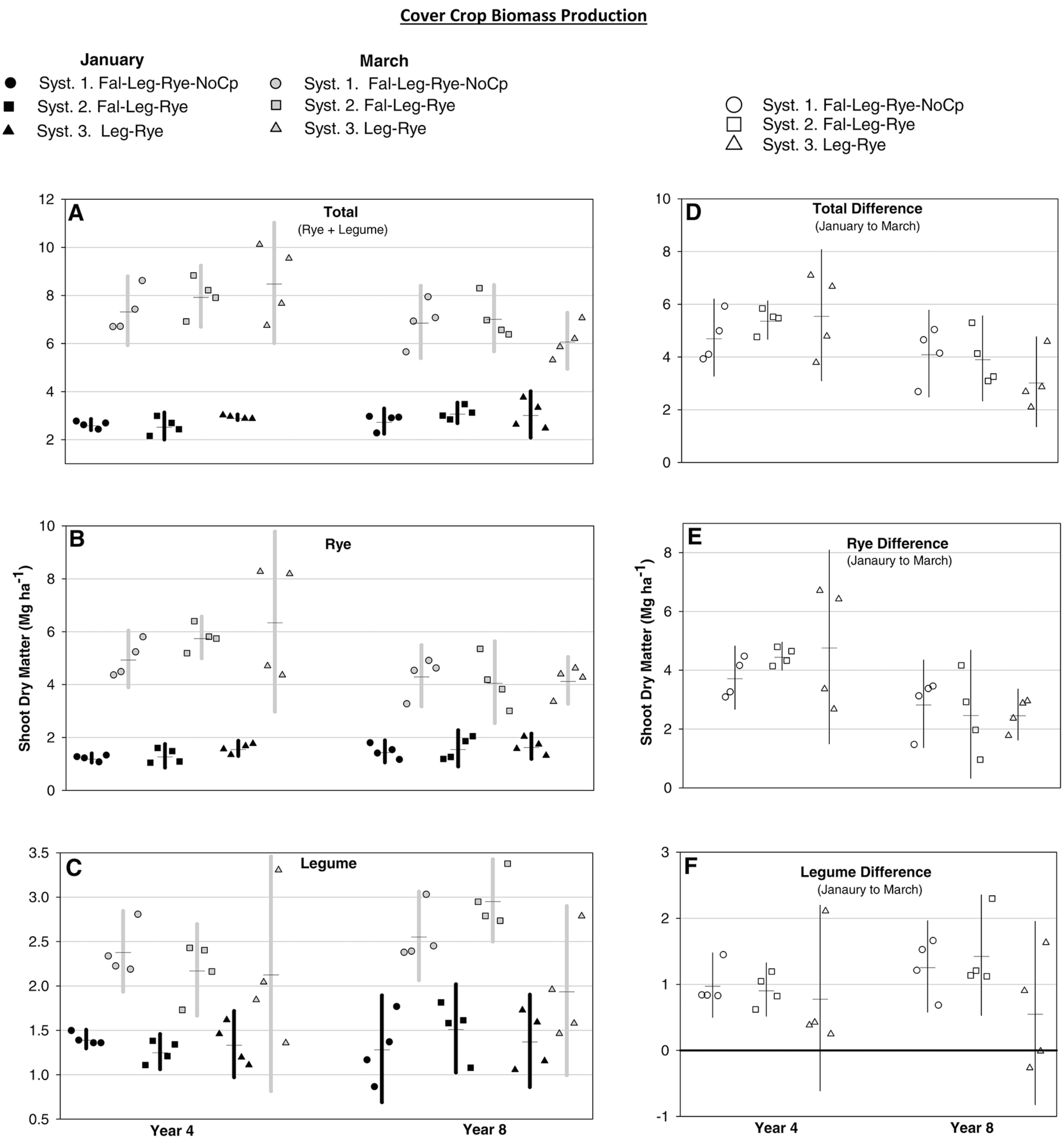

Fig. 6. (A, B, C) Total, rye, and legume aboveground cover crop biomass for three systems during January and March harvests in Years 4 and 8, and (D, E, F) the differences between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow ("Fal") for Years 1 to 3, and 5 to 7, cover cropped during Years 4 and 8, without compost ("NoCp"); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares, or triangles and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval with the mean at the central horizontal line on the bar. Differences (i.e., effect sizes) of total, rye, and legume biomass within year and from January to March are in panels D to F. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between confidence interval (CI) whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

a slight pattern of increasing average total cover crop biomass from systems 1 to 2 to 3 during March of Year 4, this pattern did not occur during Year 8 where biomass on average was lowest in System 3 that had received more organic matter inputs from cover crops and compost.

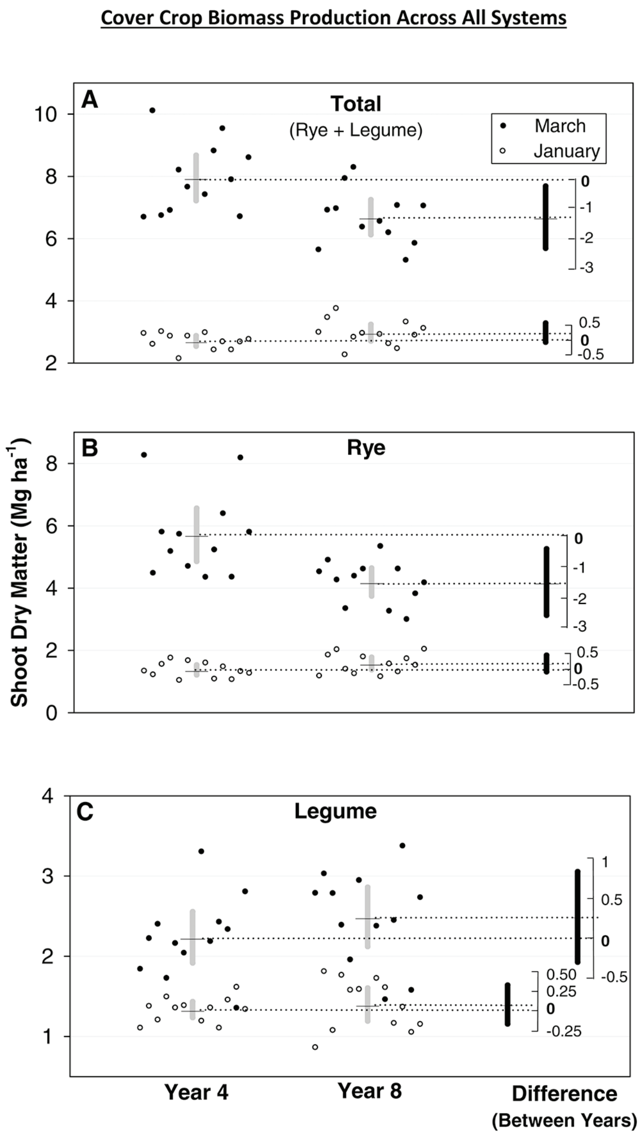

Fig. 7. Total, rye, and legume aboveground cover crop biomass across three systems during January and March harvests in Years 4 and 8 and the difference in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90% legumes and 10% rye. The cluster of 12 dots for each of the January and March harvests for each year are the raw data for the four replicates of each of three systems where the cover crops were grown. The raw data were randomly scattered so that points with similar values do not overlap; therefore the relative position of a data point for a given replicate may differ between years. The gray bar in the center of each data cluster is the 95% confidence interval (CI) with the mean (horizontal central line on each bar). The black bars on the right of the figure are the 95% CI of the mean difference (effect size) between Years 4 and 8; a floating *y* axis was added the right of the difference error bar to help visual the size of the difference. Note that the scale of the *y* axes are different between biomass types. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

Rye shoot biomass averaged across systems ranged from approximately 1 to 2 Mg ha^{-1} in January with slightly more variability and slightly higher biomass in Year 8 than 4 (Fig. 6B, 7B). By March, rye biomass had increased by an average of approximately 4 to 5 Mg ha^{-1} during Year 4 (with less rainfall), compared to an average increase of approximately 2 to 3 Mg ha^{-1} during the Year 8 (Fig. 6B, 6E). As with total shoot biomass, there were no clear or consistent differences in rye biomass production between systems either year. However, it is interesting to note that in March of Year 4, two of the four replicates produced more than 8 Mg ha^{-1} of rye in System 3 which had received compost and cover crops annually; the other two replicates in System 3 for March of Year 4 were about half as productive and similar to the lowest yielding replicates in System 1 (Fig. 6B). Averaged across systems, rye produced approximately 1.5 Mg ha^{-1} more biomass in March during Year 4 than 8 (Fig. 7B) despite the higher rainfall in Year 8 and the slightly higher biomass in January of Year 8 (Fig. 6B); rye is well-known for its cold hardiness (Fowler and Carles, 1979) and may have benefited at the expense of the legumes by a 6 d period in January of Year 4 when temperatures were below 5°C (Fig. 1). This higher production by rye in the mixture during the drier year (4) is consistent with approximately 1 Mg ha^{-1} higher production of monoculture rye in other systems during Year 4 (Brennan and Boyd, 2012a).

The legume component of the cover crop mixture was much less productive overall than the rye component (Fig. 6B, 6C). By January, the legumes usually produced 1 to 1.5 Mg ha^{-1} of shoot biomass during Year 4 and similar or slightly more during Year 8 (Fig. 6C). Legume biomass from January to March showed an average increase of approximately 1 to 1.5 Mg ha^{-1} for Systems 1 and 2, whereas for System 3 the change was more variable and less consistent (Fig. 6C, 6F). This is illustrated in the replicate data clusters (Fig. 6C), and smaller CI for the January to March difference (Fig. 6F) for Systems 1 and 2 (that never included zero) compared with System 3 (that always included zero). While the wide CI for the legume biomass for System 3 in March overlapped with the mean for System 1 both years and with the mean for System 2 in Year 4 (Fig. 6C), the fact that the legume difference from January to March for System 3 always overlapped with zero to −0.5, compared with those of Systems 1 and 2 that were always positive (Fig. 6F), provides evidence that legume growth from January to March was consistently greater in Systems 1 and 2 (that were seldom cover cropped) than in System 3; however, there is considerable uncertainty in the growth of the legumes in System 3 given that the CI of the difference for this system overlapped with mean difference of the other two systems. It is interesting and unclear why in System 3, March legume biomass in a single replicate (replicate 3 in Year 4; replicate 4 in Year 8) was considerably more productive than the other replicates (Fig. 6C); these higher replicates increased the upper bound of the CI of the difference in legume biomass from January to March (Fig. 6F).

Averaged across systems, legumes produced 0.3 Mg ha^{-1} [−0.3, 0.8] more biomass by March during Year 8 (with more rainfall) than Year 4 and a similar trend also occurred in January (Fig. 7C); however, in both cases the CI overlapped with zero indicting considerable uncertainty about the differences between years in legume growth across systems. The slight trend of increased productivity of legumes when rainfall was more abundant agrees with our previous work with several different legume–cereal mixtures in California (Brennan and Boyd, 2012a; Brennan et al., 2009, 2011b) and with pea–barley studies in Europe (Launay et al., 2009). Drought stress can affect biological N fixation by legumes and reduce the competitive ability of legumes in mixtures with grasses (Ledgard and Steele, 1992; Ofori and Stern, 1987).

Legume biomass across years accounted for an average of 45 to 53% of the total cover crop shoot biomass in January (Fig. 8A, Supplemental Fig. S7) across years, compared to a March average of 26 to 33% (Year 4) vs. 32 to 43% (Year 8). This decline in the percentage of legume biomass over the season agrees with our previous work with several different legume–cereal cover crops in California (Brennan et al., 2009, 2011b). It is important to highlight that there was more evidence of an overall decline in the percentage of legume biomass from January to March across all treatments during Year 4, where there was less rainfall, than during Year 8 (Fig. 8B); this is illustrated by the CI of the difference for all systems that all were closer to and overlapped with zero during Year 8.

