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RESEARCH ARTICLE

No-tillage, surface residue retention, and cover crops improved San Joaquin Valley soil health in the long term

The use of conservation agriculture practices in combination improves soil health, including soil stability and water retention.

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Abstract

A long-term annual crop study in Five Points, California, shows that the combined use of no-tillage, surface residue retention, and cover crops improves soil health compared to conventional practices common to the region. Several chemical, biological, and physical soil health indicators were improved when these practices were combined. Our data suggest that farmers stand to gain multiple synergistic benefits from the integrated use of these practices by increasing soil structural stability, water infiltration and storage, and agroecosystem biodiversity, and improving the efficiencies of the carbon, nitrogen, and water cycles of their production systems.

Soil health conservation efforts in many regions of the world have achieved unprecedented attention, with the recognition that maintaining the function of soil for crop production is a major requirement for global food security (Amundson et al. 2015; Wall et al. 2015). Over 10 years ago, the USDA's Natural Resources Conservation Service (NRCS) kicked off "Unlock the Secrets in the Soil" at the Carroll, Ohio, farm of a long-time no-tillage and cover crop farmer, David Brandt. This national education campaign aims to raise awareness about the core principles of conservation agriculture and soil health. California NRCS provided over $160 million in funding assistance for soil-health-related conservation activities from 2017 to 2021, supporting over 2,000 projects through the Environmental Quality Incentives Program and Conservation Stewardship Program (Programs NRCS California). The California Department of Food and Agriculture's

A public field day was held at the Conservation Agriculture Systems study site in Five Points on March 18, 2010. Results from a 20-year study indicate that soil health management systems result in improved soil properties and in greater ecological and environmental services from soil. *Photo*: Jeff Mitchell.

(CDFA) Healthy Soils Program, started in 2017, has invested over $40 million on 618 projects incentivizing adoption of soil health management practices.

These efforts have defined critical soil health principles that include (1) reducing soil disturbance, (2) retaining surface residues, (3) enhancing biological diversity, and (4) maximizing growth and longevity of living roots in the soil (USDA NRCS 2012). Together, these principles have become internationally known as the basis for "conservation agriculture" systems (Mitchell et al. 2019; Reicosky and Kassam 2021). These systems, intended to enhance soil fertility, quality, and health, share many of the same properties as "regenerative agriculture" (Newton et al. 2020).

Adherence to soil health principles has been shown to increase water infiltration and storage (Franzluebbers 2010), decrease soil erosion (Ranaivoson et al. 2017), reduce soil water evaporation (Klocke et al. 2009), optimize soil moisture utilization (Nielsen et al. 2005) and nutrient cycling (Franzluebbers 2010), and increase soil carbon stocks (Liptzin et al. 2022). In short, applying these principles regenerates a soil's ability to produce food and fiber, while performing vital ecosystem services. They have fueled a farming renaissance in several regions of the world (Anderson 2005; Anderson 2011; Crabtree 2010; Lindwall and Sonntag 2010; Peiretti and Dumanski 2014).

Government initiatives, however, tend to incentivize individual practices rather than systems-based approaches. For instance, CDFA's Healthy Soils Program and NRCS's Soil Health Campaign use soil carbon (C) as the primary metric of success, rather than considering a suite of soil health indicators. Because the full complement of soil health principles are not being implemented through these programs, the comprehensive systems goals for soil health that these agencies endorse may not be achieved. For example, cover crops typically are incorporated into the soil using intensive tillage methods that can disrupt soil structure (Kladivko 2001; Six et al. 2002) and increase compaction (Hamza and AndersoI05), which diminishes the benefits of cover crops (Mitchell et al. 2017). Until recently, information in California has been lacking on the impacts of production systems that combine multiple soil health practices, especially in regard to co-benefits and soil function.

Several studies have demonstrated the importance of deep soil inventories of C (Haddaway et al. 2017; Tautges et al. 2019), as well as the use of long-term studies to reveal "consistent dynamics and emergent outcomes" and avoid inaccurate conclusions about soil C accumulation (Cusser et al. 2019; Powlson et al. 2016). The Conservation Agriculture Systems (CAS) study in Five Points, established in 1999, is the only site in California that incorporates all four soil health principles in its experimental design. This provides a unique opportunity to measure the long-term impacts of alternative management practices on soil biodiversity, physical and chemical properties, and overall function (Mitchell et al. 2017).

Our objectives were to measure changes in physical, chemical, and biological indicators of soil health after 20 years of no-tillage and cover crop management in the historically productive San Joaquin Valley (SJV). We hypothesized that soil health indicators would improve with reduced disturbance and increased cover cropping, but that changes in C would be modest given the region's aridity and warm temperatures (Humphrey et al. 2021).

A disk plow and ring roller prepares seed beds in the standard tillage with no cover crop system. *Photo*: Jeff Mitchell.

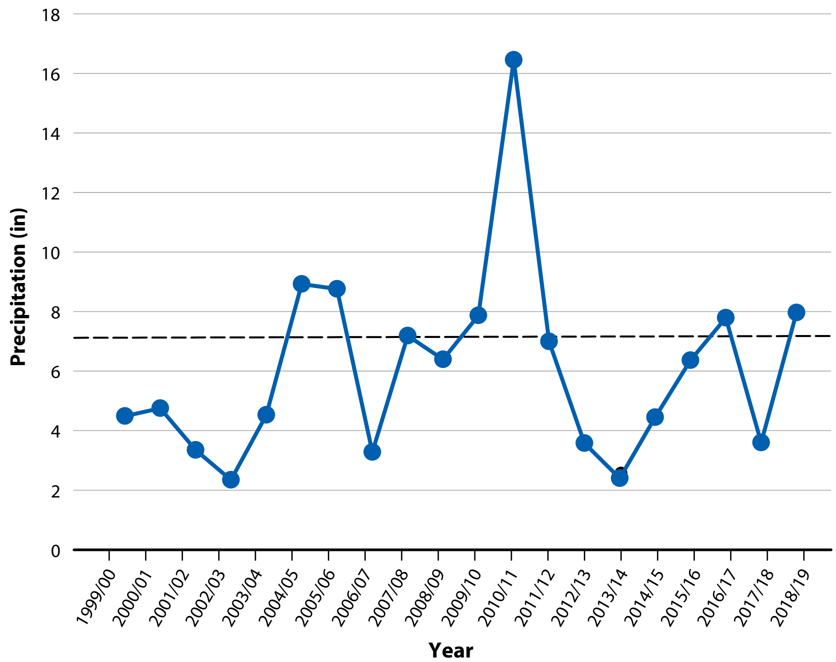

FIG. 1. Total annual precipitation (2000–2019) and the 30-year average precipitation (represented by the dotted line) at the University of California West Side Research and Extension Center in Five Points, California.

