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Trade-offs between winter cover crop production and soil water depletion in the San Joaquin Valley, California

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Abstract: Cover crops are currently not widely used in annual crop production systems in California's semiarid Central Valley due to concerns about lost opportunity costs and uncertainties about water use. From 1999 through 2014, we quantified cover crop biomass production for a variety of mixtures under winter precipitation and limited supplemental irrigation. In a separate study, we also determined changes in soil water storage under three cover crop mixtures compared to fallowed plots during two (2013 and 2014) winter periods to investigate tradeoffs associated with water use by cover crops in this region. Over the 15 years of the project that were characterized by recurring drought, a total of 22.8 Mg ha^{-1} (20,360 lb ac^{-1}) of aboveground cover crop biomass was produced with a total precipitation of 209 and 20 cm (82 and 8 in) of supplemental irrigation applied in 1999, 2012, and 2014. Cover crop biomass varied from 0.39 Mg ha^{-1} (348 lb ac^{-1}) in the low precipitation period (winter of 2006 to 2007) to 9.34 Mg ha^{-1} (8,340 lb ac^{-1}; winter of 2000 to 2001). Soil water storage in the sampled depth (0 to 90 cm [0 to 35 in]) for the fallow and each of the cover crop mixtures was compared each year from January to March, the primary growing period for cover crops in this region. Net soil water storage increased during this period by 4.8 and 4.3 cm (1.9 and 1.7 in) in 2013 and 2014, respectively, for the fallow system, but in the cover crop mixture plots, there was no additional water storage. Instead, water use by the cover crop mixes resulted in a negative water balance over the cover crop growth period on an average of 0.47 and 0.26 cm (0.19 and 0.10 in) in 2013 and 2014, respectively. Thus, compared to the fallow system, cover crops depleted 5.3 and 0.67 cm (2.1 and 0.26 in) and more water from the 0 to 90 cm (0 to 35 in) profile in 2013 and 2014, respectively. From this long-term systems research, we conclude that while vigorous growth of winter cover crops in the Central Valley of California may not be possible in all years due to low and erratic precipitation patterns, there may be benefits in terms of providing ground cover, residue, and photosynthetic energy capture in many years. However, cover crop biomass production may come at a cost of soil water depletion in this semiarid, drought-prone region.

Key words: conservation agriculture—conservation tillage—ecosystem services—residue—soil water evaporation

The value of using cover crops to improve the efficiency and productivity of cropping systems while also minimizing adverse environmental impacts has been documented (Creamer and Baldwin 2000; Sainju et al. 2001; Harrison et al. 2004; Snapp et al. 2005; Wang et al. 2006; Schipanski et al. 2014). A growing body of research has been developed, for instance, on cover crop adaptability and management for such production system goals as nonchemical weed suppression (Norsworthy et al. 2005; Isik et al. 2009; Kumar et al. 2009), nitrogen (N) provision (Creamer and Baldwin 2000; Schomberg et al. 2006, 2007; Lenzi et al. 2009), and a variety of soil function improvements including increased carbon (C) storage, fixation of N by legumes, N mineralization from cover crop residues, and the ability to support crop production through internal nutrient cycling thereby reducing use of synthetic fertilizers and associated fossil fuel emissions (Schipanski et al. 2014) and ecosystem services (Follett 2001; Alcantura et al. 2011; Ruiz-Colmenero et al. 2011; Schipanski et al. 2014).

Although the USDA National Agricultural Statistics Service has begun to include questions on cover crop use in upcoming agriculture census surveys, there is currently no consistent survey tool available, and thus, data on the extent of cover crop use in the United States have been difficult to acquire. A recent survey of the 18-state Mississippi River Basin in 2011 found over 0.7 million ha (1.7 million ac), or about 2% of the region's cropland, planted to cover crops (Bryant et al. 2013). Such surveys have not been conducted in California's semiarid, highly productive Central Valley (CV), but estimates of current cover crop use in the state's annual cropping systems are also quite low due to farmer concerns about opportunity costs involved in forgoing cash crop income (Brennan and Boyd 2012), the cost and availability of additional water needed to grow a cover crop particularly during periods of drought, and depletion of the winter soil water reserve for spring-seeded annual crops by the cover crop. While Brennan and Boyd (2012) recently anticipated an increase in cover cropping on irrigated cropland in California's Salinas Valley as a management tool to reduce runoff and nitrate (NO_3) losses from fields, decisions to include cover crops into CV cropping rotations are more difficult to justify. This difficulty may remain until accurate water use requirements of the crops are properly documented and tradeoffs between the costs and benefits associated with cover crops are well characterized. Cover crop trait selection options for something as important as low soil water depletion have also not been well addressed (Snapp et al. 2005; Wilke and Snapp 2008). Snapp et al. (2005) provided a thorough review of the general literature on cover crop adoption and the more localized farmer experience base with cover crops in Michigan and concluded that cover cropping can accrue significant benefits from environ-

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mental enhancement to improved cropping system health. The authors further suggested that improved knowledge concerning management practices is important in tipping the balance toward greater adoption.

An additional, yet currently underappreciated, positive attribute of cover crops is their potential role to provide surface residues to CV cropping systems. In regions of the world where no-tillage or reduced tillage systems are common—such as Brazil, Argentina, Paraguay, Canada, Western Australia, the Dakotas, and Nebraska—generating and preserving residues are important parts of management and are major, even primary, goals of sustainable production (Crovetto 1996, 2006). Value is derived from residues in several ways: reduced erosion (Shelton et al. 2000; Skidmore 1986), provision of C and N to soil organisms (Crovetto 2006), and reduced soil water evaporation (Klocke et al. 2009; van Donk et al. 2010). Early work by Unger and Vigil (1998) suggested that the inevitable soil water loss associated with cover crops in semiarid regions such as the CV may be offset or recovered through the use of residue-preserving and reduced soil disturbance practices such as conservation tillage (CT).

Because many of the reported benefits that may be provided by cover crops have relevance to the goals of farmers in the CV to improve soil tilth, add organic matter to the soil, and improve agroecosystem productivity and sustainability, we took advantage of a unique, long-running cropping systems study that has been underway in the CV since 1999. Our major goal was to quantify cover crop biomass production in the CV under winter precipitation and limited supplemental irrigation and to determine the effects of prior crops and tillage management on cover crop dry matter accumulation. The following specific questions are of interest to the CV:

1. To what extent is largely rainfed cover crop biomass production feasible?
2. What levels of C and N may be provided by common cover crop mixtures during the November to March window?
3. What levels of residue cover are attained by the sustained use of cover crops when incorporated either as "green manures" or left as surface mulches?
4. What do cover crops do to winter soil water storage patterns compared to fallowed soils?

Answers to each of these questions are important in helping farmers in the CV rationalize the addition of cover crops to their current cash crop rotations.

