RESEARCH ARTICLE

Long-term reduced tillage and winter cover crops can improve soil quality without depleting moisture

Long-term reduced-disturbance tillage and winter cover cropping can improve San Joaquin Valley soil quality without depleting soil moisture.

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Abstract

California farmers who use reduced-disturbance tillage and winter cover cropping can boost production and improve soil health. However, some farmers are hesitant to try these conservation practices due to uncertainty about whether planting winter cover crops will deplete soil moisture in already drought-stricken regions. Our study addresses these concerns by looking at how long-term reduced-disturbance tillage and winter cover cropping, compared to fallowed soils with standard tillage, affected soil moisture. Although we found a statistical difference in total soil water content, the difference was only about 0.3 inches of water per foot of soil. On average, the soil water content of the top 0–96 inches was highest for the reduced-disturbance fields with winter cover crops. This was especially evident during our driest field season, from November 1, 2017, to March 15, 2018, when cumulative rainfall was only 1.9 inches. Our findings show that winter cover cropping and reduced-disturbance tillage can improve soil without depleting soil water levels in row crops.

During the 2012–2016 drought, California farmers, particularly those in the San Joaquin Valley, were confronted with higher water prices and frequently turned to finite groundwater reserves to meet crop water demands (Hanak et al. 2017). The economic repercussions of prolonged water shortages in the region raise concerns about how to meet crop water requirements without degrading the environment. These concerns contribute to farmers' hesitation to adopt winter cover cropping and reduced-disturbance tillage (which relies on leaving crop residue on the field and can refer to either no tillage or reduced tillage). Although cover cropping (CC) and reduced-disturbance tillage (RD) improve soil quality and benefit ecosystems (Mitchell 2019; Yao et al. 2000), the hydrological impacts of these combined practices have not been well documented. At a time when groundwater sustainability agencies (GSAs) under California's Sustainable Groundwater Management Act (SGMA)

A tractor mows a cover crop of radish, *Phacelia*, vetch and triticale. Benefits of cover cropping include increased water infiltration and soil aggregate stability. *Photo:* Jeffrey Mitchell.

are meticulously tracking water use, including rainfed winter cover crops, there's a knowledge gap regarding the hydrologic impact of conservation agriculture practices. Simultaneously, irrigation districts are grappling with the fate of fallowing farmland and leaving some acreage unplanted (Hanak et al. 2021). Research addressing the combined impacts of winter cover cropping and reduced-disturbance tillage on soil moisture will play an important role in farmers' planting decisions.

Cover cropping has been widely studied for its agronomic and ecosystem benefits. These include improving soil porosity (Basche and DeLonge 2017), increasing water infiltration into the soil profile and reducing soil erosion (Dabney et al. 2001; Fageria et al. 2005), suppressing early-season weeds (Teasdale 1996), increasing microbial diversity (Schmidt et al. 2018), biomass and activity (Duchene et al. 2017; Fageria et al. 2005; Fernandez et al. 2016), mitigating net greenhouse gas emissions (Abdalla et al. 2019), reducing nitrogen leaching (Abdalla et al. 2019), and minimizing water quality degradation (Harter et al. 2012).

RD minimizes physical disturbance of the soil profile following the harvest of one crop and before the establishment of a subsequent crop, while leaving crop residues on the soil. Keeping the surface covered with residues is an important principle of soil health and is central to conservation agriculture (Mitchell et al. 2019). Reducing tillage and maintaining soil cover has been shown to increase soil water-holding capacity and to prevent top layer compaction and sealing, especially in dry climates (Basche and DeLonge 2017). These benefits have been observed under both irrigated (Klocke et al. 2009; van Donk et al. 2010) and rainfed or otherwise water-limited conditions (Unger and Baumhardt 1999; Unger and Parker 1976). Residues left on the soil surface reduce direct soil evaporation through the mulching and shading effect, which reduces surface soil temperature, ground heat storage, and direct wind effects on evaporation (Klocke et al. 2009; Ranaivoson et al. 2017).

Current adoption is low

Financial incentives from state and federal programs have promoted both cover cropping and reduced-disturbance tillage as multi-benefit conservation agriculture practices. However, their implementation into cropping systems can be complex. As a result, adoption rates vary widely across agroecological systems. In California, although rates have been increasing, reduced-disturbance tillage is only practiced on 7.1% of cropland acreage, compared to the U.S. average of 34.6%, and only 4.8% of California cropland acreage is cover cropped, compared to the U.S. average of 10.7% (LaRose and Myers 2019).

Understanding what drives farmers to change their agricultural practices depends on local conditions. Some consistent trends driving adoption of conservation practices include access to information, perceived costs and benefits (Bergtold et al. 2012; Knowler and Bradshaw 2007), understanding that short-term costs can lead to long-term benefits (DeVincentis et al. 2020), and social networks influencing norms of practice. Additionally, risk perceptions and acceptance, environmental attitudes, access to financial incentives for adaptation (including conservation programs such as USDA-NRCS EQIP and CDFA Healthy Soils Program), and a host of demographic variables specific to the operation and the farmer (e.g., farm size, crop type, soil type, farm income, years of farming experience, level of education, land tenure, etc.) (Knowler and Bradshaw 2007; Prokopy et al. 2008) play an important role.

Twenty-year (1999–2019) field study site at the UC West Side Research and Extension Center with surface residue preservation (center plots), cover cropping (green strips), and clean cultivation fallow plots (on the periphery of the photo). *Photo:* Jeffrey Mitchell.

While we can learn about adoption from similar research in other locations, these findings cannot provide a complete picture of farmer decision-making in California, where water limitations are unique. Due to the dynamic nature of soil and its slowly changing characteristics (Six et al. 2004), long-term research studies are critical to addressing questions of agricultural resource management, including the use of practices such as cover cropping and reduced-disturbance tillage. Long-term studies on soil water are particularly important in light of concerns that cover crops could exacerbate the depletion of soil moisture during the winter period due to evapotranspiration (Mitchell et al. 2015; Unger and Vigil 1998).