A long-term field experiment

The CAS study was established in the fall of 1999 on an 8.8-acre (3.56 hectare [ha]) field at the UC West Side Research and Extension Center in Five Points, California. The goal of the study was to compare no-tillage (NT) and standard tillage (ST) crop rotations with winter cover crops (CC) and with no cover crop (NC). This region of the SJV receives approximately 7 inches (178 millimeters [mm]) of annual precipitation and has mean maximum air temperatures of 75°F and minimum of 46°F (7.8°C). Over the 20-year project duration, recurring drought was common (fig. 1). The soil is a Panoche clay loam (fine-loamy, mixed superactive, thermic Typic Haplocambids) (Arroues 2006). Before the CAS study, the field had been variably cropped for over 40 years with wheat, tomatoes, cotton, and vegetables. Most recently, barley (*Hordeum vulgare* L.) was planted to reduce known variation in soil water and fertility due to previous research. The field was evenly divided into a cotton-tomato and a tomato-cotton rotation (*Solanum lycopersicum* L. for tomato, *Gossypium hirsutum* L. for cotton). Each year for 12 years (1999 to 2014), each crop was grown on separate halves of the experimental field. This was followed by rotation of garbanzo and sorghum (*Cicer arietum* and *Sorghum bicolor* L.) from 2015 to 2018, and finally tomato in 2019.

Each 0.2-acre (0.08 ha) treatment plot (30 feet by 300 feet) (9.1 meters by 91.4 meters [m]) was replicated four times in a two-factor (tillage and cover crop) experiment arranged as a randomized complete block design in each half of the field. The four systems were no-tillage with a cover crop (NTCC), standard tillage with a cover crop (STCC), standard tillage without a cover crop (STNC), and no-tillage with no cover (NTNC).

Tillage practices were described in detail in Mitchell et al. (2015). In summary, conventional or standard intercrop tillage (ST) consisted of (1) residue shredding; (2) before the tomato and cotton crops were planted, multiple disk passes to incorporate residues to a depth of eight inches; (3) after the tomatoes were harvested, use of a subsoiling shank to a depth of about 12 to 18 inches (0.3 to 0.46 m); (4) additional disking to eight inches (0.2 m) to break up soil clods created by the subsoiling shank; (5) listing beds; and (6) surface residue incorporation (top four inches of soil) using a cultimulcher (BW Implement Co., Buttonwillow, Calif.). These conventional intercrop tillage practices break down and establish new beds following harvest and represent normal SJV operations in terms of tillage intensity, depth, and timing.

In the NT systems, planting beds were not moved or disturbed during the entire study period. Controlled traffic farming, or zone production practices, were used to restrict tractor traffic to certain furrows. The only soil disturbance in the NT systems was shallow cultivation during the first eight years for the tomato crops and root pulling or shallow root severing for cotton; the root pulling was much less disruptive than conventional tillage and was done only to a depth of four inches in the soil. By 2012, the NT treatments became zero-tillage systems, with soil disturbance reduced to seeding or transplanting traffic only. We use the term "no-tillage," or direct planting with no primary or secondary tillage after a previous crop harvest (SSSA 1996), because this characterizes this system more aptly than previously used terms such as "reduced tillage," "minimum tillage," or "conservation tillage" (Mitchell et al. 2019; Reicosky 2015).

Tomato and cotton crops were furrow-irrigated from 2000 to 2012. They were converted to subsurface drip irrigation in 2013 with 1.34-inch (3.4 centimeter [cm]) diameter tape buried 12 inches (0.3 m) deep in the center of each 5-foot-wide (1.5 m) planting bed. Drip tape installation involved a tillage operation to all systems.

The CC treatments were a mix of Juan triticale (*Triticosecale* Wittm.), Merced cereal rye (Secale cereale L.), and common vetch (*Vicia sativa* L.). The legume species was inoculated with *Rhizobium leguminosarum biovar viciae* before seeding. They were seeded using either a 15-foot (4.6 m) John Deere 1530 no-tillage single-disc opener seeder (Moline, Ill.) or a 15-foot (4.6 m) Sunflower 1510 double-disc opener no-till drill (Beloit, Kan.). In CC plots, seeds were planted 1 inch (2.5 cm) deep, at 7.5-inch (19 cm) row spacing, and at a rate of 80 pounds (lbs) acre^{-1} (30% triticale, 30% rye, and 40% vetch by seed weight) in late October prior to winter rains.

The CC were irrigated with 4 inches (10 cm) of water in 1999 and again with 2 inches (5 cm) in 2012, 2017, and 2018, for a total of 10 inches (25 cm) over the entire

20 years. Precipitation provided an additional 127 inches (0.32 m) of water over the 20-year period (fig. 1). From 2000 to 2012 and 2013 to 2016, no irrigation was applied to the cover crops.

From 2010 to 2014, the basic CC mixture was changed to include a greater diversity of species, including pea (*Pisum sativum* L.), fava bean (*Vicia faba* L.), radish (*Raphanus sativus*), and Phacelia (*Phacelia tanacetifoli*) (40% pea, 40% fava bean, 10% radish, and 10% *Phacelia* by seed weight) (Mitchell et al. 2015). Cover crops were typically seeded by mid-November and terminated by glyphosate application and mowing in mid-March of the following spring, resulting in a 120-day growth period. Fertilizer and pesticide inputs were similar across the treatments in all years.

Measuring crops and soil

Cover crop biomass was determined each year in mid-March by harvesting all aboveground plant material in an 11 ft^2 (1 m^2) random area in each plot, drying the material to constant weight, and weighing it (Mitchell et al. 2015). After harvests and subsequent intercrop tillage (on August 10, 2014, March 19, 2016, and March 20, 2017), the percent surface residue was estimated using the line-transect method over 100 feet (30.5 m) per plot (Bunter 1990). Cash crop yield was measured annually using weighing gondolas and crop-specific commercial harvest equipment on loan from neighboring farmers.