Materials and Methods

History of the Long-Term National Research Initiative Conservation Agriculture Systems Project. In the fall of 1999, a group of CV farmers and USDA Natural Resources Conservation Service (NRCS), private sector, and university partners initiated the National Research Initiative Conservation Agriculture Systems Project. The objective of the project was to develop information on CT production systems and their ability to reduce particulate matter emissions related to the historically high soil disturbance practices that had been used in the region for over 80 years since the advent of irrigation wells in the 1930s. At the time the National Research Initiative Project was started, CT practices were used on less than 2% of annual crop acreage in the CV (Mitchell et al. 2007), and informal estimates of the extent of cover cropping were on a similar level. Since 1999, the project has consistently implemented cover crop and tillage system comparisons that differ in terms of soil disturbance intensity and organic matter inputs (Mitchell et al. 2008a, 2009; Veenstra et al. 2007). Various aspects and findings of the early stages of this long-term study have been previously reported including impacts of CT on soil C and N (Veenstra et al. 2006, 2007; Mitchell et al. 2009), dust emissions (Baker et al. 2005), and economics (Mitchell et al. 2009). In this paper we add information on the biomass production of the cover crop systems and soil water balance from 1999 through 2014.

Cropping Systems Descriptions and 15-Year Cover Crop Biomass Production Study. The study site is located at the University of California's West Side Research and Extension Center in Five Points, California (36°20'29" N, 120°7'14" W). The field size was 427 by 100 m (1,400 by 328 ft), and the soil type was Panoche clay loam (fine-loamy, mixed superlative, thermic Typic Haplocambids) (Arroues 2006) with a particle size distribution of 25% sand, 37% silt, and 39% clay. During the year before the onset of the study, a uniform barley (*Hordeum vulgare*) crop was grown and removed as green chop silage to even out differences in soil water and fertility that may have existed due to previous research.

The 3.56 ha (8.80 ac) field consisted of 32 plots each 10 m wide by 100 m long (33 ft wide by 328 ft long) with 10 m buffer or border plots between treatment plots (Baker et al. 2005). The field was divided into two halves; a tomato (*Solanum lycopersicum*)–cotton (*Gossypium hirsutum* L.) rotation was used in one half, and a cotton–tomato rotation was pursued in the other half to allow tomato and cotton plantings to occur within each year. Management treatments included a factorial arrangement of tillage and cover crop which included standard tillage without cover crop (STNO), standard tillage with cover crop (STCC), conservation tillage without cover crop (CTNO), and conservation tillage with cover crop (CTCC). Each treatment was replicated four times in a randomized complete block design on each half of the field. Treatment plots consisted of six beds, each measuring 9.1 × 82.3 m (29.9 × 270 ft). Six-bed buffer areas separated tillage treatments to enable the different tractor operations that were used in each system. A cover crop mix of Juan triticale (*Triticosecale* Wittm.), Merced ryegrain (*Secale cereale* L.), and common vetch (*Vicia sativa*) was seeded using either a 5 m (16 ft) John Deere 1530 no-tillage seeder (Moline, Illinois) or a 5 m Sunflower 1510 no-till drill (Beloit, Kansas) at 19 cm (7 in) row spacing and at a rate of 89.2 kg ha^{-1} (79.6 lb ac^{-1}; 30% triticale, 30% ryegrain, and 40% vetch by weight) in late October in the STCC and CTCC plots and irrigated once with 10 cm (4 in) of water in 1999 (table 1). The legume species was inoculated with its particular rhizobium before seeding. In each of the subsequent years through 2012, no irrigation was applied to the cover crops, which were planted in advance of winter rains. In 2012 and 2014, 5 cm (2 in) of irrigation water were also applied to establish the cover crops for a total of 20 cm (8 in) of supplemental irrigation over the 15-year period. Beginning in 2010 and then persisting through 2014, the basic cover crop mixture was changed in an attempt to diversity it as indicated in table 1.

Grass-reference evapotranspiration (ETo), total precipitation, soil temperature, and other climatic data from November through March of each year were acquired from a California Irrigation Management Information System weather station located about 200 m (656 ft) from the study site. Percentage residue cover was determined on four occasions during the 15-year study

Table 1

Descriptions of winter cover crop mixtures, planting and termination dates, and seeding rates used annually in the long-term study in Five Points, California, from 2000 to 2014.

Crop year	Planting date	Termination date	Total growing days	3-way mixture*	Brassica mixture†	Annual clover mixture‡	Legume/radish mixture§
1999 to 2000	Oct. 10, 1999	Apr. 6, 2000	148	x			
2000 to 2001	Nov. 2, 2000	Mar. 14, 2001	133	x			
2001 to 2002	Nov. 10, 2001	Mar. 15, 2002	126	x			
2002 to 2003	Oct. 18, 2002	Mar. 25, 2003	159	x			
2003 to 2004	Nov. 2, 2003	Mar. 17, 2004	136	x			
2004 to 2005	Oct. 16, 2004	Mar. 18, 2005	154	x			
2005 to 2006	Oct. 20, 2005	Mar. 21, 2006	152	x			
2006 to 2007	Nov. 22, 2006	Mar. 21, 2007	120	x			
2007 to 2008	Nov. 2, 2007	Mar. 22, 2008	140	x			
2008 to 2009	Dec. 11, 2008	Mar. 17, 2009	96	x			
2009 to 2010	Nov. 20, 2009	Mar. 20, 2010	121	x			
2010 to 2011	Nov. 24, 2010	Mar. 19, 2011	119				x
2011 to 2012	Nov. 10, 2011	Apr. 4, 2012	143				x
2012 to 2013	Oct. 30, 2012	Mar. 8, 2013	130		x	x	
2013 to 2014	Nov. 18, 2013	Mar. 24, 2014	127		x	x	

*3-way mixture = Juan triticale (*Triticosecale* Wittm.; 30% by weight), Merced ryegrain (*Secale cereale* L.; 30% by weight), and common vetch (*Vicia sativa*; 40% by weight).

†Brassica mixture = oriental mustard (*Brassica juncea*), Braco mustard (*Brassica alba*), and daikon mustard (*Raphanus sativus*).

‡Annual clover mix = crimson clover (*Trifolium incarnatum*; 30%), Hykon rose clover (*Trifolium hirtum*; 5%), Sardi Persian clover (*Trifolium resupinutum*; 10%), Parriago medic (*Medicago truncatula*; 10%), Cavalier medic (*Medicago polymorpha*; 10%), Dalkerth subclover (*Trifolium subterraneum*; 10%), Seaton Park clover (*Trifolium subterraneum*; 10%), Wooenellap subclover (*Trifolium subterraneum*; 10%), Trikkala subclover (*Trifolium subterraneum*; 7.5%), and Seaton Park subclover (*Trifolium subterraneum*; 7.5%) at a rate of 11.2 kg ha^{-1}.