Cover Crop Shoot Nitrogen Accumulation

Total cover crop N accumulation during Year 4 typically ranged from 80 to 120 kg^{-1} by January with an average increase of 38 to 61 kg ha^{-1} by March (Fig. 9A, 9D, Supplemental Fig. S8). During Year 8, the change in total cover crop shoot N from January to March was less apparent, especially in Systems 2 and 3 where the CI extended below zero. Nitrogen accumulation by the rye biomass followed a similar pattern as for total biomass, although the difference from January to March was even less apparent during Year 8 (Fig. 9B, 9E). The greater rye N accumulation from January to March during Year 4 is consistent with the greater increase in rye biomass that year (Fig. 6B, 6E).

Both years, N accumulation by the legumes was an average of 50 to 60 kg ha^{-1} in January and usually 60 to 80 kg ha^{-1} in March (Fig. 9C). The change from January to March was most variable and inconsistent in System 3 compared to Systems 1 and 2 (Fig. 9F). For example, the CI of the difference in legume N accumulation from January to March for System 3 extended from less than –30 to approximately 40 to 60, whereas the CI of the difference with Systems 1 and 2 were mostly positive with a mean difference of approximately 10 to 20 kg N ha^{-1} from January to March (Fig. 9F). While there was considerable overlap in the means and CI for the difference among all three systems both years, there is more evidence across years that legume shoot nitrogen increased with Systems 1 and 2, whereas the situation was less apparent with System 3. The trend toward greater N accumulation in System 1 and 2 than 3 was likely related to legume biomass production which may indicate greater N fixation in Systems 1 and 2 due to their lower soil nitrate concentrations in most replicates both years (Fig. 4A).

Cover Crop Residue Quality (Nitrogen Concentration and Carbon/Nitrogen Ratio)

Nitrogen concentrations of the cover crops varied considerably through the season depending on biomass type, system, and year (Fig. 10, Supplemental Fig. S9). For example, in January, the average N concentration across all biomass types was always greater than 30 g kg^{-1} (Fig. 10A–10C) and by March had declined by an average across systems and years of 18 g kg^{-1} for total biomass, 21 g kg^{-1} for rye, and 11 g kg^{-1} for legume biomass

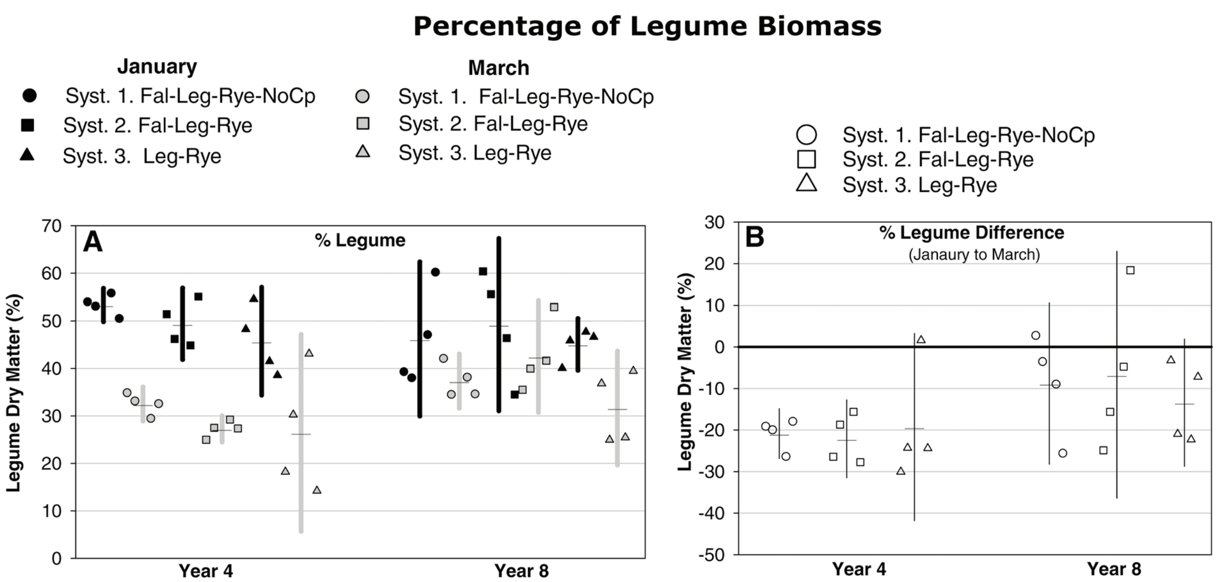

Fig. 8. (A) Percentage of legume biomass of total cover crop biomass for three systems during January and March in Years 4 and 8, and (B) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow ("Fal") for years 1 to 3, and 5 to 7, cover cropped during Years 4 and 8, without compost ("NoCp"); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares, or triangles and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval (CI) with the mean at the central horizontal line on the bar. Differences (i.e., effect sizes) in the percentage of legume biomass from January to March within year are in panel B. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

(Fig. 10D–10F). Nitrogen concentrations of legume biomass did not vary in a consistent way between systems. However, N concentrations in rye did show an increasing trend from Systems 1 to 3 during both years and harvests. For example, in March during Year 8, rye in System 3 which had received the most organic matter inputs, had an average of 10 g kg^{-1} higher N concentrations than rye in System 1 that had receive the least organic matter inputs; rye N concentrations in System 2 were intermediate in March of both years.

Carbon/N ratios of cover crops shoots were usually between 9 and 14 in January across all biomass types (Fig. 11A, 11B, 11C, Supplemental Fig S10), and by March had increased by an average of 9 to 12 for total biomass (Fig. 11D), 12 to 22 for rye (Fig. 11E), but only 4 to 6 for the legume component (Fig. 11F). In March of both years, rye shoots in System 1 had the consistently highest average C/N, followed by System 2 where they were intermediate, and then System 3 with the lowest C/N (Fig. 11B); this general pattern also occurred in January of Year 8. The data also indicate that

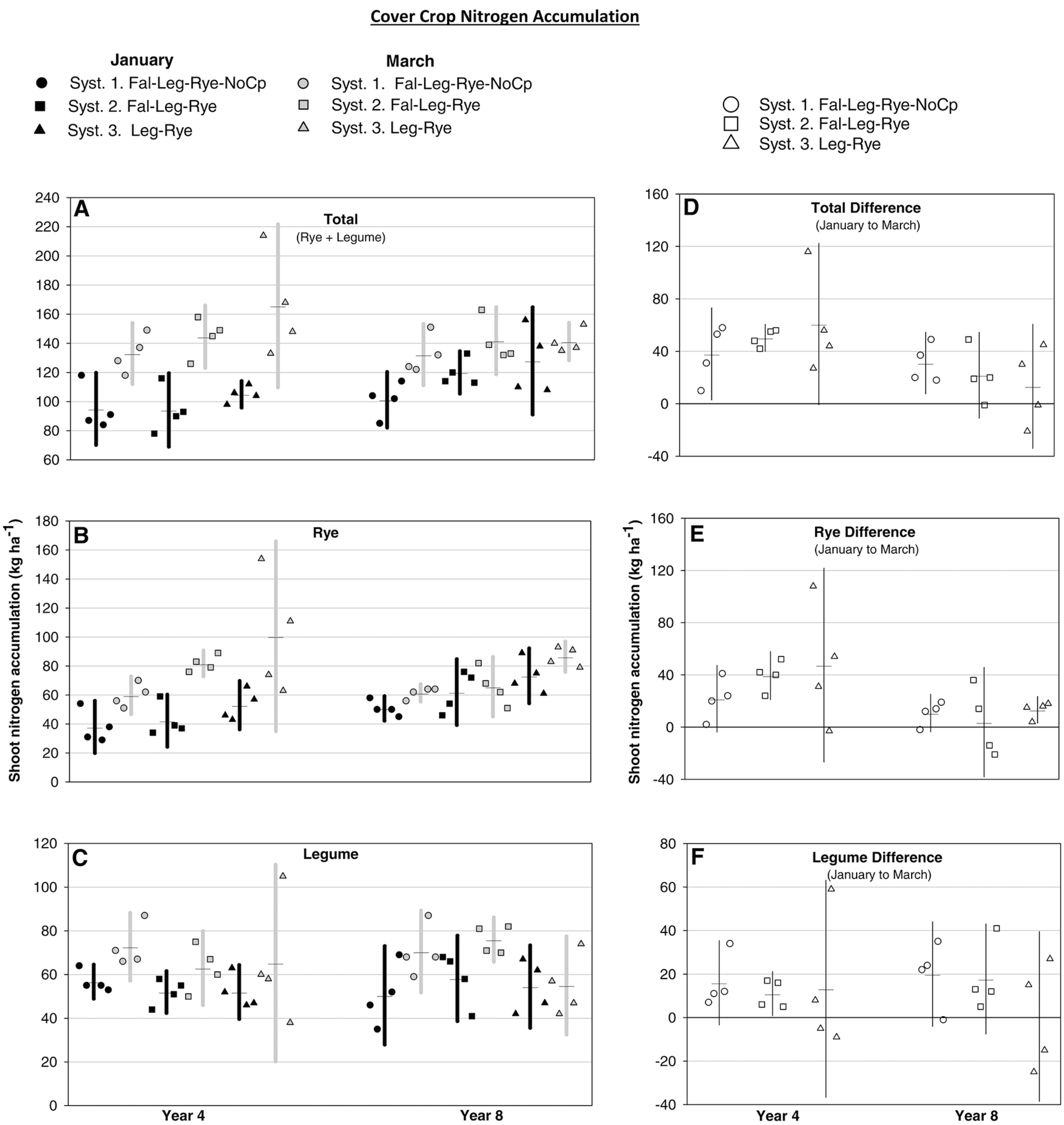

Fig. 9. (A, B, C) Total, rye, and legume shoot nitrogen accumulation for three systems during January and March harvests in in Years 4 and 8, and (D, E, F) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow ("Fal") for Years 1 to 3, and 5 to 7, cover cropped during Years 4 and 8, without compost ("NoCp"); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as circles, squares, or triangles clusters and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval with the mean as the central horizontal line on the bar. Differences (i.e., effect sizes) of total, rye, and legume biomass within year and from January to March are in panels D to F. Note that the scale of the y axes are different between biomass types. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between confidence intervals whereby the smaller the overlap between confidence intervals, the stronger the evidence of a true difference.

the C/N of rye from January to March increased more in System 1 (19–22 average difference, Fig. 11E), than System 2 (17–18), or System 3 (12–16); however, the smaller overlap of the CI of the difference of Systems 1 and 3 provide the most evidence of differences between Systems 1 and 3 where organic matter inputs differed most. Moreover, C/N ratios, within a system, tended to be higher in rye during Year 4 when rye was more productive (Fig. 11B), whereas the legume C/N ratios were usually higher during Year 8 when legumes were more productive (Fig. 11C). The general pattern of lower CI for the difference in legume C/N from January to March for Year 4 than 8 suggests that there was more of a change in C/N overtime during Year 8 (Fig. 11F); however, there pattern is relatively weak because in all systems the CI for Year 8 always overlapped with the means of Year 4.