Soils were sampled after the 2018 fall harvest at four depths: 0–6 inches, 6–12 inches, 12–24 inches, and 24–36 inches (0–15 cm, 15–30 cm, 30–60 cm, and 60–90 cm). Four 2-inch-diameter cores were collected per depth for each plot and composited before air-drying, sieving (< 0.08-inch sieve), and grinding (soil pulverizer) to pass through a 60-sieve screen with 0.25-mm-size openings, and then dried to constant weight. Protocols of the University of California, Davis, Analytical Laboratory were used to determine total soil C and nitrogen (N) using the combustion method. Surface soil aggregate slaking scores (18 determinations per plot) and water infiltration rate (four measurements per plot) were determined in 2019 using NRCS Soil Quality Test Kit procedures (USDA NRCS 2013). Slaking was visually assessed, on aggregates exposed to rapid wetting using 0.59-inch-diameter (1 cm) sieves, to determine aggregate stability. Slaking index was also measured using the Jornada Experimental Range Soil Stability Test Kit 222 (Synergy Resource Solutions), a recently developed smartphone application, SLAKES (Bagnall and Morgan 2021), and three other methods tested by the Soil Health Institute (Rieke et al. 2022). After summer cropping (soil dry), soil water infiltration was determined using a single ring (6-inch diameter) (15 cm) inserted to a soil depth of ~3 inches (7.5 cm). A volume equivalent to 1 inch of water (400 milliliters [ml]) was applied inside the ring, and repeated four times, recording the time to infiltrate for each inch.

Conservation Agriculture Systems study researcher Jeff Mitchell (right) and USDA ARS soil scientist Lauren Hale (left) examine soil health properties in a no-tillage and cover crop plot. *Photo*: Jeff Mitchell.

Additional surface soil samples (0–6 inches) (0–15 cm) were collected in March 2019 and submitted as part of the Soil Health Institute's North American Project to Evaluate Soil Health Measurements. Sampling and laboratory protocols are detailed in Norris et al. 2020. Biological community analysis included 16S and ITS amplicon sequencing, functional metagenomics (Reike et al. 2022), and phospholipid fatty acid analysis (MIDI Labs, Newark, Del.). We used the sum of all phospholipid fatty acid biomarkers with C chain length of 14 to 20 as an estimate of microbial biomass (Zhang and Rock 2008). Biological activity was assessed using a suite of potential enzyme activities and carbon mineralization incubations, including a 24- and 96-hour rewetting test (Franzluebbers et al. 2018; Haney et al. 2008).

Assessing statistical validity

Data were analyzed using PROC Mixed procedures in SAS statistical software with tillage and CC as fixed variables, and years and replication as random variables (SAS Institute 2002). Year was considered a random variable because crops rotated between the two experimental blocks each year. Interactions between years and factors were also tested. Where there was significant interaction between years and factors, data were separated by years and re-analyzed. The significance level for variables and their interactions was set at 0.05. Prior to the analysis, assumptions of ANOVA were tested. Data for total C and total N were log transformed for analysis to meet the assumption of homogeneity of variance. Means were separated using

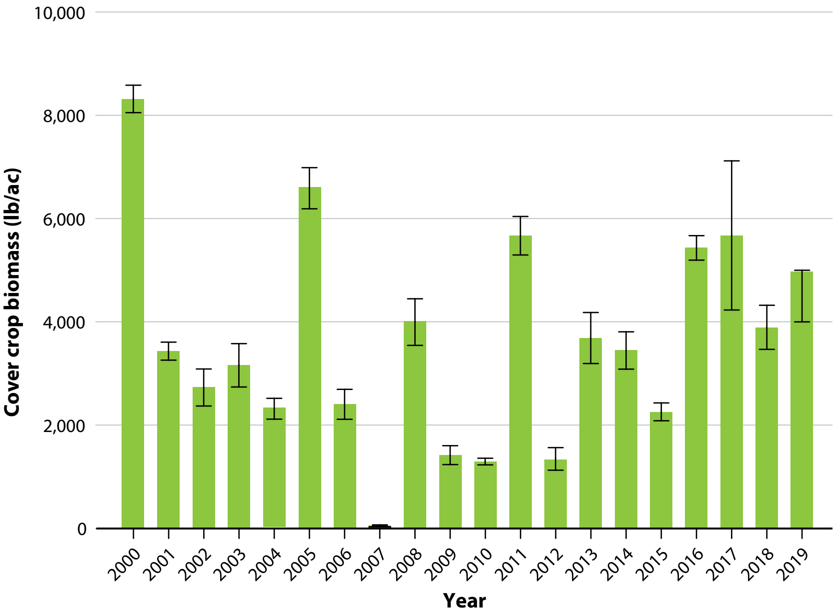

FIG. 2. Cover crop dry aboveground biomass (lbs/ac) (0.89 lbs/acre is 1 kg/ha) for 2000 through 2019 at the study site in Five Points, California.