§Legume/radish mix = Biomaster pea (*Pisum sativum* L.; 67%), faba bean (*Vicia faba* L.; 7%), blue lupin (*Lupinus difusus*), tillage radish (*Raphanus sativus*; 17%), and phacelia (*Phacelia tanacetifolia*; 3%).

using the line transect method (Bailey 1983) by taking two random 30 m (98 ft) transects in each tillage system plot. Cover crop biomass was determined usually in mid-March by harvesting all aboveground plant material in a 1 m^2 (11 ft^2) random area in each plot, drying the material to constant weight, and weighing. The N and C content of the cover crop was determined using a Carlo Erba analyzer (Veenstra et al. 2006).

Cover Crop Water Depletion Study. In a nearby field with a nine-year history of no-tillage at the University of California West Side Research and Extension Center, comparisons of changes in soil water storage under three cover crop mixes and winter-fallowed bare soil were conducted between November and April in 2012 to 2013 and 2013 to 2014. Cover crop seeding and termination information for these studies is provided in table 2. These cover crop mixtures represented a variety of common, commercially available materials that are known to be adapted to the CV (Mitchell et al. 1999). Following a pre-seeding application of 112 kg ha^{-1} (100 lb ac^{-1}) of 11-52-0 fertilizer by a 5 m (16 ft) wide John Deere 1560 no-till grain drill, the cover crop mixtures were seeded as indicated in table 2 using the same drill because the study field had not been fertilized for a number of years prior to the start of this work, but perpendicular to the direction of preplant fertilizer application. Bare untilled plots that represented conventional winter fallow conditions were maintained weed free by application of a 2% solution of glyphosate (N–[phosphonomethyl glycine]) as needed. Each cover crop and fallow plot was 10 m wide and 30 m long (33 ft wide and 98 ft long) and was replicated three times in a randomized complete block experimental design in each year. Ten centimeters (4 in) of water were applied by sprinkler in each year to establish the cover crops. These irrigations were also applied to the fallow plots.

Table 2

Cover crop mixtures used in 2013 and 2014 water depletion studies in Five Points, California.

Mixture	Composition	Seeding rate (kg ha^{-1})
Legume	Bell bean (*Vicia faba* L.; 45%)	112
	Dundale pea (*Pisum sativum* L.; 35%)	
	Common vetch (*Vicia sativa*; 20%)	
Legume/triticale	Dundale pea (*Pisum sativum* L.; 40%)	112
	Common vetch (*Vicia sativa*; 30%)	
	Triticale (*Triticosecale* Wittm.; 30%)	
Brassica	Oriental mustard (*Brassica juncea*; 45%)	24
	Martigena mustard (*Sinapsis alba*; 40%)	
	Daikon radish (*Raphanus sativus*; 15%)	

Aboveground cover crop biomass fresh weights were determined 10 times each year by harvesting and weighing all plant materials within a random 1 m^2 (11 ft^2) area in each plot. The biomass was then dried to constant weight for dry weight and N content determinations. Volumetric soil water content was monitored twice weekly in all plots using a neutron hydroprobe (Campbell Pacific Nuclear, Martinez, California) at depths of 15, 30, 60, 90, 120, 150, and 180 cm (6, 12, 24, 35, 47, 59, and 71 in) using a calibration equation that computed volumetric soil water content using raw counts from the probe detector that was developed for the site ($r^2 = 0.93$). Soil water content for each measurement depth in the 0 to 90 cm depth were then added, and the total amount of water for the cover crop treatments was compared during the January through March 27 period with the amount of water in the fallow treatment for each year.

Data for cover crop biomass, surface residue cover, cover crop N content, and soil water content in the 0 to 90 cm (0 to 35 in) depth were analyzed separately for each year. Assumptions of analysis of variance were tested prior to running the general linear model (GLM) procedures in SAS, and data were log transformed when they failed to meet the assumptions. Mean separation tests were conducted on transformed data but nontransformed means were presented. All data were analyzed using GLM procedures of SAS using an alpha level of 0.05 for significance. Tillage and cover crop were considered as fixed effects, and year and replication were considered as random effects. Interactions between tillage and cover crop were also tested as appropriate.

Results and Discussion

Weather Conditions. Despite the CV's Mediterranean-type climate with most precipitation occurring during the cooler winter months, there was a long-term average water deficit of about 12.5 cm (4.9 in) between ETo and precipitation during the five-month November through March period in Five Points, California, based on both 30-year averaged data (table 3) and the actual data during the 15 years of this investigation (table 4). These data, however, underscore the theoretical basis for identifying this winter growing "window" as being perhaps the most reasonable period for attempting to insert cover crops into the region's cropping systems during a time when daily temperatures and thus ETo are relatively lower in comparison to summer trends.

Table 3

Thirty-year average grass-reference evapotranspiration (ETo) and precipitation for November through March in Five Points, California.

Variable	November	December	January	February	March
ETo (cm)	3.36	5.88	8.51	5.48	10.52
Precipitation (cm)	2.81	1.55	4.08	3.75	3.78

Winter precipitation from November through March for the 2000 to 2014 period was about 2.2 cm (0.9 in) lower than the long-term average which ranged from a high in 2011 of 31 cm (12 in) to a low of 6.5 cm (2.6 in) in 2014; this marked one of the driest winters in history (Howitt et al. 2014). It is not only the winter seasonal total precipitation, but also the timing of precipitation that is important to sustain largely rainfed productive cover crop biomass accumulation. Ideally, for the November to March window, an early November onset of precipitation with the bulk of remaining typically available winter rain coming soon thereafter in December and early January might be the best overall precipitation timing pattern for optimal cover crop biomass production. Long-term average data, however, indicate that December and January actually tend to have the lowest monthly average precipitation of the five winter months, and the unpredictability of precipitation during this critical period is very important for eventual precipitation-limited growth as seen in table 4. Thus, if a small supplemental amount of irrigation is applied during this winter cover crop season, it might best be scheduled during the December to January early period to gain maximum value.

Over the 15 years of the study, the average planting date was November 8, and the average termination date was March 22 for a growing season of 135 days. This growing window mirrors quite closely the typical intercrop period following the harvest of most summer and fall crops and the establishment of many spring and summer crops that are customarily produced in the CV. Thus, it provides a reasonable time frame when off-season cover crops might be integrated into a common production schedule and is in line with schedules used by the few CV row crop farmers who currently use cover crops.

Comparing historically averaged ETo for July and August, which totals 43.5 cm (17.1 in), to ETo for December and January, which is 6.8 cm (2.7 in), the potential atmospheric demand for water loss via evapotranspiration during the winter is only about 15% of that in the summer in the Five Points, California, area. Thus, if suitable cover crop selections that grow well during this winter window are identified, their potential water use via transpiration would be lower and their water use efficiency would be higher relative to summer cover crops.