This study expands on earlier work that identified trade-offs between soil improvement and soil water depletion as a result of winter cover cropping (Mitchell et al. 2015) and is aligned with recent findings that cover crops do not cause significantly different soil moisture or evapotranspirative losses compared to control plots across 10 sites in California's Central Valley

(DeVincentis et al. 2022). Our 2016–2019 study builds on 17 years following the inception of the conservation agriculture treatments of reduced-disturbance tillage and winter cover cropping at a field site in the San Joaquin Valley. The focus of this research is to address a common scientific question from the local agricultural production and regulatory communities: "Do the combined soil conservation practices of winter cover cropping and reduced-disturbance tillage have an observable impact on soil moisture in San Joaquin Valley agricultural fields?"

This study addresses information gaps related to actual water use in cover cropping and how cover crops and reduced-disturbance tillage affect soil moisture. The setting is an annual crop sequence that has been underway since 1999. Our goal was to quantify and document changes in winter soil water storage due to cover crops and reduced-disturbance tillage.

Long-term field site

In 1999, the National Research Initiative (NRI) – Conservation Agriculture Systems Project (CASP) was created to evaluate reduced-disturbance tillage as a possible practice to reduce particulate matter emissions from the intensive soil disturbance tillage in a cotton-tomato rotation system. Located at the University of California's West Side Research and Extension Center (WSREC) in Five Points, California, the CASP study is the only study site in the state that has incorporated all critical soil health principles in its experimental design. For the reduced-disturbance tillage plots, the RD system fully transitioned to no tillage (NT) in 2012, with the only soil disturbance happening during seeding or transplanting. The site thus provides a unique resource that permits researchers to quantify the long-term impacts of consistently implemented alternative management practices on soil biodiversity and functions (Mitchell et al. 2017).

Since the initiation of the long-term research site, the objectives have been broadened to measure changes in soil chemical, physical, and biological properties under reduced-disturbance tillage and cover cropping management in the historically highly productive San Joaquin Valley. Previously published information from the site has documented improvements in several soil health indicators, including soil aggregate stability and water infiltration (Mitchell et al. 2017), abundance and diversity of soil macrofauna (Kelly et al. 2021), and soil porosity and water-holding characteristics (Araya et al. 2022).

Throughout the CASP's duration, the impacts of reduced-disturbannce tillage and cover cropping on crop yields have varied by crop. Half of the experimental field was in a tomato-cotton rotation and the other half was in a cotton-tomato rotation with both crops grown in each year from 1999 to 2014, followed by garbanzo (*Cicer arietinum*), sorghum (*Sorghum bicolor* L.) (2015 to 2018) and tomato and garbanzo in 2019. Tomato yields were 9.5% higher in RD versus standard tillage (ST) systems but were 5.7% higher in no-cover crop (NO) than in CC systems. The cotton yields were 10.0% higher in ST than RD and 4.8% higher in NO than CC systems in the early years of the study, largely due to problems encountered in establishing crop stands with no tillage. Sorghum yields in 2016 and 2017 were similar between RD and ST, while cover crops had no effect on sorghum yields in either year. Garbanzo yields were higher in RD than ST in 2016 and 2017, but similar in 2018. Tomato yields in 2018 were lower in the RD-CC system, due to problems that year with cover crop regrowth. In general, the yield results between treatments need to be viewed cautiously, as they reflect the inherent learning curve challenges and mistakes of experiment station work.

Experimental design

The 8.8-acre research site consists of 32 plots, each 33 feet wide by 328 feet long, with a 33-foot border plot (buffers) between treatments and six 5-foot buffers between rows (fig. 1). See the online technical appendix for cover crop mixes, planting and termination dates, and irrigation quantities with dates. The soil type is a Panoche clay loam with a fine-loamy texture, mixed, superactive, and thermic Typic Haplocambids. This soil is characterized as being well-drained with moderate permeability and formed by alluvial fans in flood plains (Mitchell 2015).

Our study consisted of four combinations of tillage and cover crop systems, arranged as a randomized

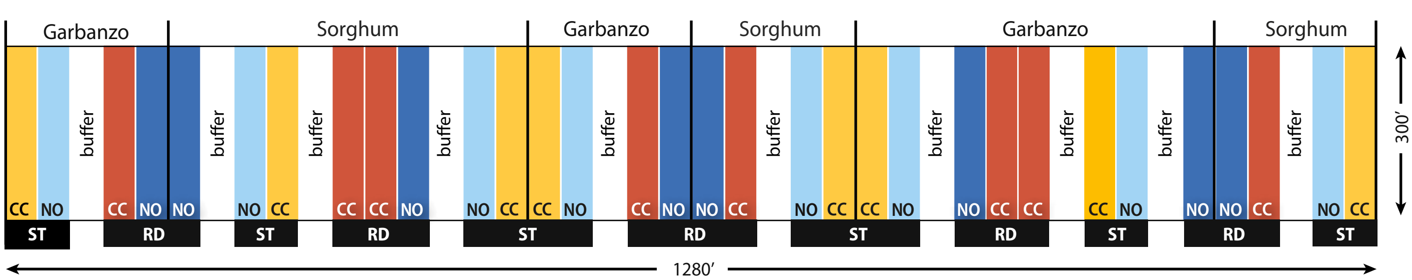

FIG. 1. Entire experimental field layout for season 1 of our study, consisting of four treatments, two cash crops, and several buffer/border rows. From 2015 to 2017, the cash crops were sorghum and garbanzos (rotated), in 2018 tomatoes and garbanzos, and in 2019 melons and tomatoes. CC = cover crop, NO = no cover crop, RD = reduced-disturbance tillage, ST = standard tillage.

complete block design in a typical row crop field in the San Joaquin Valley. The four combinations were (1) reduced-disturbance tillage with winter cover cropping (RD CC), (2) standard tillage with winter cover cropping (ST CC), (3) reduced-disturbance tillage without winter cover cropping (RD NO), and (4) standard tillage without winter cover cropping (ST NO) (fig. 1). The cash crops were rotated between seasons to maintain variability, while the soil management practices within each plot remained consistent. Standard tillage practices included surface residue shredding, multiple diskings to incorporate the residues from 8 inches to 10 inches, subsoil ripping to about 14 inches, and an additional disking, followed by bed shaping using a Wilcox Performer implement (Wilcox Agriproducts, Walnut Grove, Calif.).