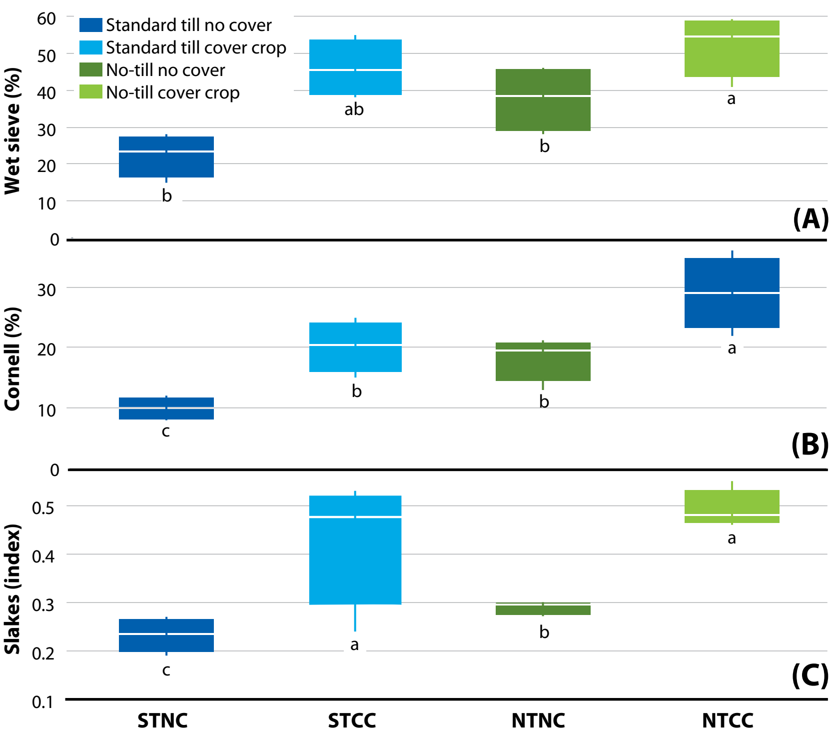

FIG. 3. Aggregate stability results as box and whisker plots using methods tested by Soil Health Institute. Within each method, result means with the same letter under the box plot are not significantly different (at a = 0.05) according to Fisher's PLSD post-hoc test. (A) The wet sieve method measures the aggregates between 1 and 2 mm that remain on a sieve after repeated dunking in water, developed by the ARS. (B) Cornell measures the aggregates between 1 and 2 mm that remain on a sieve after a simulated hard rain by a sprinkle infiltrometer used in the Cornell Assessment of Soil Health. (C) Slakes measures the change in area of three soil aggregates, 4–10 mm in size, submerged in water for 10 minutes using a smart phone application called SLAKES. Treatments that start with NT are no-till, ST are standard tillage. Treatments that end in CC had cover crops and NC indicates no cover crops.

either Fisher's Protected Least Significant Difference method or the "pdiff" option in SAS. Mean separation was based on transformed data, but non-transformed means were presented for clarity.

Cover cropping biomass

The total aboveground cover crop (CC) biomass produced and retained across these 20 winter growing seasons was 37 tons per acre (83 metric tons [mt] ha^{-1}) averaged for the STCC and NTCC plots (fig. 2). This represented 1,580 lbs (717 kilograms [kg]) N and 14.8 tons of C per acre (33.1 mt ha^{-1}) or 0.74 tons of C per acre (1.66 mt ha^{-1}) annually (Pribyl 2010). Year-to-year variability in CC biomass was quite large, ranging from a low of 54 lbs per acre (60 kg ha^{-1}) (2007, no irrigation) to a high of 8,818 lbs per acre (9,884 kg ha^{-1}) (2000, supplemental irrigation applied). Nonetheless, the CC systems had an additional 90 days annually of "green ground cover," which captures solar energy, as well as living roots. By contrast, the NC systems were bare.

Residual soil moisture following summer crops was assumed to be negligible. Adding water, if available, during dry winter periods produces additional growth and C inputs. Based on CC growth during years with supplemental irrigation, we estimate that an average of 6,082 lbs per acre (6,818 kg ha^{-1}) of dry CC biomass could be produced over the 20-year period at this site with a modest 2 inches (5.1 cm) of irrigation water. Management that more closely mimics cash crop management (i.e., earlier planting dates, strategically timed irrigation) could produce even greater CC biomass. Local dairies typically produce approximately 12,000 lbs of dry matter per acre per year (13,450 kg ha^{-1}), with winter silage triticale used as a double crop system (Miller et al. 2018; Wright et al. 2015).

Soil health indicators

As anticipated, the combination of no tillage and cover cropping resulted in improved soil health across several metrics, relative to conventional tilling and no cover crops.

Soil physical properties

Aggregate stability increased by at least twofold in the NTCC over the STNC treatment (fig. 3), using all five methodologies. The absolute value of each method differed, but the intermediate treatments, NTNC and STCC, consistently produced intermediate values compared to the extremes of full conservation treatment (NTCC) and fully conventional treatment (STNC). Both NT and CC increased aggregate stability (relative to ST and NC, respectively) using all methods, except SLAKES, where some replications were discarded for quality control. The formation of stable soil aggregates could be a result of stabilization and sequestration of C and/or a reduced rate of aggregate turnover (i.e., aggregate formation vs. disruption) (Six et al. 2000; Six et al. 2002).

Water infiltration rates were enhanced in the NT systems regardless of cover crop presence. Combining soil health practices (NTCC) had the greatest impact on water infiltration (fig. 4), and STCC improved infiltration compared to STNC. There was a difference of almost two orders of magnitude between the least disturbed NTCC (45 seconds) and the STNC system (1,620 seconds) in the time it took for infiltration. The results indicate that considerable improvements in water infiltration and movement in soils may be achieved through the combined use of CC and NT.

Soil chemical properties

For the 0–6 inch (0–15 cm) depth, soil C content in the NTCC system (12.4 tons acre^{-1}; 27.9 t ha^{-1}) was statistically different ($P \leq 0.05$) from NTNC (8.7 tons acre^{-1}; 19.6 mt ha^{-1}) and from STNC (8.5 tons acre^{-1}; 19.1 mt ha^{-1}), but not from STCC (10.3 tons acre^{-1}; 23.0 mt ha^{-1}) (fig. 5). Though tillage and cover crop management changed the distribution of C throughout the soil profile (fig. 5), the systems were not statistically different ($P \leq 0.05$) over the entire profile (0–36 inches). The two systems that most diverged in terms of C inputs — the full conservation treatment NTCC and the fully conventional treatment STNC — contained similar amounts of C stocks in the 0 to 36 inches (0–90 cm) depth: 33.1 tons acre^{-1} (74.3 mt ha^{-1}) and 31.8 tons acre^{-1} (71.3 mt ha^{-1}), respectively (fig. 5). Soil N pools also did not differ between treatments over the whole profile (table 1).