Aboveground Biomass and Nitrogen Content. The aboveground cover crop biomass was affected by the year and the previous crop in the rotation, and there was an interaction between these two factors. Therefore, data were analyzed separately for each year. The interaction was primarily caused by the lack of significant difference in cover crop biomass as an effect of the previous crop in 5 out of the 15 years; otherwise, in the other years, the cover crop biomass was always greater in the plots following tomato than the plots following cotton (figure 1). Cover crop aboveground biomass production averaged 3.42 Mg ha^{-1} (3,054 lb ac^{-1}) over the 15 years of the study (figure 1). There was, however, large variability in the amount of biomass that was produced in a given year due to differences in climatic conditions ranging from 0.039 Mg ha^{-1} (34.8 lb ac^{-1}) in the 2006 to 2007 winter, to 9.34 Mg ha^{-1} (8,341 lb ac^{-1}) in the first winter. This finding is consistent with the observation of Brennan and Boyd (2012) that cover crop performance varies considerably among years. In years when small supplemental sprinkler irrigations were applied (2000, 2013, and 2014), cover crop growth was higher than the 15-year average by 2.75, 1.22, and 1.14 times in 2000, 2013, and 2014, respectively. Productivity in 2013 and 2014, which were years with relatively low precipitation, was only modestly higher than the long-term average.

Over the 15 years, the average total of 3.42 Mg ha^{-1} (3,054 lb ac^{-1}) of aboveground cover crop dry biomass that was produced represented inputs of 1.20 Mg ha^{-1} (1,071 lb ac^{-1}) of N and 21.7 Mg ha^{-1} (19,378 lb ac^{-1}) of C based on cover crop tissue N and C determi-

Table 4

Grass-reference evapotranspiration (ETo) and precipitation for cover crop study in Five Points, California, for November through March of 2000 to 2014.

Variable	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
ETo (cm)	30.2	27.0	13.8	18.3	28.0	21.3	27.3	33.5	32.5	29.7	27.0	23.1	33.4	31.3	31.9
Total precipitation (cm)	12.0	8.1	8.8	6.4	12.1	19.2	23.1	7.8	15.0	17.0	14.8	31.0	17.5	9.6	6.5

nations made periodically during the course of the study (data not shown). The cover crop biomass production observed in this study under largely rainfed winter conditions with only small amounts of supplemental irrigation in 3 of the 15 years is generally in the intermediate range of reported cover crop biomass production in the region (Mitchell et al. 1999). With 8 cm (3 in) of irrigation water, biomass of single-species cover crops such as triticale or wheat (*Triticum aestivum*) during the same November to mid-March window of 1.12 to 12.23 Mg ha^{-1} (1,000 to 10,921 lb ac^{-1}) of dry matter was achieved (Mitchell et al. 1999). Percentage surface residue cover was affected by both cover crop and the type of tillage that was used in this study, whether CT in which cover crops were left as mulches, or standard tillage in which they were incorporated into the soil as green manures for each of the three measurement dates (table 5). However, there was no interaction (p = 0.84) between tillage type and cover crop for percentage residue cover. The combination of cover crops with CT consistently had higher percentage of residue cover than with ST.

The determination of the impacts of these cover crops on subsequent crops was beyond the scope of this paper. Those relationships have been reported in earlier studies. Mitchell et al. (2015) observed that yield differences in both cotton and tomato in treatments with and without cover crops were not consistent between years. Further, presence of a cover crop prior to tomato generally resulted in lower or similar yields between CT and ST in most years of the study due to difficulties establishing transplants as well as slower seedling early-season growth rates in cover crop plots (Mitchell et al. 2009). Presence of a cover crop for cotton, while not necessarily resulting in lower yields (Mitchell et al. 2015), presented additional crop establishment challenges that need management attention and successful implementation to avoid yield loss (Mitchell et al. 2008b).

There are examples of successful crop production in semiarid regions other than the CV that may be instructive for increas-

Figure 1

Cover crop biomass in long-term study in Five Points, California, from 2000 to 2014.

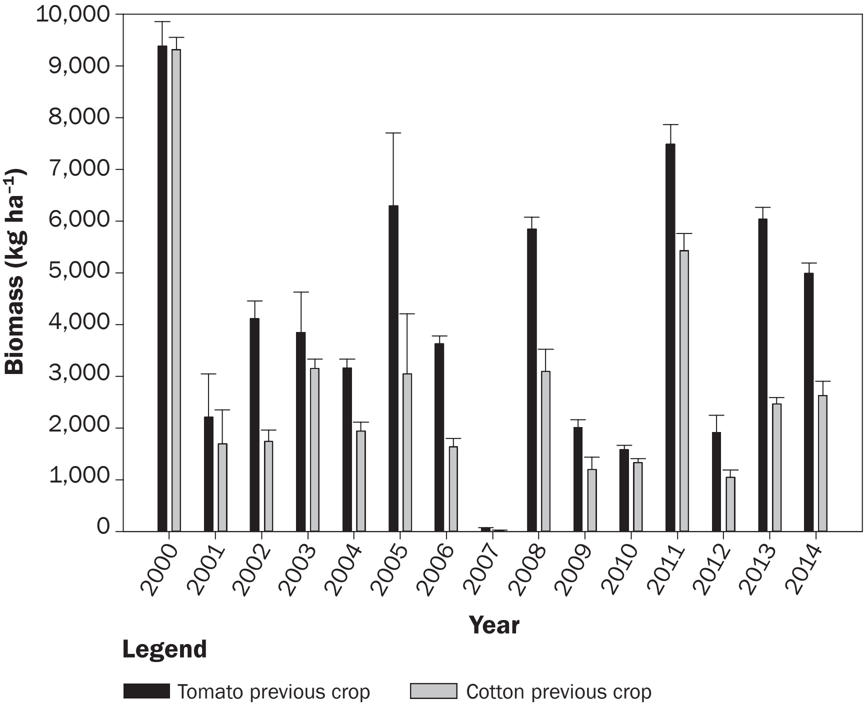


Table 5

Percentage surface residue cover on April 20, 2004; December 18, 2009; and August 10, 2014; for tillage and cover crop systems in the long-term study in Five Points, California.

	Surface residue cover (%)†		
Treatment*	Apr. 20, 2004	Dec. 18, 2009	Aug. 10, 2014
CTCC	88(0.04)a‡	91(0.71)a	97(0.7)a
CTNO	42(0.07)b	89(1.55)a	71(5.4)b
STCC	11(0.005)c	6(1.68)b	27(21.5)c
STNO	3(0.02)d	5(2.56)b	4(2.4)d

*ST = standard tillage. CT = conservation tillage. CC = winter cover crop.

†Values shown are the average of four replicate values with + one standard deviation of the average given in parentheses.