Plot treatments remained consistent throughout the study, including management practices such as fertilizer and pest management interventions. Cover crops were planted by early November of each year and terminated in mid-March by mowing and spraying the standing residue with 2% glyphosate (N-(phosphonomethyl) glycine) for the RD treatments. Afterwards, the cover crop residues were disked into the soil for ST. Spraying the cover crop decreased the lag time between the termination of the cover crop and planting of the cash crops. Irrigation water was applied through a subsurface drip system, installed at the field site in 2013, with 1.5-inch diameter tape buried 12 inches in the center of each 60-inch-wide planting bed. Each year of the study the same amount of fall pre-plant irrigation water was applied to all of the treatment plots equally (3 inches in 2016, 3.5 inches in 2017, and 4 inches in 2018; see technical appendix).

Probe collects moisture data

Data for the study were collected between November and March for the years 2016 to 2019. Soil moisture was measured using a field-calibrated Campbell Nuclear Model 503 Hydroprobe (Campbell Pacific Nuclear, Martinez, Calif.) neutron probe depth gauge (503 DR Hydroprobe). Measurements were taken at 10 different depths (6, 12, 24, 36, 48, 60, 72, 84, 96, and 106 inches beneath the soil surface), with one access tube per plot. Previous research conducted at the same study site had shown that one access tube per plot is sufficient to capture the soil moisture of the entire treatment plot (Islam et al. 2006) given the homogeneity of soil hydraulic properties across the experimental plots.

On average, the neutron probe sampled a 26.4– to 26.8-inch radius of soil moisture at each depth. Neutron probe readings (counts of slow neutrons due to the interaction with soil water molecules) were recorded during the winter periods. The neutron probe data set included soil moisture data collected approximately weekly over three winter seasons from four treatments, from November 12, 2016 to April 20, 2017; November 7, 2017 to March 26, 2018; and October 17, 2018 to March 12, 2019.

NRCS soil health coordinator training at the NRI Project site in Five Points, Calif. *Photo*: Jeffrey Mitchell.

The percent canopy cover (the proportion of the soil surface area covered by cover crop foliage) was determined during the 2017–2018 cover crop growing season using Canopeo (https://canopeoapp.com), an app that measures fractional green canopy cover based on images captured by a smartphone camera (Patrignani and Ochsner 2015). Canopeo separates the green plant area from soil surface background and provides an estimated percentage of canopy coverage.

We used these data to assess the variations of water content in the soil profile between cash crop seasons, from November to March. This is a critical period to capture water from rainfall, because California's Mediterranean climate brings rain almost exclusively during the winter months. Neutron probe raw counts were manually recorded and then digitized, with the values checked for consistency by two research team members. The data set included 13,760 observations collected over 43 days, down 10 individual soil depths, and using 32 neutron probe access tubes. In order to compare the treatments over the same time period for the three winter seasons, the data set was truncated from November 1 to March 15 for each season, resulting in 10,880 observations after removing data from the 6-inch and 106-inch depths due to concerns about surface-atmospheric interactions and missing data, respectively.

The cumulative precipitation each season, from November 1 to March 15, was 6.3, 1.9, and 7.1 inches, respectively, and the average air temperature for November through March for each of the three seasons was 50.1°F, 50.1°F, and 49.8°F (CIMIS station no. 2, located on site in Five Points, Calif.; https://cimis.water.ca.gov/WSNReportCriteria.aspx). The average daily reference evapotranspiration (ET_o) value obtained with the Penman-Monteith method (ASCE-EWRI 2005)

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from November 1 to March 15 for each season was 0.07, 0.08, and 0.07 inches, respectively. The average ET_o (PM) from January 1st, 2016 through December 31, 2019 is 0.18 inches (https://cimis.water.ca.gov/). For the purposes of this experiment, we treated the plots within the NRI field as comparable, because fall irrigation, soil type, and weather conditions remained constant among treatment plots, with cash crops being rotated each year. The plots that received tillage (ST) and winter cover crops (CC) have remained constant since the experimental field started in 1999, regardless of which rotational row crop was grown during the summer cash crop period.

Data analysis was conducted using R statistical software (R Core Team 2020, version 4.4.1). The raw neutron probe counts were transformed to volumetric water content (VWC) using a calibration equation that relates count ratios to percent soil moisture using linear regression. The raw neutron probe counts were transformed into a count ratio to minimize the impacts caused by changes in the probe functionality due to aging and decay. Count ratios were calculated by dividing each raw count by the average of the standard counts taken each day of neutron probe readings in the field (7127). The calibration equation ($VWC\% = 22.619x - 1.587$, $R^2 = 0.96$; technical appendix fig. A) was created by regressing neutron probe counts and gravimetric soil data that was simultaneously collected. In-situ field calibration of the 503 Hydroprobe was done by taking count readings using the standard calibration feature of the probe at a given soil depth, collecting three 2.25-inch diameter cores at the same depth adjacent to the access tube, weighing the soil, drying the sample for 24 hours at 105°C, weighing the sample again to determine the gravimetric water content, and then converting gravimetric water content to VWC using the soil bulk density values determined from samples that were collected in 2013.