Soil C at 12–36 inches (30–90 cm) represented 50% of total stocks across the entire soil profile (43% in NTCC to 54% in STNC), highlighting the importance of deeper monitoring (fig. 5). Subsoil C has been shown to be sensitive to management; losses can offset surface layer gains, resulting in incorrect estimation of climate impacts (Cai et al. 2022; Tautges et al. 2019). We did not collect deep samples at the start of the study and were unable to compare changes in C stocks at 12–36 inches (30–90 cm). For the two shallow depths, however, C increased in all treatments over the 20 years, likely due to the overall intensification of cropping (i.e., irrigation, fertility) (Rosenzweig et al. 2018). At 0–6 inches (0–15 cm), the NTCC (full conservation) increase was almost two times that of STNC (fully conventional). Smaller increases occurred at 6–12 inches (15–30 cm), with significant increases between NTCC and STNC.

Microbial biomass

We found that total microbial biomass (by PLFA) was significantly higher by almost 50% in systems with CC than without, regardless of tillage (table 2). Similarly, most biomarkers for specific microbial groups were significantly higher with CC than in NC treatments. The most abundant values were from CC treatments and the least abundant was the fully conventional STNC. Analyzing the two treatment factors separately, most of the biological indicators were improved by CC but not by tillage reduction. This underscores the importance of carbon inputs, in this case from roots and residues, for soil biology to thrive in our semi-arid Mediterranean climate.

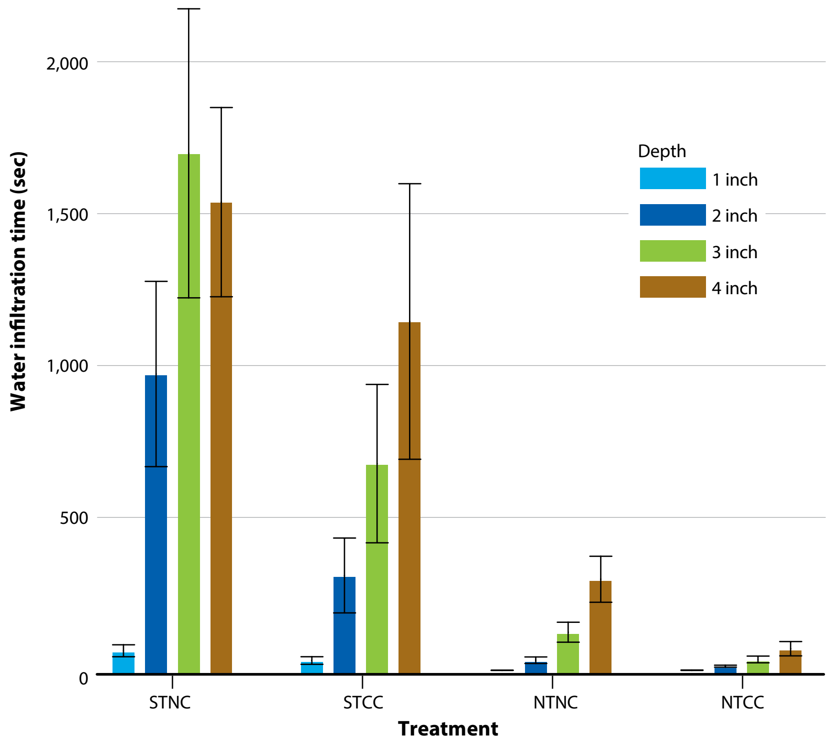

FIG. 4. Soil water infiltration times (seconds) for 1, 2, 3, and 4 inches of water into standard tillage no cover crop (STNC), standard tillage with cover crop (STCC), no-tillage no cover crop (NTNC), and no-tillage with cover crop (NTCC) soils.

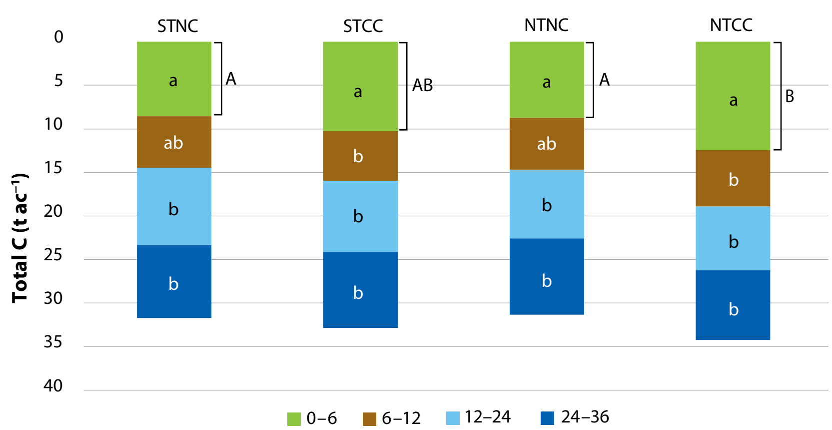

FIG. 5. Soil carbon in tons per acre at 0–6 inch, 6–12 inch, 12–24 inch, and 24–36 inch (0–15 cm, 15–30 cm, 30–60 cm and 60–90 cm) depths for standard tillage no cover crop (STNC), standard tillage with cover crop (STCC, no-tillage no cover crop (NTNC), and no-tillage with cover crop (NTCC) systems. Capital letters represent statistically significant ($P \leq 0.05$) differences between treatments at one depth; small letters represent significant differences between depths.

TABLE 1. Soil carbon (C) and nitrogen (N) stocks in tons per acre (followed in brackets by real units) for standard tillage (STNC), standard tillage with cover crop (STCC), no-till no cover crop (NTCC), and no-till with cover crop (NTCC) at 0–6 inches, 6–12 inches, 12–24 inches, and 24–36 inches (0–15 cm, 15–30 cm, 30–60 cm, and 60–90 cm) depths in Five Points, Calif.