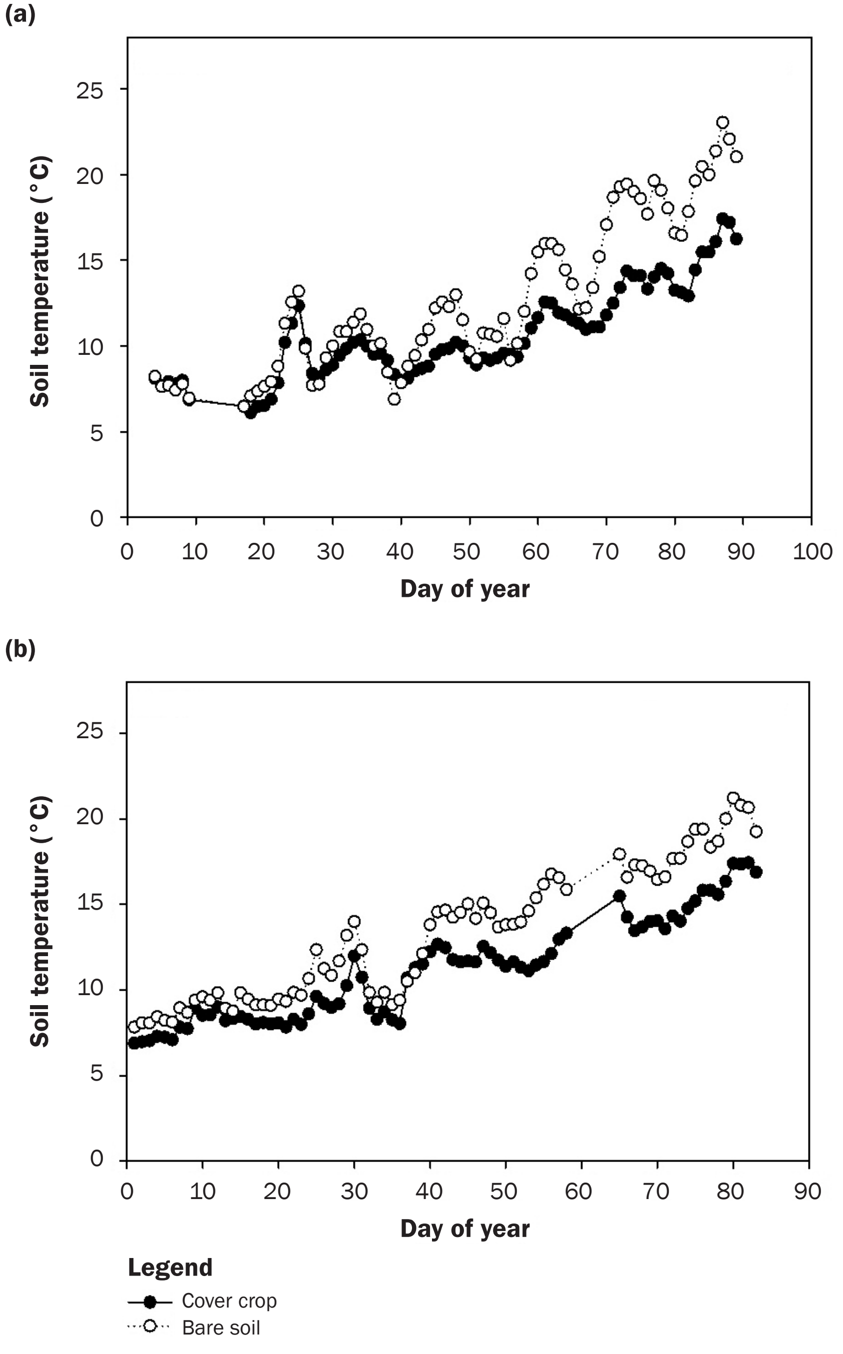
‡ Means with the same letter are not significantly different, Fisher's least significant difference, (p > 0.05).

ing winter cover crop productivity. Farmers in western Australia, for instance, have been coupling no-tillage, high residue production techniques under similar rainfed regimes for a number of years and achieving economically viable wheat grain yields with an average of 30.5 cm (12 in) of precipitation (Crabtree 2010). Other work with conservation agriculture practices that reduce soil disturbance and preserve residue, so as to increase precipitation capture and storage and reduce soil water evaporation losses (Klocke et al. 2009; van Donk et al. 2010; Mitchell et al. 2012), may thus have increased relevance and potential for adoption in future CV cropping than they have now. Merging of these practices along with cover cropping may increase the overall water use efficiency of CV production systems in the future (Mitchell et al. 2012) and improve the economic tradeoffs or reduce risks associated with cover cropping in this region.

The effect of the legume/triticale cover crop on soil temperature is seen in figures 2a and 2b for 2013 and 2014, respectively. In general, the combination of the cover crop canopy as well as surface residues from prior no-tillage management in each cover crop plot resulted in soil temperatures at the 10 cm (4 in) depth being an average of 5°C to 8°C (9°F to 14°F) lower under the cover crop relative to bare soil, which may contribute to decreased soil water evaporation. Lower soil temperatures under surface mulches, however, may also result in slower early-season growth of crops such as tomato that follow the cover crop (Mitchell et al. 2009).

Figure 2

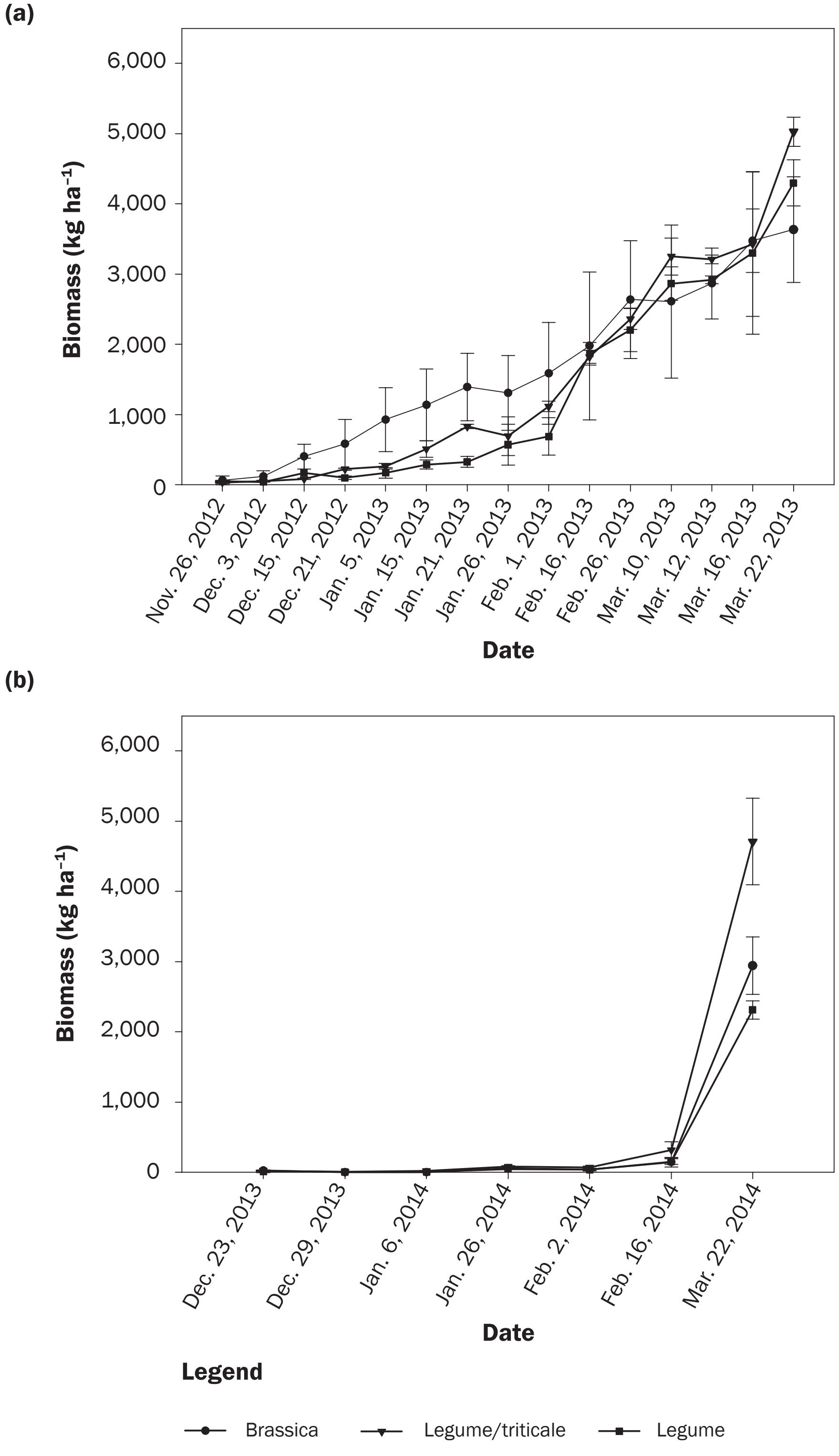
Soil temperature at the 10 cm depth under legume/triticale and fallow plots in (a) 2013 and (b) 2014.