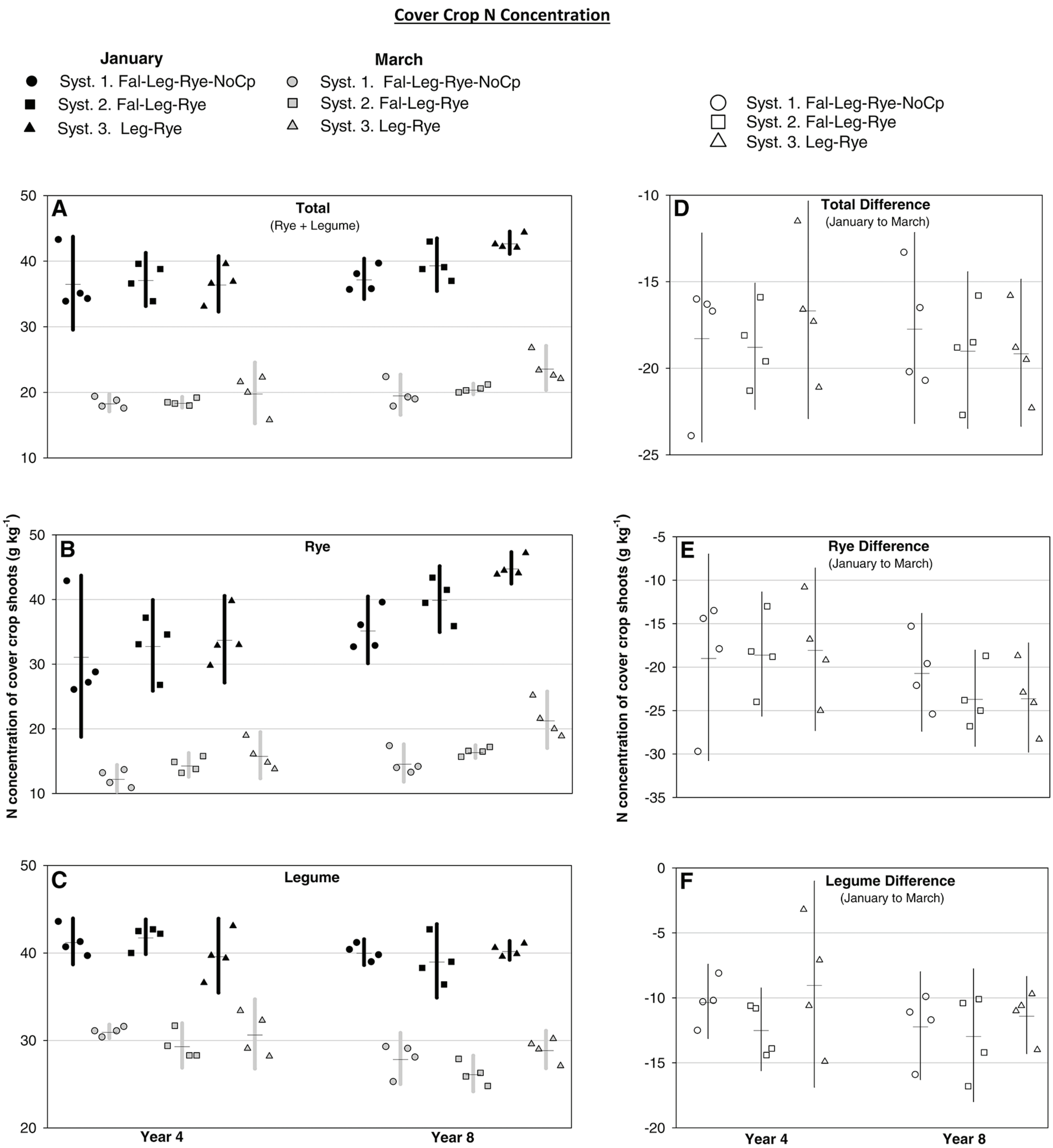

Fig. 10. (A, B, C) Cover crop shoot nitrogen concentration of total, rye, and legume cover crop shoot biomass for three systems during January and March harvests in Years 4 and 8, and (D, E, F) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90 and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow ("Fal") for Years 1 to 3, and 5 to 7, cover cropped during years 4 and 8, without compost ("NoCp"); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as circles, squares, or triangles clusters and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval with the mean at the central horizontal line on the bar. Differences (i.e., effect sizes) of total, rye, and legume biomass within year and from January to March are in panels D to F. Note that the scale of the y axes are different between biomass types. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between confidence intervals whereby the smaller the overlap between confidence intervals, the stronger the evidence of a true difference.

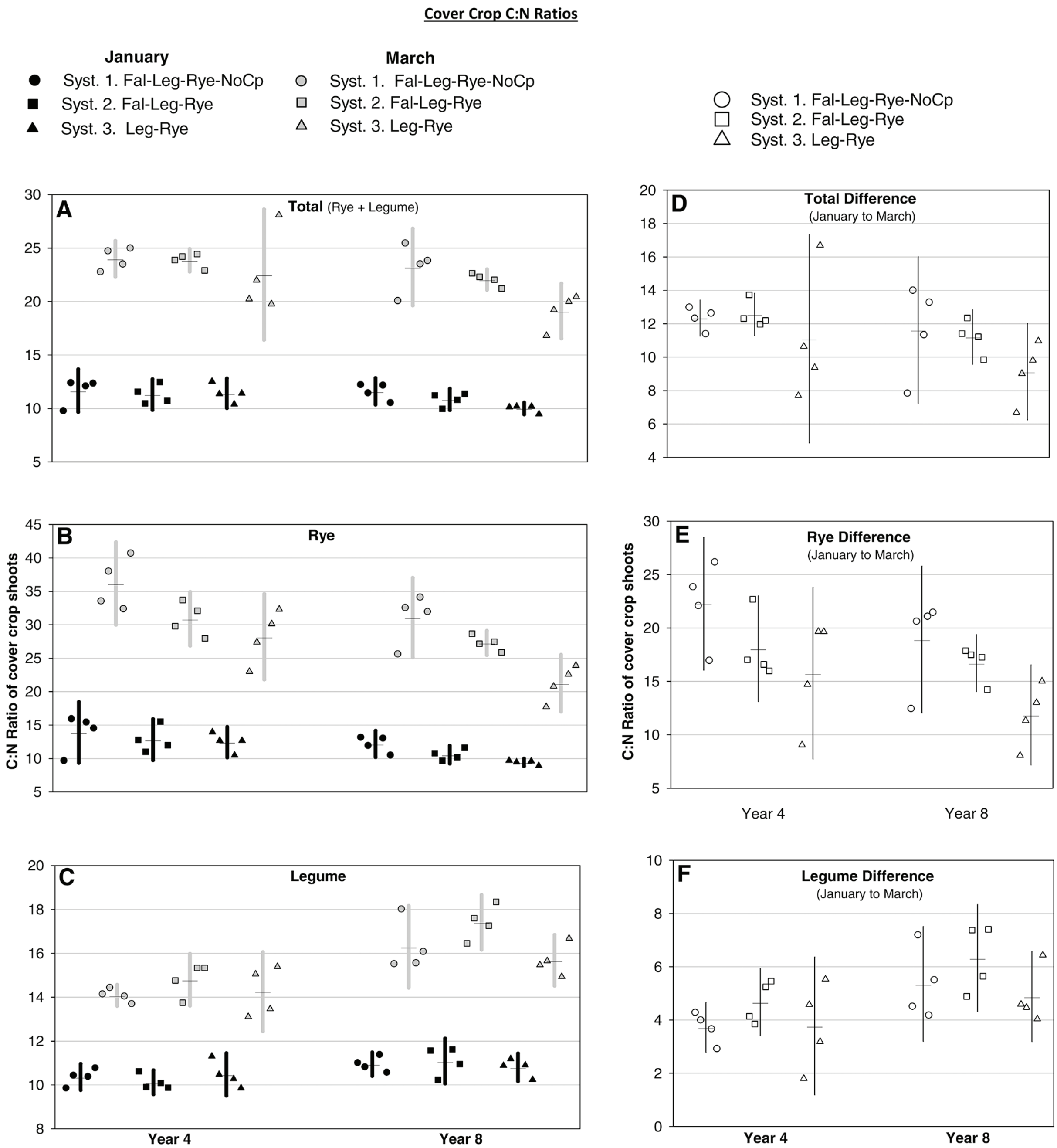

Fig. 11. (A, B, C) Cover crop shoot C/N ratios total, rye, and legume cover crop shoot biomass for three systems during January and March harvests in Years 4 and 8, and (D, E, F) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90 and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow ("Fal") for Years 1 to 3, and 5 to 7, cover cropped during Years 4 and 8, without compost ("NoCp"); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as circles, squares, or triangles clusters and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval (CI) with the mean at the central horizontal line on the bar. Differences (i.e., effect sizes) of total, rye, and legume biomass within year and from January to March are in panels D to F. Note that the scale of the *y* axes are different between biomass types. The "rule of eye method" (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

Practical Implications

The growth dynamics of legume–cereal cover crop mixtures in high-value vegetable rotations are complex due to competition between mixture components that can be influenced by mixture composition (i.e., the proportion of legume vs. cereal seed), weather difference between years, and soil differences (Brennan and Boyd, 2012a; Brennan et al., 2011a, 2011c). The results described here provide several unique insights on how different soil management strategies with cover crops and compost in high-input vegetable rotations can affect mixture dynamics, and illustrate how several types of data collected over a relatively long time period can help us to understand this complexity. For example, despite evidence of soil C and N differences among the three systems over time (Fig. 3 and 4) due to large differences in the amount and type of organic matter inputs, total biomass production of the legume–rye mixture at season-end was relatively similar in all systems within both years (Fig. 6A). This is particularly surprising given the relatively large differences in rainfall (>100 mm) between years (Fig. 2). This illustrates that total mixture biomass production within a given field can mask differences in soil quality caused by previous management practices like cover crop frequency and compost additions (Brennan and Acosta-Martinez, 2017; Ferris et al., 2012). However, legume biomass production of the mixture was somewhat indicative of the differences in soil management between the three systems, as shown by the higher (i.e., 0.5–1 Mg ha^{-1}) and less variable final legume biomass in Systems 1 and 2, vs. System 3 both years (Fig. 6C). While the growth of a uniformly planted cover crop may provide a simple and visual diagnostic into parts of a field with potential problems (low soil fertility, drainage, compaction, etc.), our data suggest that such underlying differences may be difficult to detect with legume–cereal mixtures, particularly when there are multiple legume components (i.e., vetch, pea, faba bean) which together only represent approximately 25 to 40% of the final cover crop biomass as in our study.

Integrating cover crops into vegetable rotations can be challenging in regions like the Salinas Valley where high land rents put pressure on growers to bare fallow fields over the winter to simplify early spring vegetable plantings (Brennan, 2017). However, winter cover cropping seems particularly useful after crops like summer broccoli that leave large amounts of leachable N in their residue after harvest. For example, in this study, the broccoli shoot oven-dry matter on 28 Sept. 2010 (2 d before the commercial scale harvest began) averaged across systems was 60 g per transplant and had a N concentration of 3.6% At a typical high density spacing of approximately 119 thousand broccoli transplants ha^{-1} (Brennan, 2016) this shoot biomass would contain more than 250 kg N ha^{-1} most of which remains in the field after harvest because the harvest index for broccoli is typically quite low (i.e., 0.24, Smith, unpublished data, 2014). The annual winter cover cropping that occurred in System 3 would presumably recycle more of this residual N and reduce potential leaching than occurred in Systems 1 and 2 that were only cover cropped every fourth winter. This recycling of N combined with the potential biological fixation from the legume component may explain the higher total soil nitrate in System 3 vs. Systems 1 and 2 prior to cover crop planting that was most apparent in Year 8 (Fig. 4A). While systems with legume–rye mixtures in this experiment typically had about 40 kg ha^{-1} more N in their cover crop shoots than occurred in systems with only mustard or rye cover crops (Brennan and Boyd, 2012b), the seed cost of legume–rye cover crops mixtures are several times more costly than non-legume seed (Brennan and Boyd, 2012a). This cost difference and the inability of legume–cereals mixtures to adequately weed suppress winter weed growth and seed production unless they are planted at high seeding rates (i.e., >250 kg ha^{-1}) have raised questions about whether legume–cereal mixtures are well-suited for organic vegetable production systems in California (Brennan, 2014).