After every soil neutron probe count was converted into VWC (%) using the calibration equation, then converted to inches of water per foot of soil (e.g., 30% × 12 inches = 3.6 inches of water per foot), these values were compared individually (ANOVA), and then averaged and compared (Tukey test of means). Prior to conducting an analysis of variance (ANOVA) test, the statistical assumptions were tested. A two-factor ANOVA test was performed, comparing the tillage and cover factors on each date-depth combination from the three field seasons. The date-depth analysis is based on the method proposed by DeVincentis et al. (2022). Of the 1,032 ANOVA tests, 16% (193) observations showed significantly different ($P < 0.05$) soil water content. We removed the data sets that were collected on three date-depth combinations that showed significant interaction (tillage: cover) between Feb. 28, 2017 and March 10, 2017. The remaining analysis was conducted with the final data set of 10,784 individual winter soil water content values from 43 days of observation (over three field seasons), four treatments, and eight depths.

A post-hoc Tukey test was then performed with all the data to determine whether there were differences between the average soil water content values of the respective treatments. Two main comparisons were conducted: (a) the average value (inches of water per foot of soil) for each of the four treatments across the three seasons (depth aggregated), and (b) the average value at each depth for each of the four treatments (depth resolved). Then, in order to estimate the differences in soil water storage between various treatments, the averages from part (b) above were summed across the measured soil depth along the depth of measurement (0–96 inches) for each treatment.

Depth aggregated: soil water content comparison between treatments

$$\overline{W}^T = \frac{\sum_{d=1}^{43}\sum_{z=1}^{8}\sum_{r=1}^{4} W^T_{d,z,r}}{N_d \times N_z \times N_r}$$

Depth resolved: soil water content comparison between treatments

$$\overline{W}_z^T = \frac{\sum_{d=1}^{43}\sum_{z=1}^{8}\sum_{r=1}^{4} W^T_{d,z,r}}{N_d \times N_r}$$

where $\overline{W}^T$ is the mean water content of treatment T; subscripts d, z, and r represent indices of the measurement day, depth, and replication number; $\overline{W}_z^T$ is the mean water content of treatment T at depth z; $W^T_{d,z,r}$ represents an individual water content measurement on day d, depth z and replication number r; and d, z, and r represent the total number of measurement days, depths and replicates, respectively (i.e., $d = 43$, $z = 8$, and $r = 4$). Following the calculation, we ended up with a total of 4 $\overline{W}^T$ means, one for each treatment, and 4 × 8 = 32 means, one for each treatment-depth pair.

Less tillage, more moisture

We found that the plots with combined reduced-disturbance tillage and winter cover crops had the highest average winter soil moisture from 2016 to 2019. After conducting a pair-wise test, all treatment averages are statistically different from each other ($P < 0.05$). However, the differences between the four combinations were minimal. Measured in inches of water per foot of soil, the differences were less than 0.5 inch (fig. 2), which is a small fraction of the average seasonal tomato water requirements (about 30 inches) in the southern San Joaquin Valley (Turini et al. 2018). For instance, when comparing ST NO to RD CC, there is on average 0.3 in/ft less water in the standard tillage, no cover crop treatment than in the treatment with both soil conservation practices. The main takeaway is that the ST NO to RD CC comparison of means is the farthest from the zero line in figure 2, and hence has the largest difference in soil water content.

Translating this further, the results show that, on average throughout the November 1–March 15 season, there is more water in the plots under RD with winter cover crops, compared to the plots under ST without

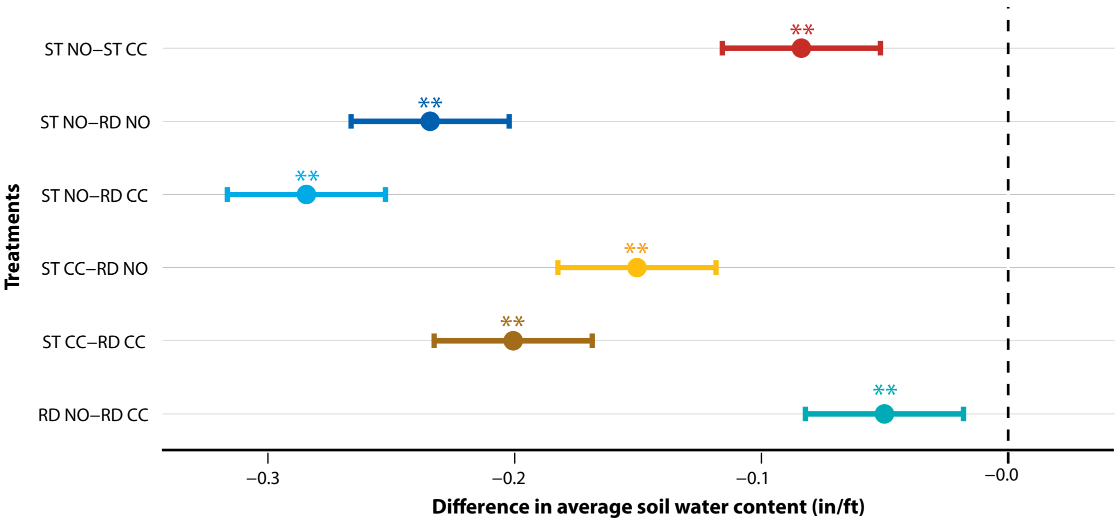

FIG. 2. Pairwise comparisons between soil water content (in/ft) between two different treatment means (95% family-wise confidence level). Soil water content differences between the treatment means (in/ft) as a result of the Tukey test of means. The results are averaged across the entire soil profile (0–96 inches) grouped by treatment. Error bars indicate standard errors. ** signifies that differences are statistically significant at $P < 0.05$. CC = cover crop, NO = no cover crop, RD = reduced-disturbance tillage, ST = standard tillage.

winter cover crops. When comparing the effect of tillage and cover crops on soil water content, CC has less of an impact on the soil moisture than the choice of tillage system (i.e., ST NO–ST CC and RD NO–RD CC have the least difference in mean levels). In short, compared to fallow or clean-cultivated soil, the cover crops are not depleting the soil moisture.