Biomass accumulation for the cover crop mixtures used in the soil water study for 2013 and 2014 is shown in figures 3a and 3b. There was a difference between the years in cover crop biomass and an interaction between year and cover crop type. Therefore, data were analyzed separately for each year. More biomass was produced in 2013 than in 2014 by each mixture with the legume/triticale mix having the highest production with 5 and 4.7 Mg ha^{-1} (4,465 and 4,197 lb ac^{-1}) in 2013 and 2014 (figures 3a and 3b). Although, initially, more biomass was produced by the brassica treatment in 2013 the total biomass at termination of the cover crop was greatest in the legume/triticale mixture while there was no difference in total biomass between the brassica and legume-only plots (figure 3a). However, such differences in the initial growth period were not observed in 2014 (figure 3b). In 2014, the total biomass was greatest in the legume/triticale mixture and least in the legume-only plots, while the biomass in the brassica plot was intermediate (figure 3b). Accumulation was more gradual in all mixtures and typified routine cover crop growth dynamics in 2013, whereas the pattern of growth in 2014 indicated a longer lag in vegetative biomass increase perhaps due to low and late precipitation of this year. Biomass accumulation in both 2013 and 2014 was about one-third of what might be expected for similar species mixes in this region with supplemental irrigation (Mitchell et al. 1999). There was more consistent and evenly distributed precipita-

Figure 3

Cover crop aboveground biomass for brassica, legume, and legume/triticale mixtures in the water depletion study in the winter of (a) 2012 and 2013 and (b) of 2013 and 2014 in Five Points, California.

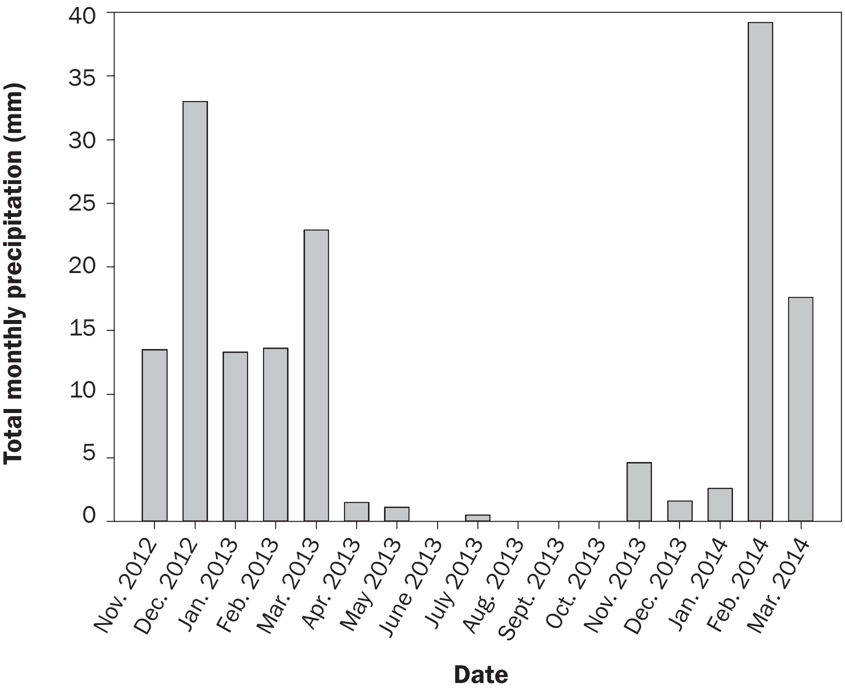


tion and a greater amount of precipitation during the 2012 to 2013 five-month winter period from November through March than in 2013 to 2014 (figure 4), and this may have accounted for the higher cover crop growth that was measured during the first year.

Data for N content of the three cover crop mixtures were analyzed separately for each year as the samples were taken at different times during the two years (figures 5a and 5b). Significant differences in cover crop N content were seen during the different sampling dates in each year of the study. In 2013, at the initial sampling date, the N content in the biomass of the brassica plots was the greatest, followed by the legume plots. The least amount of N content was in the legume/triticale mixture plot (figure 5a). Although this difference did not hold true at each sampling date, in general, the N content in the biomass of the brassica plots was generally greater than the other cover crop mixtures. Similarly, for most of the season, including at termination, the N content of the legume/triticale cover crop plots was greater than that of the legume-only plots (figure 5a). In 2014, the trends were different. For example, the N content in the legume-only plots was greatest at the first and last sampling dates (figure 5b). Contrary to 2013, the least N content was in the legume/triticale plots. Nitrogen content tended to decrease during each winter growing season from about 4% to 2% or 3% at the time of termination in late March. Because all aboveground biomass within a sampling area was harvested, including weeds, expected higher N content for the legume mix might have been diluted, particularly in 2013 (Mitchell et al. 1999). Using biomass and N-content data for each mixture for the final sampling dates in each year, 127, 52, and 136 kg N ha^{-1} (113, 46, and 121 lb N ac^{-1}) were accumulated in the brassica, legume, and legume/triticale mixes in 2013, and 46, 68, and 85 kg N ha^{-1} (41, 61, 76 lb N ac^{-1}) were accumulated for the same species, respectively, in 2014. The risk of N loss by leaching in this region during the winter growing period would be relatively low due to low precipitation rates. Therefore, a proportion of these measured cover crop tissue N levels is assumed to have derived from soil pools that might otherwise have provided N to subsequent cash crops in the following spring.

Soil Water Content. Volumetric soil water content data for the 0 to 90 cm (0 to

Figure 4
Precipitation (mm) from November of 2012 through March of 2014 in the water depletion study in the winter of 2012 and 2013 in Five Points, California.