	Total C		Total N	
	t ac^{-1}	Mg ha^{-1}	t ac^{-1}	Mg ha^{-1}
Tillage				
ST	32.0 ± 4.6	71.8 ± 10.3	3.4 ± 0.4	7.7 ± 0.8
NT	32.5 ± 4.9	72.8 ± 11.0	3.5 ± 0.5	7.8 ± 1.2
Cover crop				
CC	33.0 ± 4.7	73.9 ± 10.6	3.5 ± 0.5	7.9 ± 1.1
NC	31.6 ± 4.7	70.8 ± 10.5	3.4 ± 0.4	7.6 ± 0.9
Depth				
0–6 in	9.9 ± 2.7a*	22.1 ± 6.0a	1.14 ± 0.27a	2.6 ± 0.6a
6–12 in	6.0 ± 1.5b	13.5 ± 3.4b	0.74 ± 0.16b	1.7 ± 0.36b
12–24 in	8.1 ± 1.7c	18.1 ± 3.7c	0.85 ± 0.17c	1.9 ± 0.38c
24–36 in	8.5 ± 2.0c	19.0 ± 4.4c	0.75 ± 0.12c	1.7 ± 0.27c
Treatment				
STNC	31.8 ± 5.0	71.3 ± 11.3	3.4 ± 0.3	7.7 ± 0.7
STCC	32.8 ± 4.4	73.6 ± 9.8	3.5 ± 0.4	7.8 ± 1.0
NTNC	31.4 ± 4.6	70.3 ± 10.4	3.4 ± 0.5	7.5 ± 1.2
NTCC	33.1 ± 5.4	74.3 ± 12.2	3.6 ± 0.5	8.1 ± 1.2

ANOVA	DF	Total C *P*-value	Total N *P*-value
Replication	7	0.0084	0.0002
Tillage	1	0.82	0.83
Cover	1	0.21	0.17
Depth	3	< 0.0001	< 0.0001
Tillage:Cover	1	0.56	0.36
Tillage:Depth	3	0.35	0.94
Cover:Depth	3	0.029	0.011
Tillage:Cover:Depth	3	0.28	0.20

± indicates standard error of the mean.

* For each measurement, means with the same letter are not significantly different by depth (at a = 0.05) according to Fisher's PLSD post-hoc test.

No-till planted sorghum in cotton, tomato and cover crop residue. *Photo*: Jeff Mitchell.

New management insights

Because of the unique and long-term nature of the Five Points study site, we provide additional perspectives here from previously published work. We also offer an in-depth discussion of our new findings on management impacts of reduced tillage, cover cropping, and surface residue preservation practices.

Surface residue management

Getting rid of residues is the norm in California (Mitchell et al. 2012). However, generating and preserving residue are indispensable to conservation agriculture systems in several parts of the world (Crovetto 1996). Following 20 years of seasonal planting, harvest, and tillage (where applicable), surface residue averaged over 90% of the cover for NTCC, 40%–70% for NTNC, 10%–20% for STCC, and below 5% for STNC (Mitchell et al. 2019). In NT systems, the resulting increase and retention of surface residues mitigates the impacts of water shortfalls and reduces local soil disaggregation, leading to reduced erosion (Barrios 2007). Retention of residue also decreases soil surface temperatures (Mitchell et al. 2012) and increases moisture retention (Klocke et al. 2009), as well as soil C and nitrogen (Crovetto 1996). A meta-analysis of surface residues in no-till systems in other regions (Ranaivoson et al. 2017) found similar results as NTCC, with annual surface soil C gains (0.17 tons acre^{-1}) (420 kg ha^{-1}), decreased soil water evaporation (30%), and increased water infiltration (two-fold). Potential drawbacks of high-residue retention include difficulties operating planting equipment in heavy residues (i.e., seed drills) and pest issues, which may become a serious issue in high-value vegetable crops.

Soil carbon

No statistical difference in total soil C between NT and ST treatments was observed. We explain this in light of the two pathways for maintaining or increasing soil C: a reduction in losses or an increase in C inputs. First, NT and ST had similar crop yields (as discussed below), and higher yields imply higher inputs of C to the soil. Second, although increased soil disturbance has been known to decrease soil C (Reicosky and Archer 2007), California's intensive agriculture has been more productive than the previous dryland grasslands. The net result of soil disturbance and increased yield has been a slight increase in soil C in California since the mid-1900s (DeClerck and Singer 2003).

Thus, while eliminating tillage is an effective practice for reducing erosion and conserving water, alone it cannot provide the increase in C inputs necessary to increase overall soil C (Blanco-Canqui et al. 2021; Powlson et al. 2016). Instead, the presence or absence of CC appears to be more important for year-round vegetative cover, buffering soil temperature, and increased above- and below-ground C inputs (Mitchell et al. 2015; Poeplau and Don 2015). Roots, which may be more important than residues in contributing to soil C (Rasse et al. 2005; Schmidt et al. 2011), may be restricted in soils where compaction is aggravated by conventional tillage (Martinez-Mena et al. 2008).

Further, soil C may accumulate more slowly under NT in semi-arid climates (Francaviglia et al. 2017; Franzluebbers 2010; Six et. al. 2002). This is because periods of low winter rainfall can limit CC productivity (and thus C inputs). In addition, summer irrigation is typically accompanied by warm temperatures that can speed up decomposition (Blanco-Canqui 2020). In these conditions, soil microbes may exhibit higher specific respiration rates (unit of C respired/unit consumed) (Doetterl et al. 2015).

Our findings for soil C agree with other no-till studies that have reported enrichment of C in the surface layer, but no change when analyzing to a depth of 1 meter (Haddaway et al. 2017; Syswerda et al. 2011). Several meta-analyses have similarly reported that soil C increases under no-till are limited to topsoil layers (Luo et al. 2010; Ogle et al. 2019; Powlson et al. 2014). Cai et al. (2022) found that, although soil C increased from 0 to 10 centimeters under NT, losses at 10 to 60 centimeters resulted in an overall decline in soil C that did not recover until 14 years after NT had been implemented. In contrast, a recent global study using the equivalent soil mass method to calculate bulk density found that, while C increases associated with NT were reduced with depth, NT soils contained higher C to at least 100 centimeters (39.3 inches) (Sun et al. 2020). In addition, Sun et al. (2020) reported that both soil C and crop yields were highly climatic-region dependent, and specifically that NT in warm, dry regions like California's Central Valley typically led to increases in both soil C and crop yield. However, our results show that irrigation mitigates water deficits and tillage effects in dry climates. Kravchenko and Robertson (2011) warned that C stock measurements are highly variable and that a common mistake is to "interpret a lack of statistical significance for the absence of differences" between different management systems.