According to the Tukey test of means, there is a statistically significant difference between the aggregated four treatments (fig. 3). For the ST NO treatment, the distribution of observations peaks at the low end of the soil moisture spectrum, i.e., around 1–2 inches of water per foot of soil, indicating that this treatment generally had the least soil water (fig. 3). In contrast, both the reduced-disturbance treatments (RD CC and RD NO) have distributions that are concentrated farther to the right compared to standard tillage treatments (ST CC and ST NO), around the upper end of the soil moisture spectrum (2–3 inches) (fig. 3). This behavior indicates a tendency toward higher soil moisture in reduced-disturbance treatments.

The conservation agriculture practice of reduced-disturbance tillage coupled with winter cover cropping shows a combined positive impact on soil moisture,

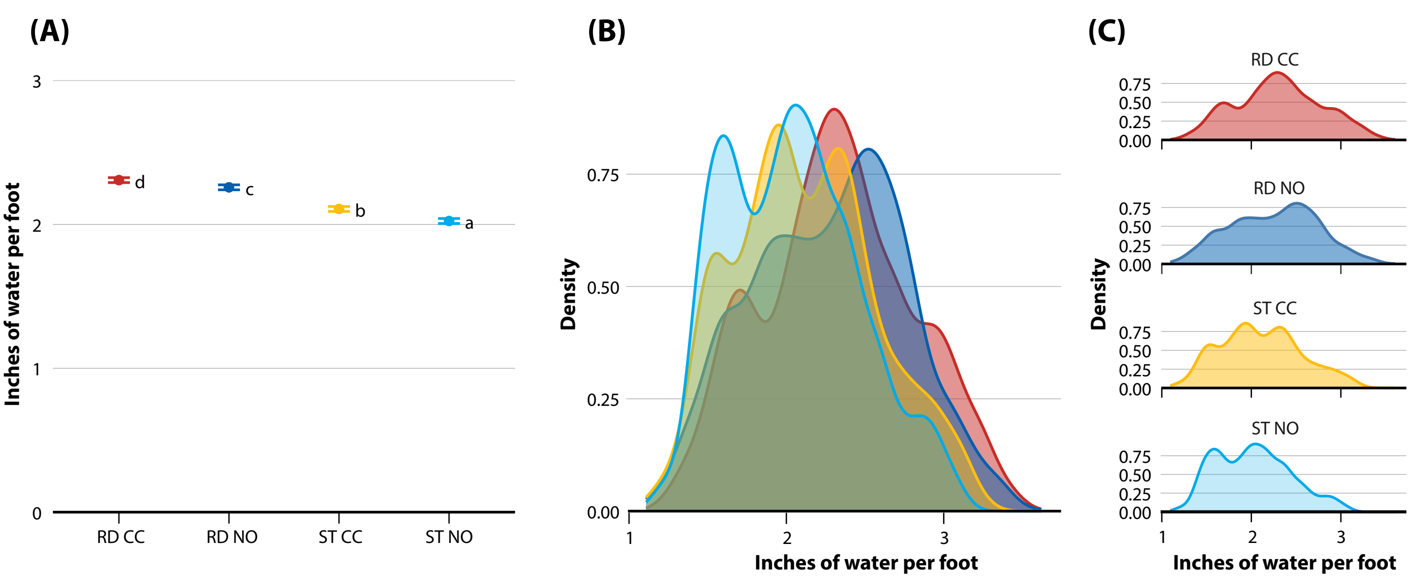

FIG. 3. Soil moisture (in/ft soil) density distribution. The overall trend in the dataset illustrates that there is a high degree of overlap between soil moisture comparing the four treatments. CC = cover crop, NO = no cover crop, RD = reduced-disturbance tillage, ST = standard tillage. (A) Average wintertime soil moisture from 2016 to 2019. Means followed by a common letter are not significantly different according to the Tukey test. (B) Density distribution of wintertime soil moisture from 2016 to 2019. (C) Density distribution per individual treatment.