California growers in regions such as the Salinas Valley that use winter cover crops have historically relied on winter rainfall to meet cover crop moisture needs, although sprinkle irrigation may be used to establish a stand. The similar growth of the legume–rye mixture in the three systems during years with large differences in winter rainfall suggests that winter rainfall these 2 yr had relatively little impact on the overall productivity of the cover crop or their ability to scavenge large amounts of N in their shoots. We speculate that this may have been due in part to the ability of the cover crops to utilize residual soil moisture from the previous irrigated broccoli crop each year. The rainfall patterns during the past several winters (2006–2015) in this region have been somewhat less conducive to rain-fed winter cover cropping due to lower overall rainfall and the relatively long dry periods particularly during January. For example, there was less than 40 mm of rain in January during seven of the past 10 yr (2006–2015), compared with the previous 10 yr (1996–2005) when only 3 yr had less than 40 mm of rainfall in January (CIMIS, station no. 116). Despite this challenge, high-biomass winter cover cropping is still considered an excellent strategy to add organic matter and to reduce nitrate leaching from previous vegetable crops in this region. Recent work with low-residue cover crops in the Salinas Valley also look promising due to their ability to increase groundwater recharge by reducing winter runoff (Heinrich et al., 2014); low-residue cereal cover crops are terminated with a conventional herbicide after producing relatively little biomass (1 Mg ha^{-1}, oven-dry shoots) that decomposes quickly, and in contrast to a standard cover crop, does not typically delay or complicate spring vegetable planting (Brennan, 2017). A study in California's Sacramento Valley found that after field capacity was reached, winter cover crops reduced runoff and increased infiltration compared with bare fallow fields (Joyce et al., 2002), but others (McGuire et al., 1998; Mitchell et al., 1999) found that cover crops in California can deplete soil moisture. This highlights the need for careful management of cover crop termination to achieve potential water conservation benefits (Alonso-Ayuso et al., 2014), and the need for research on alternative cover crop management strategies (Brennan, 2017).

Managing cover crop residue in rotations with small seeded vegetable crops can be challenging because the residue can hamper the precision, vegetable planting equipment and delay planting when farmers need to wait for the residue to decompose sufficiently before planting. This can be particularly difficult with cover crops like rye that can develop relatively lignified residue with high C/N ratios (i.e., >30); a C/N ratio of 20:1 is typically considered the dividing line between N immobilization and release from decomposing plant residue in soil (Iritani and Arnold, 1960). Our results suggest that frequent cover cropping with a legume–rye cover crop as occurred in System 3 improved residue quality (i.e., increased N concentrations, reduced C/N ratios) which could hasten cover crop residue decomposition and thus reduce residue management challenges in subsequent vegetables. However, it is unclear if the relatively small differences in C/N ratios of 23 to 22 in Systems 1 and 2, respectively, vs. 19 in System 3 (Year 8, Fig. 11A) would have a practical effect on management. It is important to note that while adding a legume to a mixture, reduces the overall C/N of the mixture biomass, the presence of the legume in the mixture also can reduce the C/N of the non-legume component like rye (Brennan et al., 2013).

CONCLUSION

To our knowledge this is the first report on the response of legume–cereal cover crops to different soil management strategies in high-value vegetable production systems over a relatively long period. At the beginning of Year 8 (i.e., prior to cover crop planting) the cumulative inputs of organic dry matter in Mg ha^{-1} from cover crop shoots and compost in the three systems were: System 1 (7.4 cover crop), System 2 (8.0 cover crop + 106.4 compost), System 3 (53.8 cover crop + 106.4 compost); the cover crop dry matter inputs for System 3 for Years 1 to 3, and Years 5 to 7 were from Brennan and Boyd (2012a). Despite these large differences in organic matter inputs between systems which in turn affected soil C and N, the overall performance of the cover crop mixture was surprisingly similar between systems in terms of total shoot biomass production and total N accumulation. This stability illustrates the remarkable ability of legume–cereal mixtures to perform consistently well under a variety of conditions, which is likely due to the N scavenging ability of the rye component and the N fixing ability of the legume component. Our results suggest that cover crop residue quality was somewhat higher in the System 3 that was cover cropped every winter and also received compost annually. In future research with cover crops and compost in vegetable production, it would be useful to include treatments with frequent cover cropping, with and without compost.

SUPPLEMENTAL MATERIAL

This section includes several figures to help readers better understand our statistical analysis that relied on raw data and confidence intervals: (i) Supplemental Fig. S1 illustrating how to visualize confidence intervals as "cats eyes", (ii) Supplemental Fig. S2 showing the arrangement of the raw data clusters for replicates 1 to 4, and (iii) Supplemental Fig. S3 to S10 with the results of more traditional statistical approach to data analysis alongside the published figures.

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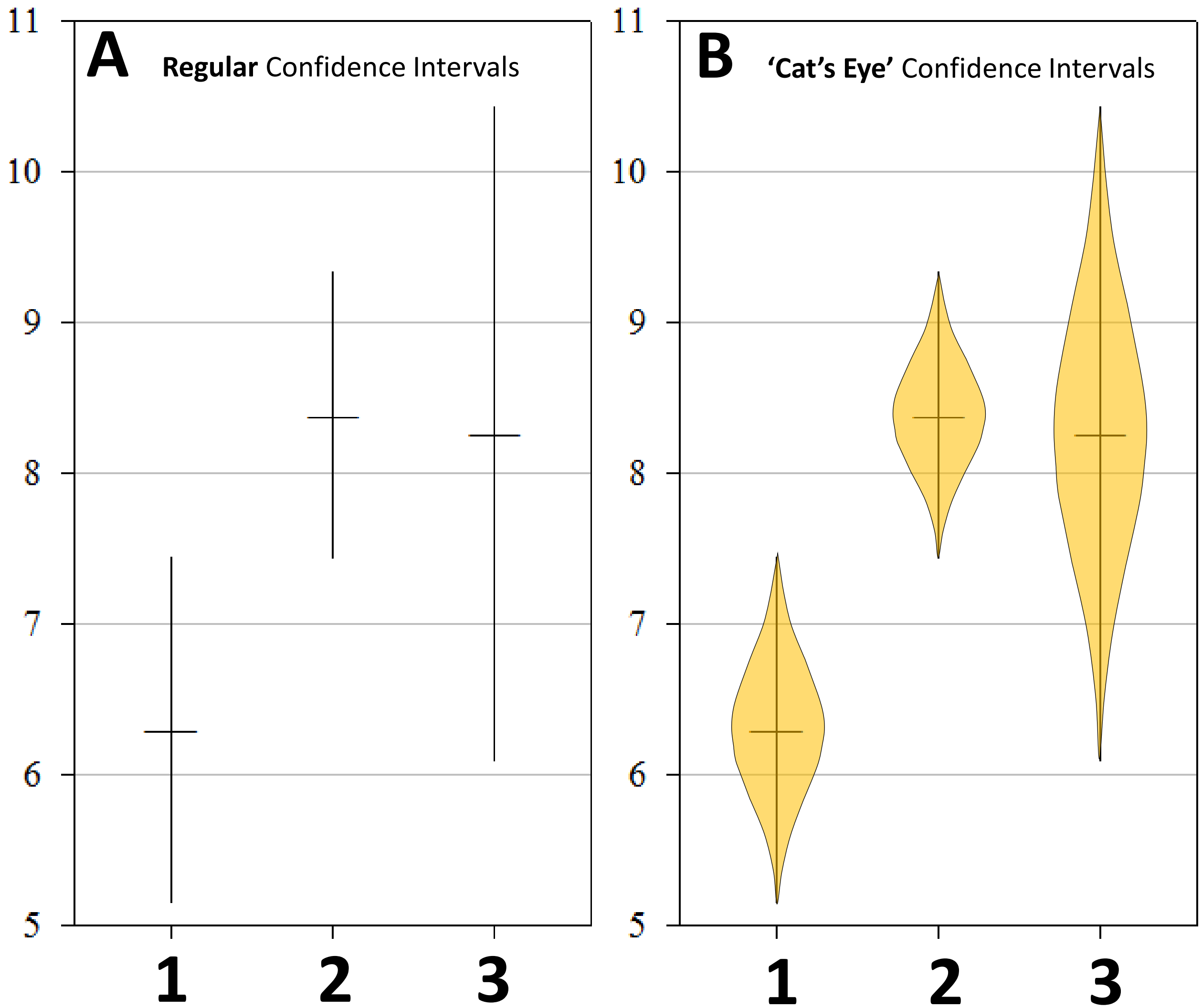
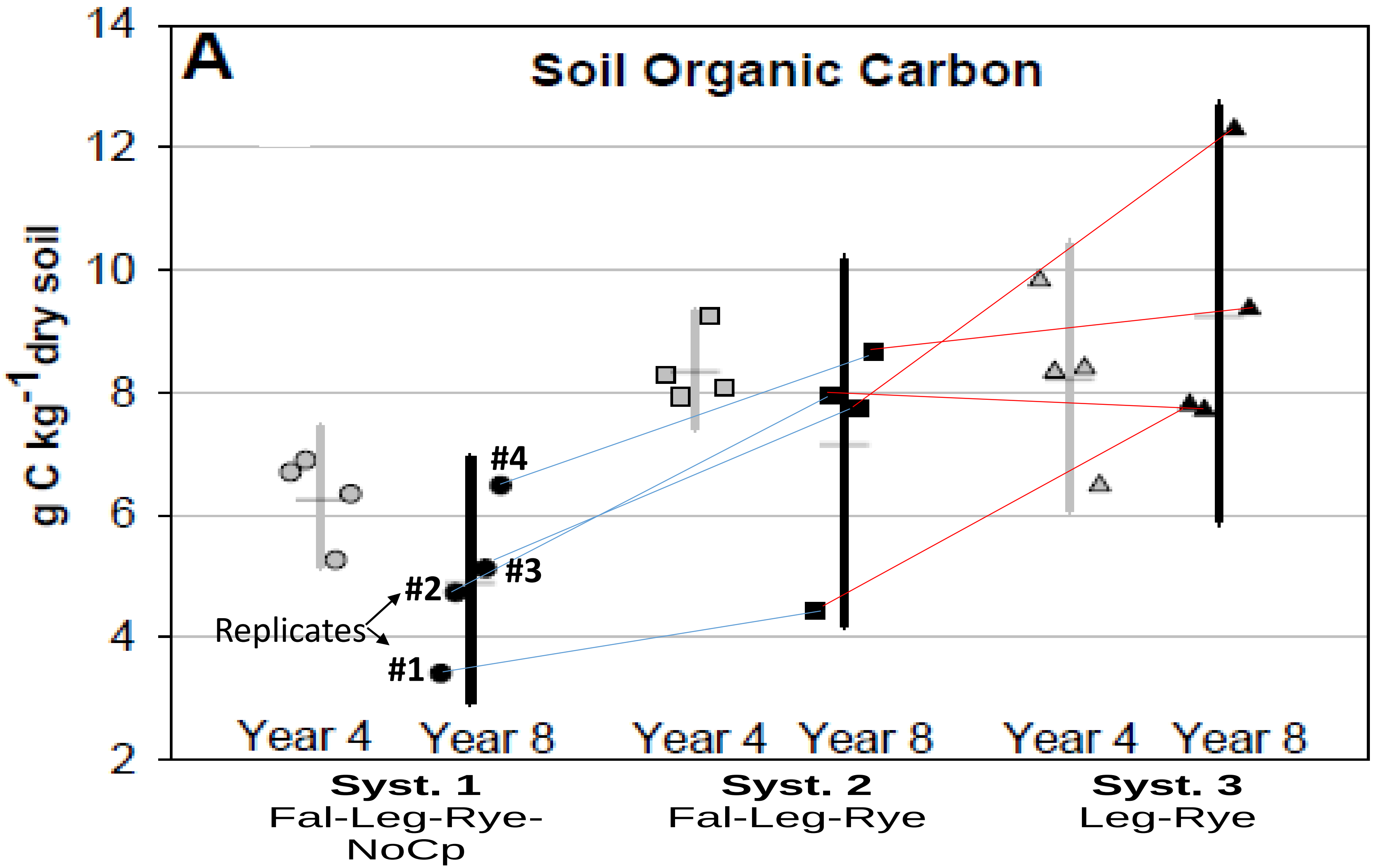