Although increases in total C stocks were not detectable under NT alone, improvements in other soil health parameters indicate improvements in C cycling and potential for future soil C storage. Greater soil

TABLE 2. Soil total carbon for 0–6 inch and 6–12 inch (0–15 cm and 15–30 cm) depths at the start of the study in Five Points, Calif., and in 2019

Treatment	Depth	Total C (t ac^{-1}) 1999	Total C (t ac^{-1}) 2019	Change in TC (%)
STNC	0–6 in	3.9 ± 0.4	8.5 ± 1.3	117%[b]
STCC	0–6 in	4.1 ± 0.5	10.3 ± 1.6	149%[ab]
NTNC	0–6 in	4.2 ± 0.5	8.7 ± 3.1	110%[b]
NTCC	0–6 in	4.1 ± 0.4	12.4 ± 3.1	204%[a]
STNC	6–12 in	4.0 ± 0.5	6.0 ± 0.7	48%[a]
STCC	6–12 in	4.4 ± 1.1	5.7 ± 1.5	30%[a]
NTNC	6–12 in	4.6 ± 1.1	6.0 ± 1.7	30%[a]
NTCC	6–12 in	4.2 ± 0.3	6.5 ± 2.2	55%[a]
Treatment	**Depth**	**Total C (Mg ha^{-1}) 1999**	**Total C (Mg ha^{-1}) 2019**	**Change in TC (%)**
STNC	0–15 cm	8.8 ± 0.9	19.1 ± 3.0	117%[b]
STCC	0–15 cm	9.3 ± 1.1	23.0 ± 3.6	149%[ab]
NTNC	0–15 cm	9.3 ± 1.1	19.6 ± 7.0	110%[b]
NTCC	0–15 cm	9.2 ± 0.8	27.9 ± 7.0	204%[a]
STNC	15–30 cm	9.1 ± 1.2	13.4 ± 1.5	48%[a]
STCC	15–30 cm	9.8 ± 2.5	12.8 ± 3.4	30%[a]
NTNC	15–30 cm	10.3 ± 2.6	13.4 ± 3.8	30%[a]
NTCC	15–30 cm	9.4 ± 0.7	14.5 ± 4.9	55%[a]

Numbers are means for each tillage/cover crop treatment ± standard error (n = 8). The relative increase in total carbon from 1999 to 2019 is indicated as a percentage in the right column. In the 1999 to 2019 change, different letters within the same soil layer indicate statistically significant difference ($P \leq 0.05$). Numbers following ± are standard errors of the means.

For all the soils sampled in 1999, only average bulk density of 1.24 was available for the entire field site. In converting C concentration to C stock, we used the constant value. Plot-level measured values were available for 2019. We used the 2019 data to develop a pedotransfer function to estimate the plot level bulk density. However, this analysis did not change the conclusion, so it is not reported.

Soil health technical training field course for USDA NRCS conservationists at the long-term conservation agriculture study site in Five Points, Calif., June 19, 2014. *Photo*: Jeff Mitchell.

aggregate stability under NT provides increased protection of soil C against decomposition (Schmidt et al. 2011). Previous studies at the same site have also found an increase in minerally associated soil C, indicating a potential for greater stabilization and preservation of soil C (Mitchell et al. 2015; Mitchell et al. 2017).

Soil structure and biology

The long-term combination of NTCC altered soil structure, as well as the soil hydraulic properties and water storage, compared to STCC. Our previously published determinations of soil hydraulic properties over time — as opposed to static analysis such as Araya et al. (2022) — indicated that reduced disturbance with cover cropping led to a bimodal pore size distribution in surface soils (0–2 inch) (0–5 cm) and a 20% increase in water storage. Increased aeration and higher saturated hydraulic conductivity allow more water to be retained in the root zone without becoming waterlogged (Araya et al. 2022). While variability was too high to show a statistical difference ($P \leq 0.05$), the mean saturated hydraulic conductivity of the STNC treatment was roughly three times slower than each of the other treatments (Araya et al. 2022).

Our soil biology results are consistent with previously published work (Schmidt et al. 2018; Schmidt et al. 2019) at the same site, which demonstrated major shifts in soil biology in response to CC. The presence of CC was the most important factor determining soil biota's contributions to ecosystem services. Enzyme potential activity for β-glucosidase and N-acetyl-β-glucosaminidase were both elevated under NT, indicating that microbes are more actively breaking down residues in these systems (table 3). Increases in microbial activity and associated biomass and C turnover may far outstrip observed increases in the C content (Don et al. 2013; Marks et al. 2022). It is this increased turnover that may be critical for increased soil resilience, as microbial activity improves soil structure, reduces erodibility, increases water infiltration and water holding capacity, and enhances adaptability and resistance to climatic perturbations.

The long-term combination of reduced disturbance and increased plant cover led to a more diverse, symbiotroph-enriched fungal community, and a more diverse bacterial community; these conditions are generally associated with more efficient resource utilization and greater competition (Schmidt et al. 2018; Schmidt et al. 2019). Positive benefits of cover cropping on the abundance and activities of microbivore nematodes outweighed any negative effects of the environmental perturbation caused by tillage (Zhang et al. 2017). Finally, we found that soil macrofauna abundance increased by 93% with the addition of cover crops and by 50% with elimination of tillage (Kelly et al. 2021).

Productivity and economics

The impacts of reduced disturbance, surface residue, and CC on crop yields varied by crop (Mitchell et al. 2015; Mitchell et al. 2016). While it is not the intent of this paper to provide overall productivity data, we provide the following summary. Tomato yields were 9.5% higher in NT versus ST systems and 5.7% higher in NC versus CC systems. Cotton yields were 10.0% higher in ST than NT and 4.8% higher in NC systems in the early years of the study, largely due to problems in establishing crop stands with NT. Yield patterns were not, however, consistent from 2005 to 2009 (Mitchell et al. 2015), and there were no yield differences between the STNC and NTNC from 2010 to 2013 (Mitchell et al. 2015). Neither tillage nor cover crop had an effect on

TABLE 3. Biological soil health indicators demonstrate consistently higher values in treatments that include cover crops

		MB		Cmin		POXc		WEOC		ACE		PMN		β-gluc		NAG		ArylS	
		nmol g^{-1} soil		*mgCO$_2$-C g^{-1} day^{-1}*		*pmn*								*mg PNP kg^{-1} hr^{-1}*					
Cover crop	CC	127	***	62	***	548	***	240	**	3.5	**	84	***	198	***	25	***	36	**
	NC	88		44		417		178		2.6		58		103		14		21	
Tillage	NT	105	ns	50	ns	506	*	213	ns	3.3	*	71	ns	180	**	22	*	31	ns
	ST	110		56		460		206		2.7		71		121		18		26	
Interaction			ns		*		ns		ns		ns		ns		ns		ns		ns