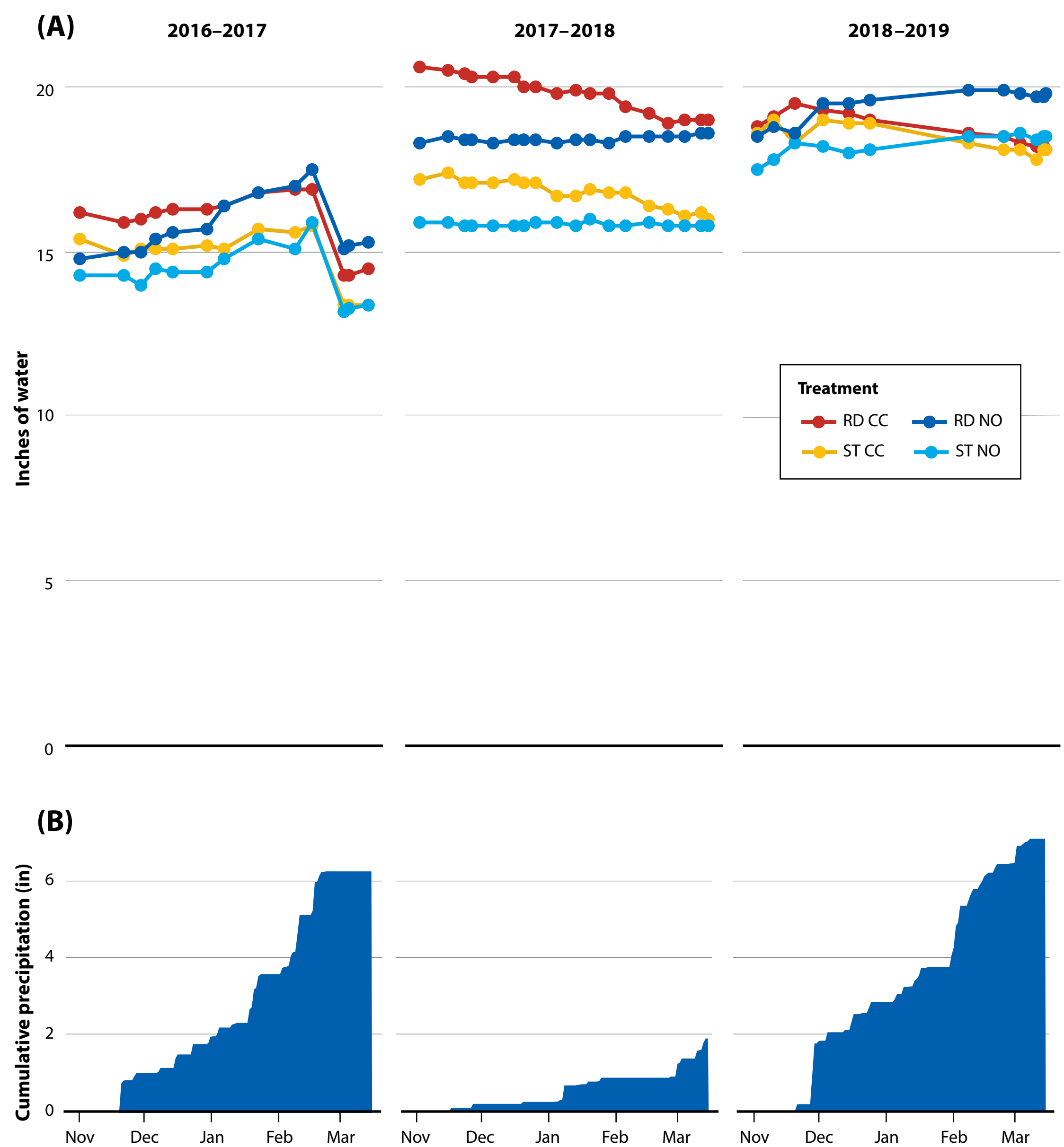

FIG. 4. Soil moisture response and precipitation patterns over the winter cover crop growing season. (A) Daily sum of average wintertime soil moisture in top 96 inches. (B) Cumulative precipitation between Nov. 1 and Mar. 15 in Five Points, Calif. CC = cover crop, NO = no cover crop, RD = reduced-disturbance tillage, ST = standard tillage.

most prominently during drought conditions. In relating our results to precipitation patterns, despite the low precipitation (1.9 inches) during the second season (November 1, 2017 to March 15, 2018), the RD CC treatment plots showed higher soil moisture content throughout the winter season compared to the other three treatments (fig. 4). For all three seasons, despite the water used to grow cover crops during the winter season, there was no noticeable difference in winter soil water content between the cover cropped plots and the fallow or clean-cultivated plots at the end of the cover crop season in March (fig. 4).

The four treatments differed slightly in behavior among the three seasons. The most distinctive differences in soil water content down the profile can be highlighted in the 2017 drought season, when the reduced-disturbance plots had a higher sum of average soil water content compared to the standard tillage plots (fig. 5). When examining the differences in soil moisture across depths along the soil profile, water down the soil profile follows a similar pattern across treatments, with a greater amount of soil water in the top and around 72 inches depth (fig. 6). Comparing soil water at the same depths in the profile among treatments, again we find that reduced-disturbance tillage plots had more soil water than standard tillage plots for most of the depths, regardless of the presence of cover crops (fig. 6). Additionally, the ST NO plots consistently show the lowest soil water (in water/ft soil) down the profile across the three seasons (fig. 6).

Extensive cover crop canopy

The cover crops were typically seeded by November 15 of each fall and terminated around March 15 of the following spring. This time accounts for a period of actively growing biomass, or “solar energy-capturing green ground cover,” allowing for about 120 additional

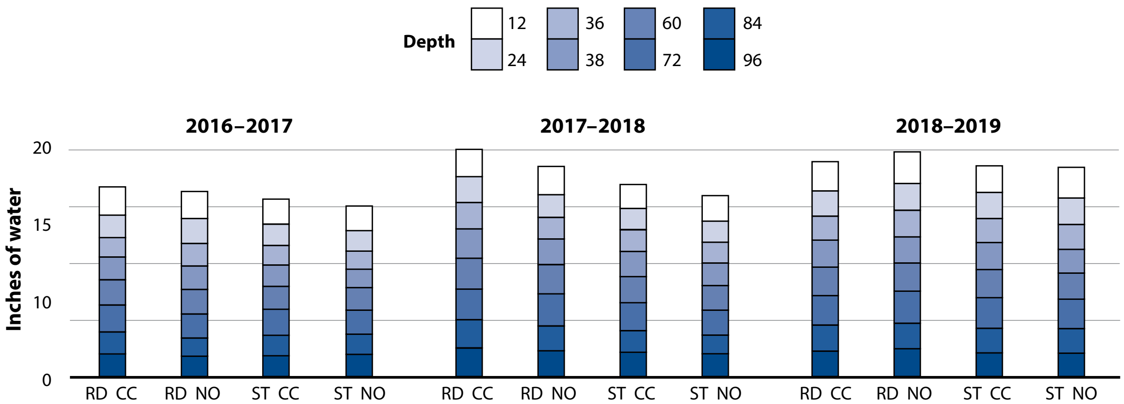

FIG. 5. Sum of average wintertime soil moisture in top 96 inches. This data represents the sum of the averages at each depth, allowing for understanding the distribution of water throughout the depth of the profile for each treatment, and any differences among seasons. CC = cover crop, NO = no cover crop, RD = reduced-disturbance tillage, ST = standard tillage.