35 in) depth from the fall of 2012 through the summer of 2014 for the cover crop soil water depletion study are shown in figure 6 for the three cover crop mixtures and the fallow systems. For the purposes of this analysis, we compared soil water content as measured by neutron probe from the 0 to 90 cm depth from January 5 in 2013 and January 2 in 2014 through March 27, a reasonably average termination date in each year, and determined changes in stored water in each system during this time. In general, soil water content was similar among all treatments at the start of the winter growing season in early January with a 0.22 cm (0.09 in) difference between the four treatments in 2013 and a 1.64 cm (0.65 in) difference between treatments at the start of 2014 for the 0 to 90 cm depth.

Total soil water storage in the 0 to 90 cm (0 to 35 in) profile for the fallow and each of the cover crop treatments compared across the January to March 27 period differed between years, and there was a year by treatment interaction. Therefore, data were analyzed separately for each year. In 2013, the fallow system had the most (4.8 cm [1.9 in]) total soil water, and it was greater than the cover crop treatments (figure 7). There was no difference between the cover crop treatments in total soil water storage, and amounts ranged from –0.57 to 0.12 cm (–0.22 to 0.05 in). Similarly, in 2014, the fallow plots had the most (0.43 cm [0.17 in]) total soil water (figure 7). However, contrary to 2013, cover crop treatments differed in total soil water. The cover crop mixture and brassica plots had similar amounts of total soil water, but the legume plot had less total soil water than the cover crop mixture plots. Compared to the fallow system, cover crops thus depleted 5.3 cm (2.1 in) more water from the 0 to 90 cm profile in 2013 and 0.67 cm (0.26 in) more water in 2014. Most of the difference in soil water depletion between the fallow and cover crop systems occurred during March of each year.

These findings and the range of difference in soil water storage between the no cover crop, bare soil check, and the three cover crop mixtures are generally similar to the findings of other studies. For example, Stivers and Shennan (1991) reported that water content in the 60 cm (24 in) depth was reduced by 2 cm (0.8 in) in oat (*Avena sativa* L.) plots, but only by 1 cm (0.4 in) in vetch (*Vicia dasycarpa*) plots relative to that in fallow plots in Davis, California, another predominantly winter-precipitation semiarid region (Unger and Vigil 1998). In slight contrast, in our earlier work in Five Points, California, three-year average water contents were 7.4 cm (2.9 in) less in barley, 7.9 cm (3.1 in) less in barley + vetch, and 6.6 cm (2.6 in) less in vetch cover crops than in fallow plots (Mitchell et al. 1999). Soil water content in fallow plots increased by 9.4 cm (3.7 in) in the first two years, but only by 4.1 cm (1.6 in) in the third year when precipitation was lower, as was the case in 2014 of the present study.

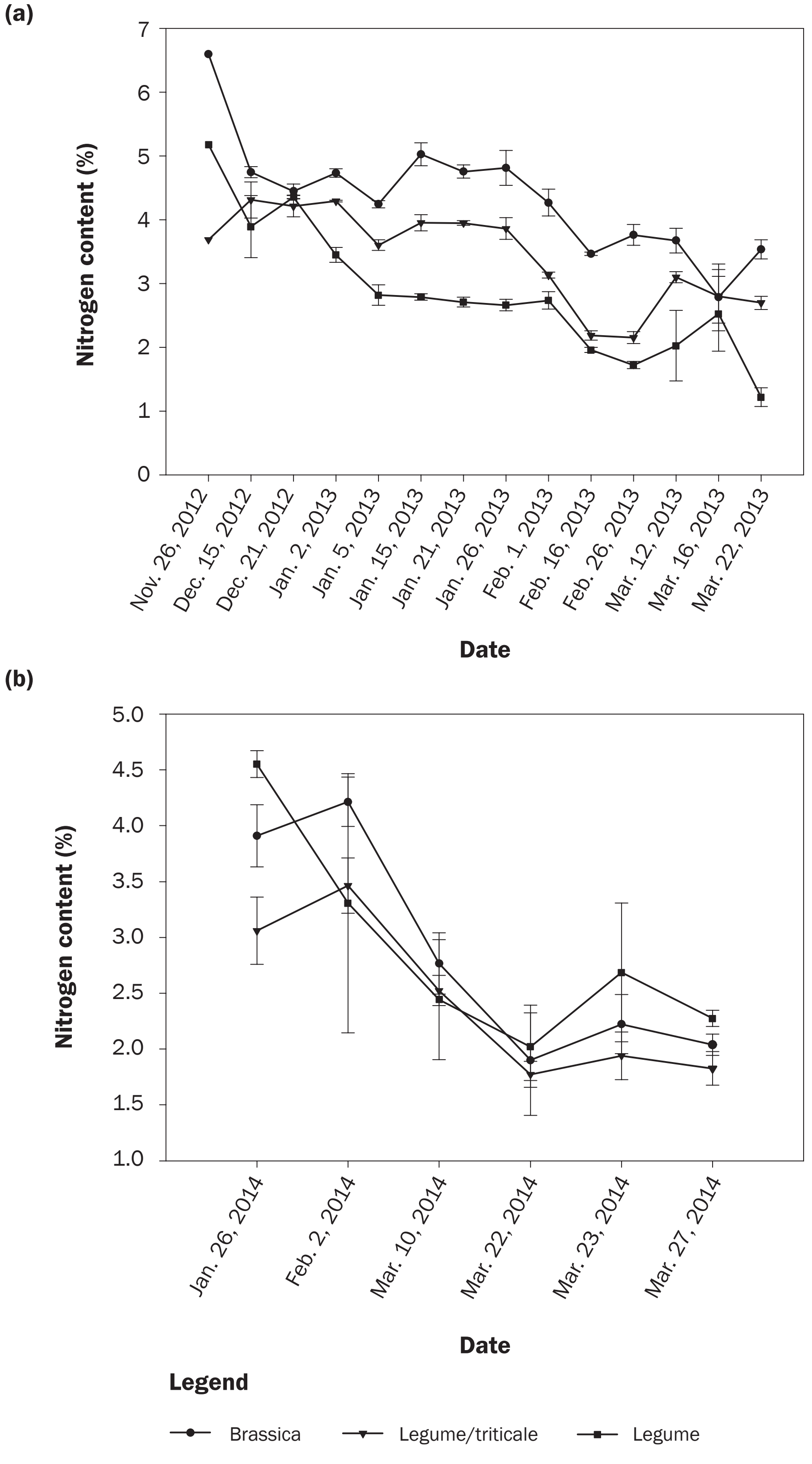
Unger and Vigil (1998) reviewed the effects that cover crops have on soil water relations and concluded that because cover crops use water they may be more suited to humid and subhumid regions than to the hot summer Mediterranean climate of California's CV (Peel et al. 2007). The overall effect of cover cropping on soil water relations depends on the timing and amount of precipitation during the winter, water infiltration and soil evaporation, as well as transpiration rate by the cover crop. Where precipitation is limited as it is in the CV, there is thus a definite risk that cover crops will deplete soil water to some extent and reduce yields of subsequent cash crops because of reduced soil water storage. Unger and Vigil (1998) point out, however, that these losses in storage may be recovered by CT that involves crop residue maintenance on the soil surface and reduced soil disturbance. Indeed, our own recent work with surface residue mulches and no-tillage in the CV has demonstrated this very important tradeoff (Mitchell et al. 2012). Coupling no-tillage or reduced tillage with practices preserving high residues reduced summer soil evaporation losses by about 10.2 cm (4.0 in) which is about 13% of a typical summer crop's evapotranspiration (Mitchell et al. 2012) and roughly equal to the determinations of winter cover crop water use reported here. There are many examples of benefits derived from generating and preserving residues as a means for reducing soil water evaporation (Klocke et al. 2009; van Donk et al. 2010; Crovetto 1996, 2006), but no work has been done to evaluate potential benefits and tradeoffs associated with high residue-preserving production practices. Therefore, this is an important area for future research.