Supplemental Fig. 1. Confidence intervals (95%) for three experimental treatments where n=4. Plot A shows the confidence intervals (CI) as vertical lines with the mean value at the horizontal central line. Plot B has the same CI as plot A, however, 'cat's eyes' have been added to the intervals to help illustrate the plausibility of the true mean for each treatment. The most plausible areas are at the 'fattest' part of the cat's eye, for example, in treatment 3 the most plausible area is between approximately 7.5 and 9. Cumming (2014) suggested that when we see CI as in plot A, it can be helpful to visualize a 'cat's eye' "which is a beautiful picture of the uncertainty of our data." Cumming G. 2014, Observer, March, No. 3. There's life beyond .05. http://www.psychologicalscience.org/index.php/publications/observer/2014/march-14/theres-life-beyond-05.html



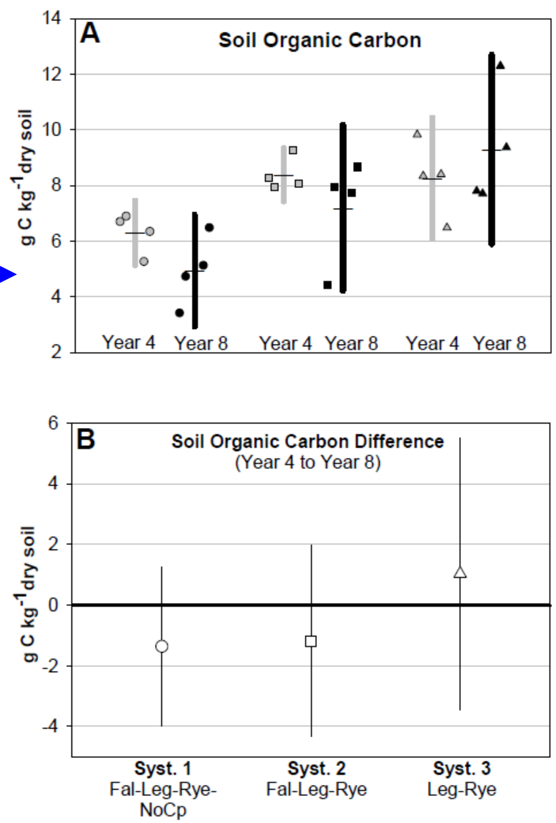
Supplemental Figure 2. Soil organic carbon (SOC) in the top 30 cm of soil for three systems prior to planting cover crops during Years 4 and 8 in the Salinas Organic Cropping Systems trial at Salinas, CA. This figure was modified from Figure 3A in the paper. Blue lines were added to illustrate the change in SOC at Year 8 from System 1 to 2 within each of the four replicates (#1 to 4) and red lines show the change from System 2 to 3. In all replicates there was an increase in SOC from System 1 to 2 to 3, except with replicate #2 where there was slight decline from System 2 to 3. See Figure 3 in the paper for more details on the three systems.

Supplemental Fig. 3. (A) Soil organic carbon (SOC) in the top 30 cm of soil for three systems prior to planting cover crops during Years 4 and 8 and (B) the difference between years in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume–rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1- Winter fallow (“Fal”) for Years 1 to 3, and 5 to 7, cover cropped duringYears 4 and 8, without compost (“NoCp”); System 2- Same as System 1 but received annual compost additions; System 3- Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares or triangles and are in order of replicates 1 to 4 for each data cluster; the vertical bar within each data cluster is the 95% confidence interval (CI) with the mean at the central horizontal line on the bar. Means and CI in brackets [ ] of SOC for Systems 1, 2, and 3 were 6.3 [5.1, 7.5], 8.4 [7.4, 9.3], and 8.3 [6.1, 10.4] for Year 4, and 4.9 [2.9, 6.9], 7.2 [4.2, 10.2], 9.3 [5.9, 12.7] for Year 8. Mean and CI of SOC differences between years were –1.4 [–4.0, 1.3], –1.2 [–4.3, 2.0], and 1.0 [–3.4, 5.5] for Systems 1, 2, and 3, respectively. The “rule of eye method” (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

ANOVA
P-values

Year 0.52
Syst. **0.02**
YxS 0.21

P-values ≤0.15 are highlighted in **blue.**



Year	Soil Organic Carbon Comparison	Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	**0.10**	0.58
Year 4	Syst. 1 vs 3	**0.14**	0.83
Year 4	Syst. 2 vs 3	0.82	1.00
Year 8	Syst. 1 vs 2	**0.05**	0.27
Year 8	Syst. 1 vs 3	**<0.01**	**0.01**
Year 8	Syst. 2 vs 3	**0.10**	0.58
Year 4 & 8	Syst. 1 vs 2	**0.03**	**0.08**
Year 4 & 8	Syst. 1 vs 3	**0.01**	**0.02**
Year 4 & 8	Syst. 2 vs 3	0.29	0.88

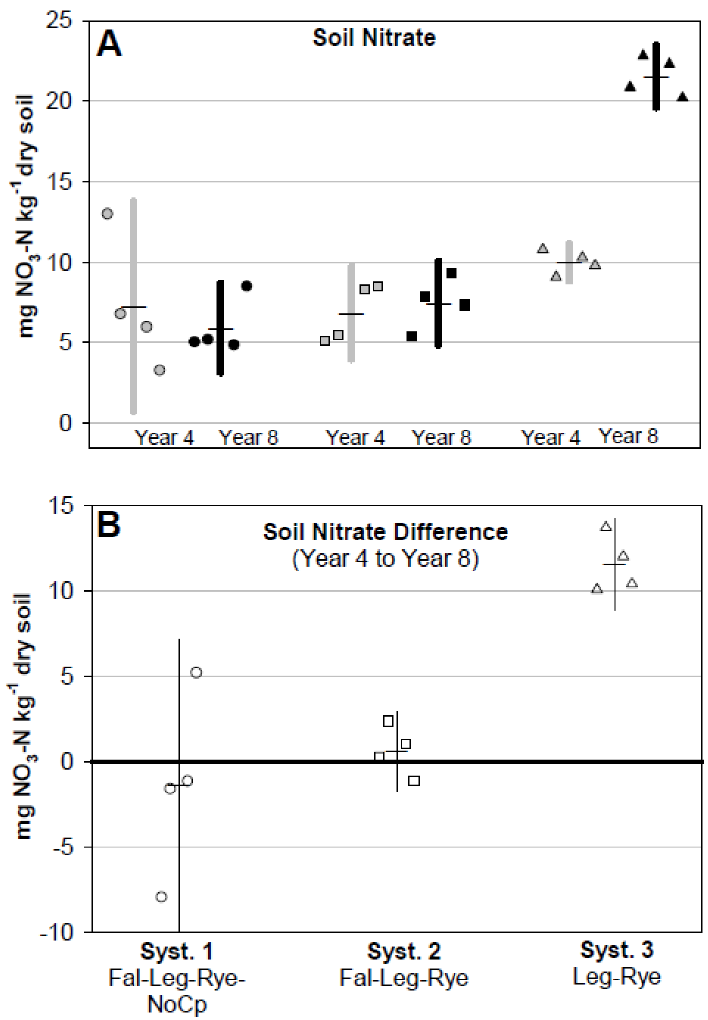
-**Unadj. P.** indicate the unadjusted comparison-wise error rates
-**Adj. P** – Bonferroni adjusted P-values to control the family-wise error rate; adjusted P values are 6 times larger than unadjusted P values because six comparisons are made.

Supplemental Fig. 4. (A) Soil nitrate concentrations in the top 30 cm of soil in three systems prior to planting cover crops during Years 4 and 8, and (B) the difference between years in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume-rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1 - Winter fallow ('Fal') for years 1 to 3, and 5 to 7, cover cropped during years 4 and 8, without compost ('NoCp'); System 2 - Same as System 1 but received annual compost additions; System 3 - Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares or triangles and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval (CI) with the mean at the central horizontal line on the bar. Means and CI in [ ] of soil nitrate for Systems 1, 2 and 3, were 7.3 [0.8, 13.8], 6.9 [4.0, 9.7] and 10.0 [8.8, 11.2] for Year 4, and 5.9 [3.2, 8.7], 7.5 [4.9, 10.1], 21.6 [19.6, 23.5] for Year 8. Mean and CI of soil nitrate differences between years were -1.4 [-9.9, 7.2], 0.6 [-1.7, 3.0], and 11.6 [8.9, 14.2] for System 1, 2, and 3, respectively. The 'rule of eye method' (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between confidence intervals, the stronger the evidence of a true difference.

ANOVA
P-values

Year <**0.01**
Syst. **<0.01**
YxS **<0.01**

P-values ≤0.15 are highlighted in **blue**.



Year	Nitrate Comparison	Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.79	1.00
Year 4	Syst. 1 vs 3	**0.11**	0.64
Year 4	Syst. 2 vs 3	**0.07**	0.41
Year 8	Syst. 1 vs 2	0.33	1.00
Year 8	Syst. 1 vs 3	**<0.01**	**<.01**
Year 8	Syst. 2 vs 3	**<0.01**	**<.01**

-**Unadj. P.** indicate the unadjusted comparison-wise error rates
-**Adj. P** – Bonferroni adjusted P-values to control the family-wise error rate; adjusted P values are 6 times larger than unadjusted P values because six comparisons are made.

Supplemental Fig. 5. (A,B,C) Total, rye, and legume cover crop densities for three systems during Years 4 and 8, and (D,E,F) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume-rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1 - Winter fallow ('Fal') for years 1 to 3, and 5 to 7, cover cropped during years 4 and 8, without compost ('NoCp'); System 2 - Same as System 1 but received annual compost additions; System 3 - Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares or triangles and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval (CI) with the mean at the central horizontal line on the bar. For Systems 1, 2 and 3, mean total densities and 95% CI in [ ] were 329 [248, 410], 317 [224, 410], 335 [202, 467] for Year 4, and 308 [240, 364], 322 [280, 364], and 313 [291, 335] for Year 8. The 'rule of eye method' (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between CI, the stronger the evidence of a true difference.

Cover Crop Biomass Production

P-values ≤0.15 are highlighted in **blue.**

ANOVA P-values (Total)

March
Year **0.01**
Syst. 0.76
YxS 0.19

January
Year **0.09**
Syst. 0.30
YxS 0.41

ANOVA P-values (Rye)