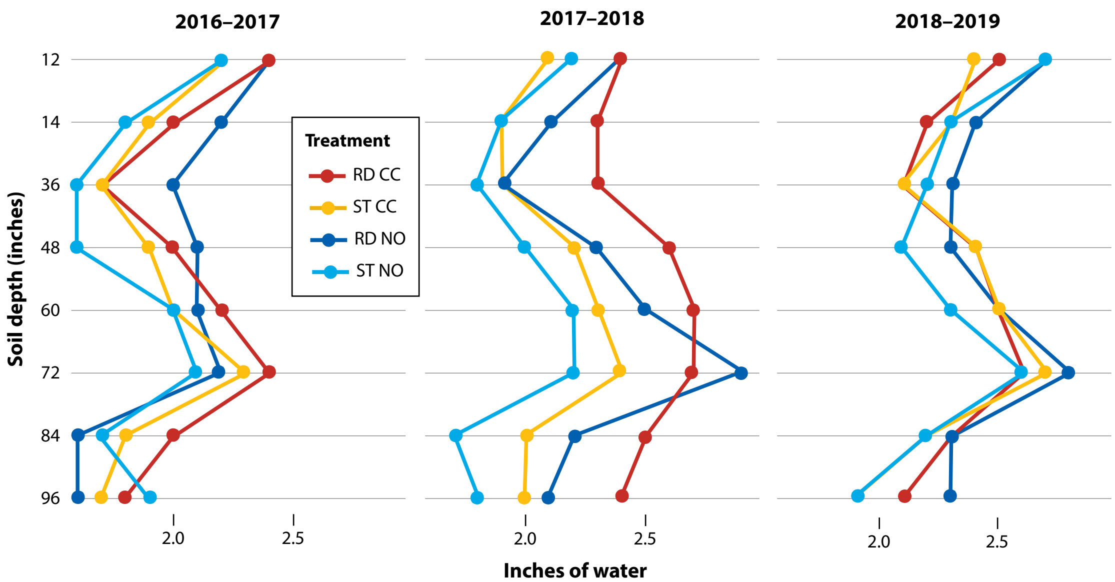

FIG. 6. Seasonal average wintertime soil moisture along the soil profile. CC = cover crop, NO = no cover crop, RD = reduced-disturbance tillage, ST = standard tillage.

days of living roots in the soil during the year relative to the NO systems, which were instead fallow during that time. The percent canopy cover, measured during the 2017–2018 winter, showed that the cover crop increased steadily to over 90% canopy cover during the 87-day period from November 12 through February 7.

Previous studies have shown that, depending on rainfall, climate, and the duration of the growing period, cover crops use water for growth and may create a water deficit for farmers (Mitchell et al. 2015; Unger and Vigil 1998). By contrast, our results suggest that, despite the water used by the cover crops, numerous benefits can be obtained from these conservation agricultural practices without depleting soil moisture from the active rootzone, provided the cover crop growth is terminated before periods of higher evapotranspiration demand, i.e., beyond March 15. Our results for the aggregated 2016–2019 winter seasons indicate that the reduced-disturbance tillage and cover crops (RD CC) plots had the most total soil water. This was especially evident during the drought of November 2017–March 2018, with the lowest cumulative rainfall of the three seasons of our study — only 1.89 inches, compared to 6.28 and 7.08 inches during the first and third season (fig. 4).

The tradeoff outlined in Mitchell et al. (2015) between winter cover crop growth and soil water depletion was based on the same field site as our study, in the 2013 and 2014 seasons. That study found that, compared to the fallow soils, cover crops depleted 2.1 inches of water in 2013 and 0.26 inches in 2014. We hypothesize that this tradeoff has now been overcome due to the extended period of reduced-disturbance tillage, and the accompanying benefits, including high surface residue and retainment of soil moisture. Furthermore, Mitchell et al. (2015) measured the soil water content only from 0–35 inches of the soil profile, and from early January to late March. By comparison, this study measured 0–106 inches of the profile with soil water data from mid-November to mid-March. Estimating the water content at the end of the study period (mid-March) is critical to analyzing our data.

The power of living cover

Our study illustrates the effects of winter soil cover from living biomass (cover crops) and surface residues. In the 2017–2018 winter cover crop season, the RD plots started the winter cover crop growing season with noticeably more water (fig. 3). This is most likely due to post-summer 2017 retention of soil water from higher water infiltration combined with higher water retention. This aspect can be further explained by the comparable summer 2017 cash crop yields and the lack of precipitation in October 2017 (CIMIS station No. 2; https://cimis.water.ca.gov/WSNReportCriteria.aspx).

Reduced water application would also result in tangible energy savings.

As the cash crop yields have remained high (Mitchell et al. 2022), we hypothesize that the higher soil moisture results from the higher profile-level water storage and water availability following irrigation of these plots (Araya et al. 2022), developed over several years of consistent reduced tillage (Burgess et al. 2014; Busari et al. 2015). Combined, these practices lead to improved soil water infiltration with increased soil water holding capacity, due to the avoidance of soil compaction from machinery passes, the additional water held by surface residue, and the relatively higher levels of soil organic matter in the RD CC plots. Cover crops have a mulching effect, lowering soil temperatures and reducing soil water loss through evaporation. By combining reduced-disturbance tillage with winter cover cropping, the increased water held in the soil profile in the reduced-disturbance tillage plots can allow for growth of cover crops without depleting soil moisture for the subsequent cash crop.