Summary and Conclusions

This study illustrates the importance of long-term systems research in providing clear, robust implications of crop manage-

Figure 5

Cover crop nitrogen (N) content for brassica, legume, and legume/triticale mixtures in the water depletion study in the winter of (a) 2012 and 2013 and (b) 2013 and 2014 in Five Points, California.



ment options that may not be apparent in shorter duration investigations. Data from this study provide invaluable information in terms of interannual variation in cover crop biomass and soil-water depletion in response to variations in climatic conditions. Our data suggest that while vigorous growth of winter cover crops in this area of the CV may not be possible consistently in all years due to the low and erratic precipitation patterns, in most years there may be benefits in terms of providing some amount of crop cover and increasing the efficiency of the cropping system to capture photosynthetic energy throughout a year. Other benefits include the cycling and capturing of both C and N and the addition of biological diversity and activity to the soil during periods that might otherwise be devoid of such soil-building life (Ferris et al. 2004; DuPont et al. 2009).

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Figure 6

Total soil water in the 0 to 90 cm soil depth in fallow and brassica, legume, and legume/triticale cover crop plots from November of 2012 through May of 2014 in the water depletion study in the winter of 2012 and 2013 in Five Points, California.

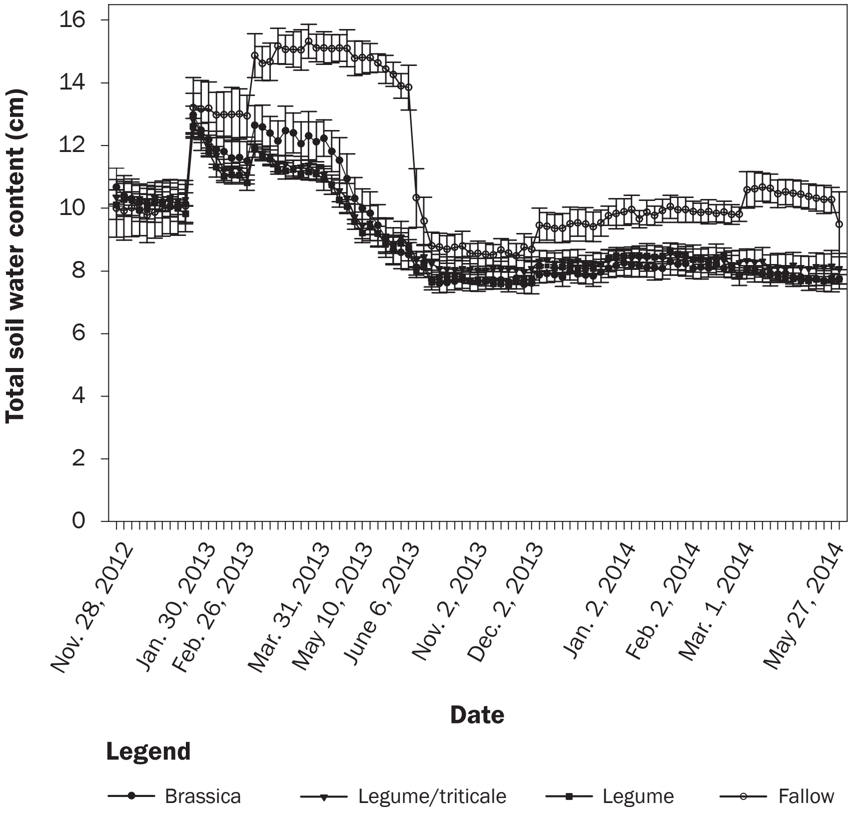

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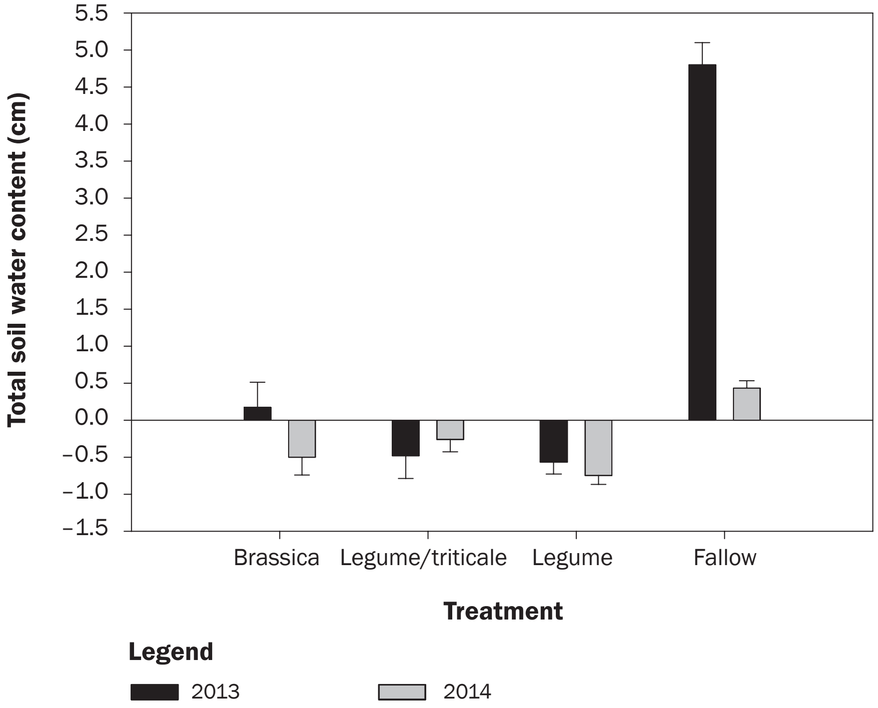
Figure 7

Changes in total soil water in the 0 to 90 cm soil depth under fallow and brassica, legume, and legume/triticale cover crops in the water depletion study in the winter of 2012 and 2013 in Five Points, California. These changes occurred the period from January 5 to March 27 in 2012 and from January 2 through March 27 in 2013.



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