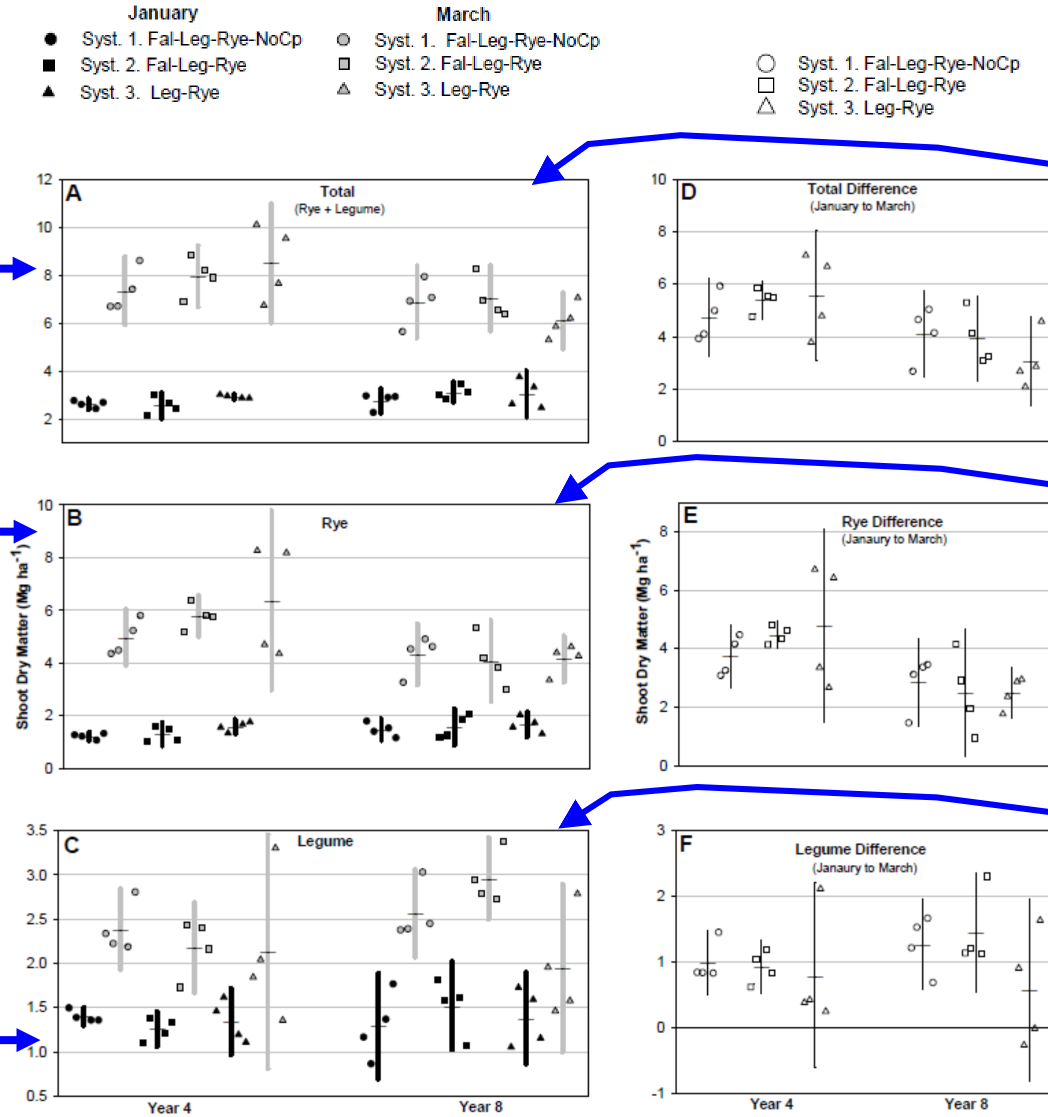
March
Year **0.01**
Syst. 0.56
YxS 0.37

January
Year **0.11**
Syst. 0.21
YxS 0.74

ANOVA P-values (Legume)

March
Year 0.23
Syst. **0.15**
YxS 0.19

January
Year 0.57
Syst. 0.95
YxS 0.41



Year	TOTAL Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.81	1.00	0.42	1.00
Year 4	Syst. 1 vs 3	0.24	1.00	**0.14**	0.84
Year 4	Syst. 2 vs 3	0.16	0.98	0.46	1.00
Year 8	Syst. 1 vs 2	0.19	1.00	0.83	1.00
Year 8	Syst. 1 vs 3	0.27	1.00	0.30	1.00
Year 8	Syst. 2 vs 3	0.81	1.00	0.22	1.00

-**Unadj. P.** indicate the unadjusted comparison-wise error rates
-**Adj. P** – Bonferroni adjusted P-values to control the family-wise error rate; adjusted P values are 6 times larger than unadjusted P values because six comparisons are made.

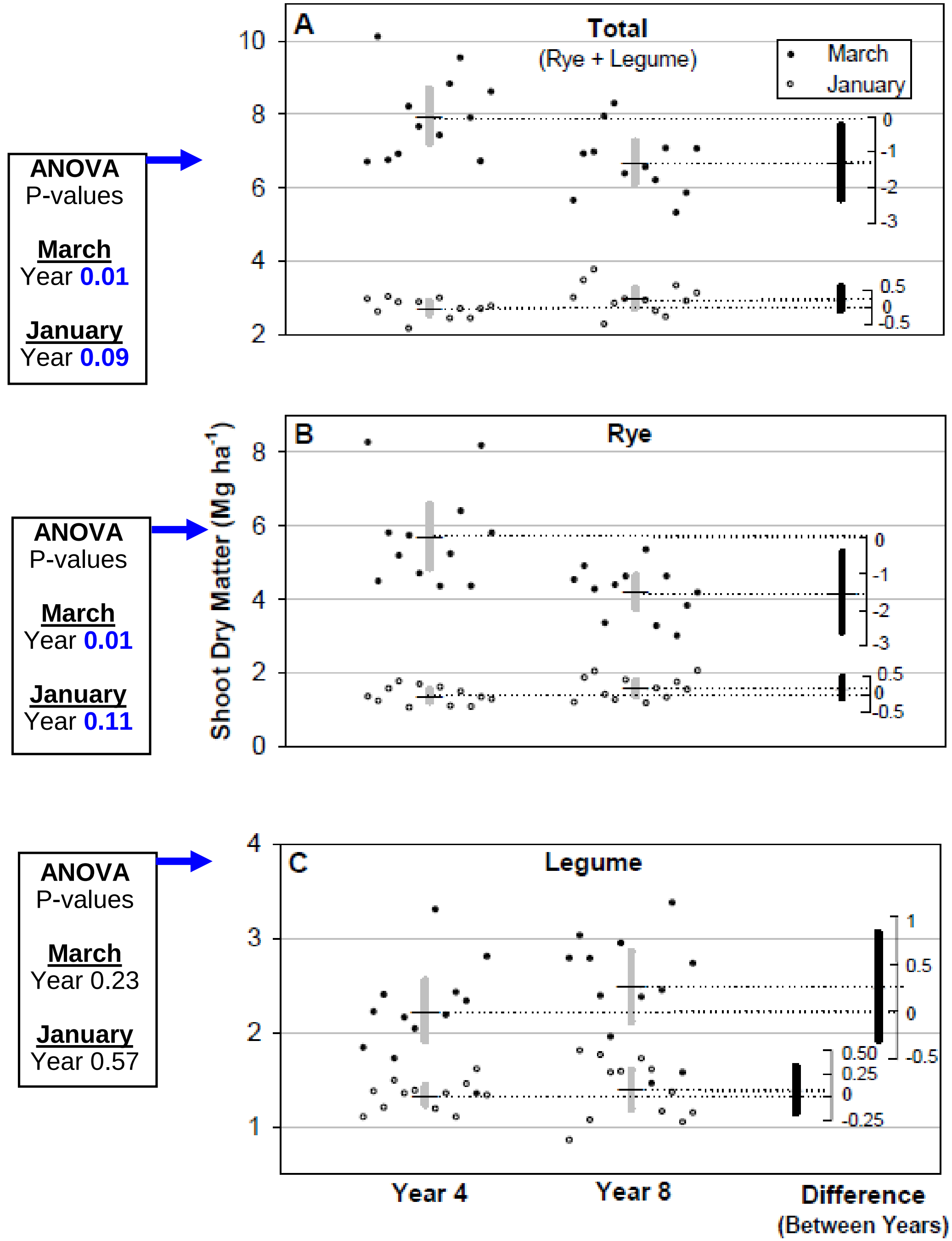
Year	RYE Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.69	1.00	0.32	1.00
Year 4	Syst. 1 vs 3	**0.10**	0.60	**0.10**	0.60
Year 4	Syst. 2 vs 3	0.19	1.00	0.46	1.00
Year 8	Syst. 1 vs 2	0.58	1.00	0.76	1.00
Year 8	Syst. 1 vs 3	0.36	1.00	0.83	1.00
Year 8	Syst. 2 vs 3	0.70	1.00	0.93	1.00

--See footnote in table above describing Unadj.P and Adj. P.

Year	LEGUME Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.47	1.00	0.56	1.00
Year 4	Syst. 1 vs 3	0.77	1.00	0.48	1.00
Year 4	Syst. 2 vs 3	0.66	1.00	0.90	1.00
Year 8	Syst. 1 vs 2	0.25	1.00	0.28	1.00
Year 8	Syst. 1 vs 3	0.64	1.00	**0.11**	0.64
Year 8	Syst. 2 vs 3	0.48	1.00	**0.02**	**0.10**

-See footnote in table above describing Unadj.P and Adj. P.

Cover Crop Biomass Production Across All Systems



Supplemental Fig. 6. Total, rye, and legume above ground cover crop biomass across three systems during January and March harvests in Years 4 and 8 and the difference between years in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume-rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1 - Winter fallow ('Fal') for years 1 to 3, and 5 to 7, cover cropped during years 4 and 8, without compost ('NoCp'); System 2 - Same as System 1 but received annual compost additions; System 3 - Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares or triangles and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval with the mean at the central horizontal line on the bar. Differences (i.e. effect sizes) of total, rye, and legume biomass within year and from January to March are in panels D-F. The 'rule of eye method' (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between confidence intervals, the stronger the evidence of a true difference.

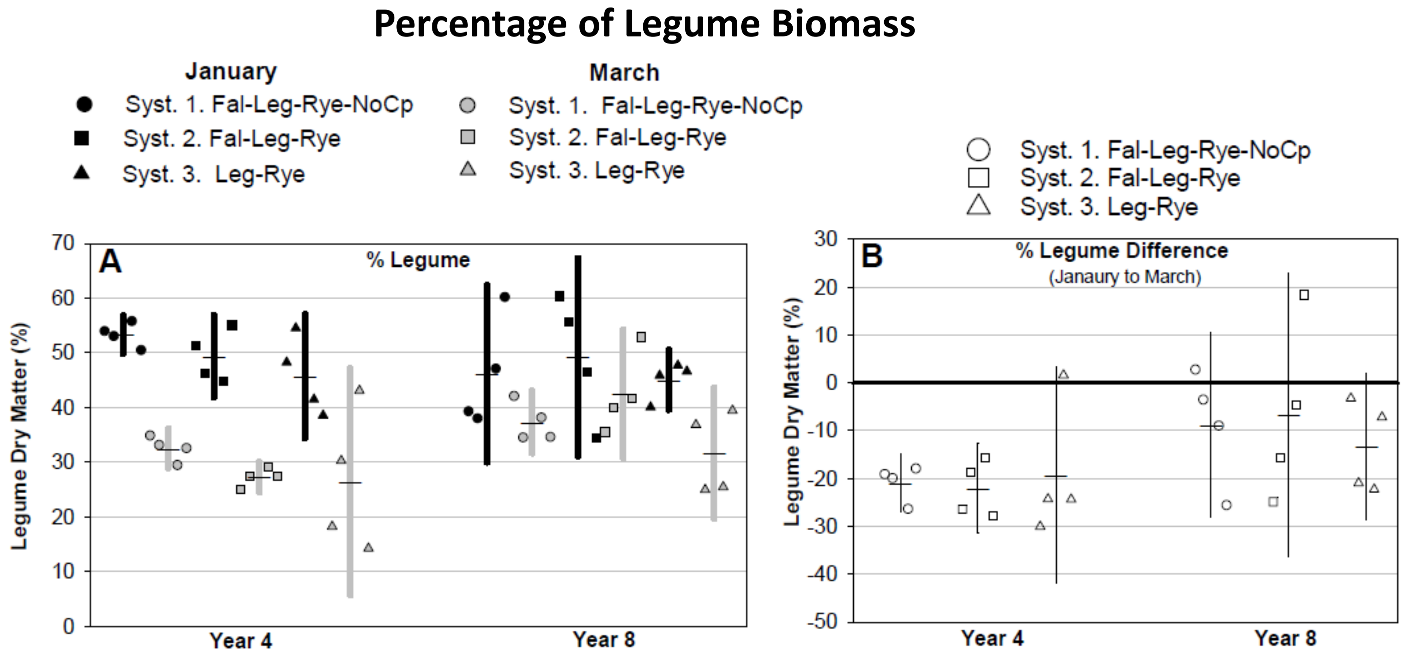
P-values ≤0.15 are highlighted in **blue.**

Supplemental Fig. 7. (A) Percentage of legume biomass of total cover crop biomass for three systems during January and March of Years 4 and 8, and (B) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume-rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1 - Winter fallow ('Fal') for years 1 to 3, and 5 to 7, cover cropped during years 4 and 8, without compost ('NoCp'); System 2 - Same as System 1 but received annual compost additions; System 3 - Cover cropped annually with annual compost additions. Raw data points are shown as clusters of circles, squares or triangles and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence intervals (CI) with the mean at the central horizontal line on the bar. Differences (i.e., effect sizes) in the percentage of legume biomass from January to March within year are in panel B. The 'rule of eye method' (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between CI whereby the smaller the overlap between confidence intervals, the stronger the evidence of a true difference.