Our results are in line with similar studies measuring the impact of these practices on soil water content. Villamil et al. (2006) found that the combined effect of no tillage and winter cover crops increased plant-available water in an Illinois corn and soybean rotation. Blanco-Canqui et al. (2011) found improved soil physical properties, including aggregate stability, and hence soil water infiltration, after 15 years of cover cropping with no-till. Basche and DeLonge (2017) found that total soil porosity and soil water held at field capacity increased after 10 years of continuous living soil cover, suggesting cover crops as a practice that can mitigate the effects of rainfall variability due to climate change. Rankoth et al. (2021) found that cover crop treatments had higher soil water in the top 12 inches of the soil profile, compared to plots without cover crops. DeVincentis et al. (2022) found that the differences in soil water content between the cover cropped and fallowed soil were minimal, aligning with our conclusion that conservation practices do not deplete the soil water.

Our study further supports the conclusions of Araya et al. (2022), whose research was conducted at the same site at WSREC in Five Points, that combining reduced-disturbance tillage with winter cover crops increases water capture and retention in the soil profile. The complexity of the wintertime soil water dynamics must include the shading and mulching effects of cover crops, which reduce the soil temperature; this reduces the heat transfer into the ground, thus decreasing soil evaporation losses (Mitchell et al. 2012).

Future research should include monitoring the response-to-rain of these treatments in order to understand the benefits to infiltration and overall increasing soil moisture, ensuring that the soil system can "catch and store every drop" of rain or irrigation where it falls (USDA 1938). The role of living cover crop biomass in capturing, condensing, and percolating moisture from fog and dew, in addition to monitoring soil moisture and actual ET in cover cropped and clean cultivated grounds through the end of April, should be included in future investigations of the on-farm water-related implications of conservation tillage with winter cover crops.

Cost savings vs. new costs

Translating our results for soil water into economic terms, we found that the RD CC had on average 0.3 in/ft more soil water than the ST NO treatments (fig. 3), which summed to 2.4 inches of water for the 8-foot (96 inches) soil profile. For garbanzo production in ET_o Zone 15, where seasonal net water requirements are 19.8 inches (Long et al. 2019), and considering an average root depth of 5 feet, our suggested practices could allow about 6.5% in water saving for farmers. This was calculated assuming an average irrigation application efficiency of 85%, which results in a seasonal gross water demand of $19.8/0.85 = 23.3$ inches. The water saving using RD + CC equals 0.065×23.3 inches = 1.5 inches (0.12 acre-foot). Considering an average cost of water of $400 per acre-foot during normal years, and $2,000 per acre-foot during dry years, the resulting economic savings range from $50/acre (normal year) to $240/acre (dry years).

Reduced water application would also result in tangible energy savings. California agriculture relies on energy for lifting, filtering, and pressurizing water. From this perspective, the additional soil water storage capacity of conservation agriculture plots could result in measurable benefits to farm budgets and the environment (i.e., reductions in water diversions/extractions, energy usage, and greenhouse gas emissions).

However, our economic considerations do not include the cost to farming operations to establish and terminate the cover crops, compared to standard tillage and clean cultivated ground. New farm management practices will require new farm machinery, as well as possible changes in labor demands, irrigation practices, and land ownership. The timing of winter cover crop termination or cash crop planting needs to be assessed to determine technical and economic viability. Our long-term perspective may help address farmers' uncertainty by illustrating the returns from the financial investments required.

Different farming systems

In organic farming systems, winter CC and RD may pose additional complications. The NRI field site is set up as a conventional farming system, using herbicide spray to terminate the winter cover cropping before planting the cash crops. Terminating the cover crops with herbicides greatly shortens the transition time between cover crops and cash crops due to the fast decomposition time of residues from the terminated cover crops. For organic farms, mowers, crimpers, or other farm machinery can be used to terminate the cover crops, and may have weed reduction benefits (Wortman et al. 2013), but these represent a significant capital expenditure.

Regarding specialty crops in California, DeVincentis et al. (2020) conducted an extensive cost-benefit analysis of winter cover cropping. That study found that the long-term benefits depend on several factors, including irrigation, water savings due to soil properties, financial subsidies, the cropping system, and finally the impacts of climate change. Future research should include a cost-benefit analysis of the transition from standard tillage and fallow field treatment to reduced-disturbance tillage and winter cover cropping for row crops. The implementation of such practices is currently supported in California through financial subsidies provided by state programs such as the Healthy Soil Initiative (CDFA-HSP).

Our research conclusions may hold in similar Mediterranean climate cropping systems, with cash crops other than grain sorghum, garbanzo, and tomatoes. With a focus on drought-tolerant cash crops in combination with winter cover cropping, we have shown that reduced-disturbance tillage and winter cover crops can be implemented together without compromising the available soil moisture.

Capturing every drop

Understanding how winter cover crops affect water balance and water management is critical, as climate change increases both the frequency and intensity of California droughts (Diffenbaugh et al. 2015) and their alternation with wet years and flooding. A report by the California Department of Water Resources (DWR 2015) found that California is expected to be 15% to 35% drier by 2100, with snowpack under a high warming scenario likely to be reduced by 65%, jeopardizing our surface water supply in a state where groundwater is also scarce.

Even if rain does fall during the winter season, the intensity or amount of rain over a given period of time is projected to increase (Pathak et al. 2018), which emphasizes the need to build soil that can capture every drop and hold this moisture in the profile. The combined use of winter cover crops with reduced-disturbance tillage can be a strategy for improved economic water productivity, with more marketable product per unit of consumptive water use within the San Joaquin Valley water portfolio options (Hanak et al. 2021), and should be politically and financially incentivized for farmer adoption.

Twenty years of continuous reduced-disturbance tillage coupled with winter cover crops have provided evidence that these practices can be implemented in unison without depleting soil moisture levels in the drought-prone San Joaquin Valley. Going forward, these findings will hopefully encourage farmers to implement conservation practices that help foster viable production and healthy soils despite very challenging circumstances.

Diverse, multi-species (triticale, *Phacelia*, mustard and vetch) cover crop planted in a reduced-disturbance plot to improve soil function at the long-term NRI Project study site in Five Points, Calif.

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