ANOVA
P-values

January
Year 0.40
Syst. 0.47
YxS 0.59

March
Year **0.02**
Syst. 0.24
YxS 0.31



P-values ≤0.15 are highlighted in **blue.**

Year	% Legume Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.47	1.00	0.32	1.00
Year 4	Syst. 1 vs 3	0.18	1.00	0.26	1.00
Year 4	Syst. 2 vs 3	0.50	1.00	0.87	1.00
Year 8	Syst. 1 vs 2	0.57	1.00	0.33	1.00
Year 8	Syst. 1 vs 3	0.84	1.00	0.29	1.00
Year 8	Syst. 2 vs 3	0.45	1.00	**0.06**	0.36

-**Unadj. P.** indicate the unadjusted comparison-wise error rates
-**Adj. P** – Bonferroni adjusted P-values to control the family-wise error rate; adjusted P values are 6 times larger than unadjusted P values because six comparisons are made.

Supplemental Fig. 8. (A,B,C) Total, rye, and legume shoot nitrogen accumulation for three systems during January and March harvests in in Years 4 and 8, and (D,E,F) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA By seed weight the legume-rye cover crop included 90% legumes and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1 - Winter fallow ('Fal') for years 1 to 3, and 5 to 7, cover cropped during years 4 and 8, without compost ('NoCp'); System 2 - Same as System 1 but received annual compost additions; System 3 - Cover cropped annually with annual compost additions. Raw data points are shown as circles, squares or triangles clusters and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval with the mean at the central horizontal line on the bar. Differences (i.e. effect sizes) of total, rye, and legume biomass within year and from January to March are in panels D-F. Note that the scale of the y-axes are different between biomass types. The 'rule of eye method' (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between confidence intervals whereby the smaller the overlap between confidence intervals, the stronger the evidence of a true difference.

P-values ≤0.15 are highlighted in **blue.**

Cover Crop Nitrogen Accumulation

ANOVA P-values (Total)

March
Year 0.25
Syst. 0.16
YxS 0.40

January
Year **<0.01**
Syst. 0.16
YxS 0.31

ANOVA P-values (Rye)

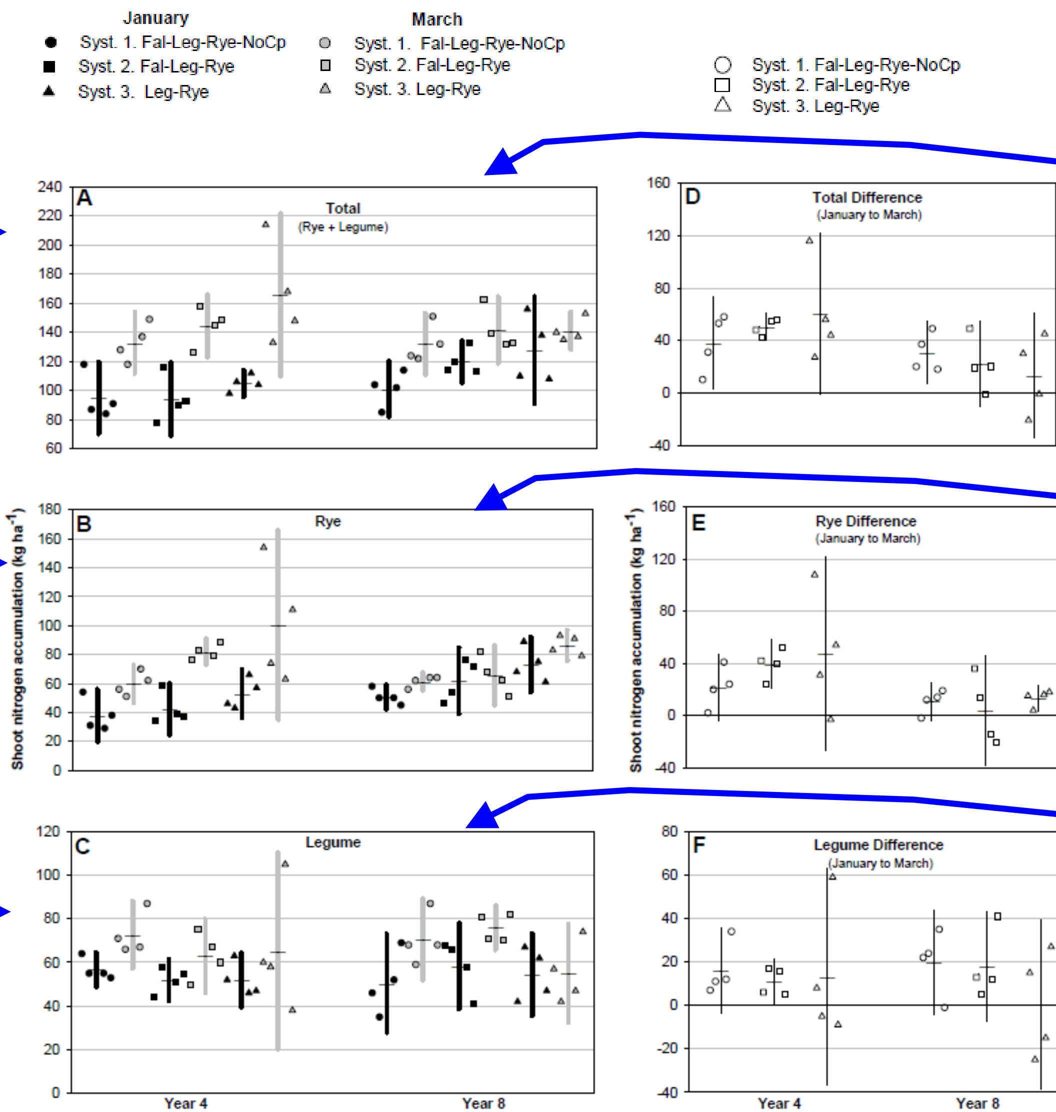
March
Year 0.24
Syst. **0.03**
YxS 0.59

January
Year **0.04**
Syst. <**0.01**
YxS 0.76

ANOVA P-values (Legume)

March
Year 0.98
Syst. 0.34
YxS 0.34

January
Year 0.84
Syst. 0.93
YxS 0.48



Year	TOTAL Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.94	1.00	0.40	1.00
Year 4	Syst. 1 vs 3	0.36	1.00	**0.03**	0.20
Year 4	Syst. 2 vs 3	0.33	1.00	**0.14**	0.83
Year 8	Syst. 1 vs 2	**0.10**	0.63	0.49	1.00
Year 8	Syst. 1 vs 3	**0.03**	0.18	0.51	1.00
Year 8	Syst. 2 vs 3	0.46	1.00	0.97	1.00

-**Unadj. P.** indicate the unadjusted comparison-wise error rates
-**Adj. P** – Bonferroni adjusted P-values to control the family-wise error rate; adjusted P values are 6 times larger than unadjusted P values because six comparisons are made.

Year	RYE Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.60	1.00	**0.12**	0.74
Year 4	Syst. 1 vs 3	**0.09**	0.54	**0.01**	**0.07**
Year 4	Syst. 2 vs 3	0.21	1.00	0.18	1.00
Year 8	Syst. 1 vs 2	0.19	1.00	0.75	1.00
Year 8	Syst. 1 vs 3	**0.02**	**0.11**	**0.09**	0.52
Year 8	Syst. 2 vs 3	0.19	1.00	**0.14**	0.86
Year 4 & 8	Syst. 1 vs 2	0.21	0.64	0.20	0.61
Year 4 & 8	Syst. 1 vs 3	**0.02**	**0.05**	**0.01**	**0.03**
Year 4 & 8	Syst. 2 vs 3	**0.10**	0.29	**0.07**	0.22

-See footnote in table above describing Unadj.P and Adj. P.

Year	LEGUME Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.52	1.00	0.39	1.00
Year 4	Syst. 1 vs 3	0.52	1.00	0.50	1.00
Year 4	Syst. 2 vs 3	1.00	1.00	0.84	1.00
Year 8	Syst. 1 vs 2	0.31	1.00	0.62	1.00
Year 8	Syst. 1 vs 3	0.59	1.00	0.18	1.00
Year 8	Syst. 2 vs 3	0.61	1.00	**0.08**	0.50

-See footnote in table above describing Unadj.P and Adj. P.

Supplemental Figure 9. (A,B,C) Cover crop shoot nitrogen concentration of total, rye, and legume cover crop shoot biomass for three systems during January and March harvests in in Years 4 and 8, and (D,E,F) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume-rye cover crop included 90% and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1 - Winter fallow ('Fal') for years 1 to 3, and 5 to 7, cover cropped during years 4 and 8, without compost ('NoCp'); System 2 - Same as System 1 but received annual compost additions; System 3 - Cover cropped annually with annual compost additions. Raw data points are shown as circles, squares or triangles clusters and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval with the mean at the central horizontal line on the bar. Differences (i.e. effect sizes) of total, rye, and legume biomass within year and from January to March are in panels D-F. Note that the scale of the y-axes are different between biomass types. The 'rule of eye method' (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between confidence intervals whereby the smaller the overlap between confidence intervals, the stronger the evidence of a true difference.

P-values ≤0.15 are highlighted in **blue.**

Cover Crop Nitrogen Concentration

ANOVA
P-values

January
Year **0.01**
Syst. 0.17
YxS 0.14

March
Year **<0.01**
Syst. **0.06**
YxS **0.15**

ANOVA
P-values

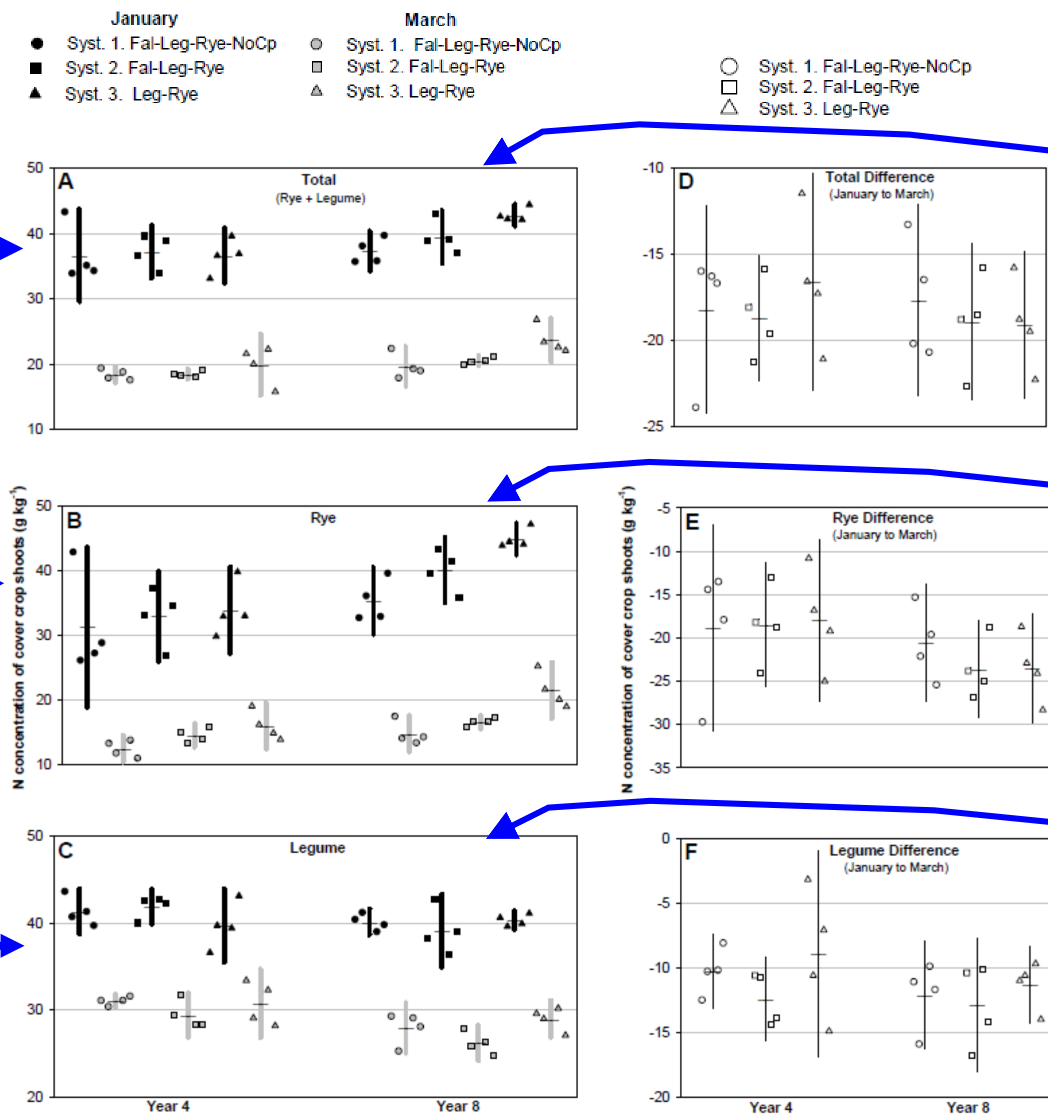
January
Year **0.003**
Syst. 0.091
YxS 0.34

March
Year **<0.01**
Syst. **<0.01**
YxS **0.01**

ANOVA
P-values

January
Year **0.14**
Syst.0.76
YxS 0.19

March
Year **<0.01**
Syst. 0.12
YxS 0.45



Year	TOTAL Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.77	1.00	0.95	1.00
Year 4	Syst. 1 vs 3	0.96	1.00	0.22	1.00
Year 4	Syst. 2 vs 3	0.73	1.00	0.25	1.00
Year 8	Syst. 1 vs 2	0.28	1.00	0.46	1.00
Year 8	Syst. 1 vs 3	**0.01**	**0.06**	**0.01**	**0.04**
Year 8	Syst. 2 vs 3	**0.10**	0.60	**0.02**	**0.13**

-**Unadj. P.** indicate the unadjusted comparison-wise error rates
-**Adj. P** – Bonferroni adjusted P-values to control the family-wise error rate; adjusted P values are 6 times larger than unadjusted P values because six comparisons are made.

Year	RYE Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.61	1.00	**0.11**	0.67
Year 4	Syst. 1 vs 3	0.43	1.00	**0.01**	**0.08**
Year 4	Syst. 2 vs 3	0.77	1.00	0.23	1.00
Year 8	Syst. 1 vs 2	0.17	1.00	0.16	0.97
Year 8	Syst. 1 vs 3	**0.01**	**0.09**	**<0.01**	**<0.01**
Year 8	Syst. 2 vs 3	0.16	0.98	**<0.01**	**0.01**

-See footnote in table above describing Unadj.P and Adj. P.

Year	LEGUME Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.69	1.00	0.16	0.97
Year 4	Syst. 1 vs 3	0.24	1.00	0.78	1.00
Year 4	Syst. 2 vs 3	**0.13**	0.76	0.24	1.00
Year 8	Syst. 1 vs 2	0.45	1.00	**0.14**	0.84
Year 8	Syst. 1 vs 3	0.88	1.00	0.36	1.00
Year 8	Syst. 2 vs 3	0.37	1.00	**0.03**	0.18

-See footnote in table above describing Unadj.P and Adj. P.

Supplemental Figure 10. (A,B,C) Cover crop shoot carbon to nitrogen ratios total, rye, and legume cover crop shoot biomass for three systems during January and March harvests in in Years 4 and 8, and (D,E,F) the difference between harvests in the Salinas Organic Cropping Systems trial at Salinas, CA. By seed weight the legume-rye cover crop included 90% and 10% rye. Systems are in order (from left to right) of increasing organic matter inputs: System 1 - Winter fallow ('Fal') for years 1 to 3, and 5 to 7, cover cropped during years 4 and 8, without compost ('NoCp'); System 2 - Same as System 1 but received annual compost additions; System 3 - Cover cropped annually with annual compost additions. Raw data points are shown as circles, squares or triangles clusters and are in order of replicates 1 to 4 for each data cluster. The vertical bar within each data cluster is the 95% confidence interval with the mean at the central horizontal line on the bar. Comparisons between independent treatment means (i.e., between systems within year and harvest) can be made using the ''rule of eye'' method (Cumming and Finch, 2005) whereby confidence intervals that overlap with a mean are not different, and intervals that overlap by half of one interval arm are significantly different at P≈0.05 where sample size (n) ≥ 10; where n=3, CI overlap can be 1 arm length for a significant difference of P≈0.05 (Cumming et al., 2007). Such comparisons are not adjusted to control the familywise error rate. Differences (i.e., effect sizes) of total, rye, and legume biomass within year and from January to March are in panels D-F. Note that the scale of the y-axes are different between biomass types. The 'rule of eye method' (Cumming and Finch, 2005; Cumming et al., 2007) described in the Statistical Analysis section can be used to compare the overlap between confidence intervals whereby the smaller the overlap between confidence intervals, the stronger the evidence of a true difference.

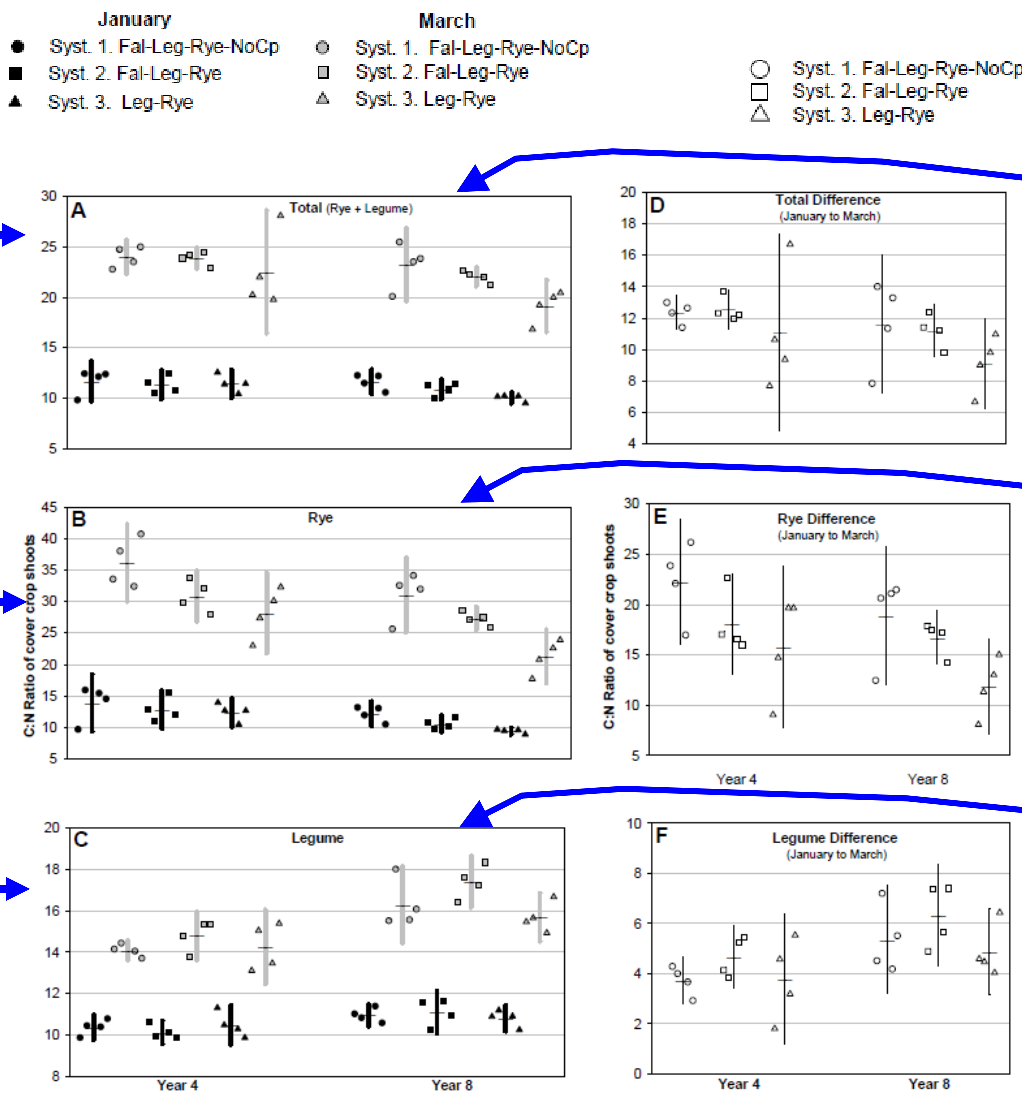
P-values ≤0.15 are highlighted in **blue.**

Cover Crop C:N Ratios

ANOVA
P-values

March
Year **<0.01**
Syst. **0.12**
YxS 0.25

January
Year **0.09**
Syst. **0.12**
YxS 0.28



Year	Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.56	1.00	0.92	1.00
Year 4	Syst. 1 vs 3	0.69	1.00	0.31	1.00
Year 4	Syst. 2 vs 3	0.85	1.00	0.36	1.00
Year 8	Syst. 1 vs 2	0.22	1.00	0.42	1.00
Year 8	Syst. 1 vs 3	**0.02**	**0.09**	**0.02**	**0.09**
Year 8	Syst. 2 vs 3	0.18	1.00	**0.06**	0.37

-**Unadj. P.** indicate the unadjusted comparison-wise error rates
-**Adj. P** – Bonferroni adjusted P-values to control the family-wise error rate; adjusted P values are 6 times larger than unadjusted P values because six comparisons are made.
-P values ≤ 0.15 are highlighted in bold.

ANOVA
P-values

March
Year **<0.01**
Syst. **<0.01**
YxS 0.37

January
Year **0.01**
Syst. **0.07**
YxS 0.74

Year	Comparison	---January--- Unadj. P	Adj. P	---March--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.49	1.00	**0.03**	0.19
Year 4	Syst. 1 vs 3	0.36	1.00	**<0.01**	**0.02**
Year 4	Syst. 2 vs 3	0.81	1.00	0.23	1.00
Year 8	Syst. 1 vs 2	**0.03**	0.16	**0.10**	0.60
Year 8	Syst. 1 vs 3	**<0.01**	**0.01**	**<0.01**	**0.01**
Year 8	Syst. 2 vs 3	**0.09**	0.53	**0.02**	**0.10**
Year 4 & 8	Syst. 1 vs 2			**0.04**	**0.12**
Year 4 & 8	Syst. 1 vs 3			**<0.01**	**0.01**
Year 4 & 8	Syst. 2 vs 3			**0.05**	**0.14**

-See footnote in table above describing Unadj.P and Adj. P.

ANOVA
P-values

March
Year **<0.01**
Syst. **0.11**
YxS 0.23

January
Year **<0.01**
Syst. 0.98
YxS 0.29

Year	Comparison	---January--- Unadj. P	Adj. P	---Final--- Unadj. P	Adj. P
Year 4	Syst. 1 vs 2	0.48	1.00	0.24	1.00
Year 4	Syst. 1 vs 3	0.74	1.00	0.77	1.00
Year 4	Syst. 2 vs 3	0.31	1.00	0.37	1.00
Year 8	Syst. 1 vs 2	0.68	1.00	0.08	0.49
Year 8	Syst. 1 vs 3	0.67	1.00	0.31	1.00
Year 8	Syst. 2 vs 3	0.40	1.00	**0.01**	**0.08**

-See footnote in table above describing Unadj.P and Adj. P.