Numbers are means for each factor from a two-way ANOVA. *** = *P*-value of ≤ 0.0001, ** = *P*-value of ≤ 0.001, * = *P*-value of ≤ 0.05. MB is microbial biomass as the sum of PLFA biomarkers, Cmin is potential carbon mineralization with a 24-hr burst test, POXc is potassium permanganate oxidizable carbon, WEOC is water extractable organic carbon, ACE is autoclaved citrate extractable protein, PMN is potential nitrogen mineralization with a 7-day anaerobic incubation, β-gluc is β-glucosidase, NAG is N-acetyl-β-D-glucosaminidase, ArylS is arylsulfatase, ns is not significant.

sorghum grain yield, indicating that similar yields can be obtained with NT as with ST (Mitchell et al. 2016). Mitchell et al. (2012a) similarly found no difference in cotton and tomato yields between NT and ST. Garbanzo yields in NT matched or exceeded ST, depending on the year (Mitchell et al. 2021).

It takes time to achieve economically viable yields with alternative management techniques, and this ultimately determines whether a practice is adopted by farmers (Haddaway et al. 2017). Our yield results should be viewed cautiously, as they reflect the inherent "learning curve" challenges and mistakes of experiment station work. A meta-analysis by Pittelkow et al. (2016) found lower yields with NT when no other amendment or soil health practices were used, but higher yields with NT when the full suite of conservation agriculture practices (no-till, cover crop, residue management) was added. Nonetheless, our findings do suggest that NT could be profitable to California farmers, as it reduces inputs of energy and the associated costs (Jackson et al. 2011; Mitchell et al. 2012a), while increasing the efficiency of resource use and improving soil function. Cusser et al. (2020) emphasized that the likelihood of NT systems becoming more economically profitable increases with longer periods of implementation. Agronomic improvements and refinements with the use of cover crops will be needed to consistently provide adequate cash crop plant populations needed for expected productivities (Blanco-Canqui 2020).

Policy implications

The remarkable improvements in soil health reported here were not achieved easily. These improvements represent opportunities currently not being realized in any SJV annual crop field of which we are aware. From a policy perspective, reliance on ecosystem services that result from healthy, functioning soils — rather than on synthetic, non-renewable inputs and high-disturbance approaches — is increasingly seen as a socially important and environmentally sustainable way to improve food production systems (Bowles et al. 2016; Mitchell et al. 2012a; Mitchell et al. 2012b; Upadhyaya et al. 2001). Reducing tillage and using cover crops may reduce not only fuel use, but also nitrogen fertilizer inputs, for which costs have risen dramatically in recent months (Schnitkey et al. 2022). Our results suggest that SJV annual crop farmers could greatly improve not only the function and efficiency but also the sustainability of their production systems by adopting reduced disturbance, residue retention, and cover cropping practices. Practical progress toward these goals will involve encouraging farmers to increase residue cover, reduce tillage intensity, and use CC to add organic matter to their soils.

It is often less expensive to prevent degradation of soil function and productivity than to remediate poor soil conditions after they occur (Barrios 2007). While the up-front implementation costs may discourage adoption, the common good costs of achieving such sustained ecosystem improvement rightly need to be borne by our food system at large, rather than farmers themselves. Thus, we recommend market- and outcome-based mechanisms that enable farmers to change. While soil C is well recognized as a leading indicator of soil health, sequestration potential may be limited in arid climates, soil types, and/or cropping systems. By contrast, other soil health indicators may still be sensitive to management. Although whole soil profile inventories are necessary to provide accurate accounting for carbon credits or other climate change mitigation, we must still incentivize surface C gains and other improvements in soil health indicators, which are more relevant for soil function and agricultural productivity, especially in an increasingly warmer and drier California.

Conservation Agriculture Systems researcher Jeff Mitchell stands behind winter cover crop in the no-tillage with cover crop system. *Photo*: Jeff Mitchell.

Value of soil health management

After 20 years of consistent soil health management with reduced soil disturbance, winter CC, and surface residue generation and preservation, several indicators of soil function improved dramatically. Our findings indicate that implementation of soil health management systems results in not only improved soil chemical, physical, and biological properties, but also in greater ecological and environmental services provided by soil. The benefits of these practices included increased C and N sequestration with cover crops in the surface soil, soil structural stability, water infiltration and storage, green cover, surface protection (resulting in reduced soil water evaporation), and biodiversity.

Our findings affirm the value of soil health management to improve soil function and climate resilience, while reducing labor and fuel use compared to current standard practices (Mitchell et al. 2012b). We demonstrated that cover crops play a more impactful role than reduced tillage in improving soil properties and function, but that the combination of these

Our findings affirm the value of soil health management to improve soil function and climate resilience, while reducing labor and fuel use.

practices consistently produced the greatest positive effects. Employing NT or ST plus cover crops increased both soil C and N in the 36-inch profile, compared to NT and ST with no cover crop. Equally important are improvements in soil hydraulic function and their positive impacts on soil water storage. The uniquely comprehensive nature and timespan of our work indicates opportunities to greatly improve soil function and resiliency across this region with the addition of cover crops and a minimum disturbance approach. CA

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References

Amundson R, Berhe AA, Hopmans JW, et al. 2015. Soil and human security in the 21st century. Science 348(6235). https://doi.org/10.1126/science.1261071

Anderson RL. 2005. Improving sustainability of cropping systems in the Central Great Plains. J Sustain Agr 26:97–114. https://doi.org/10.1300/J064v26n01_08

Anderson RL. 2011. Synergism: A rotation effect of improved growth efficiency. Adv Agron 11:205–26. https://doi.org/10.1016/B978-0-12-385538-1.00005-6

Araya SN, Mitchell JP, Hopmans JW, Ghezzehei TA. 2022. Long-term impact of cover crop and reduced disturbance tillage on soil pore size and soil water storage. SOIL 8(1):177–98. https://doi.org/10.5194/soil-8-177-2022

Arroues K. 2006. Soil Survey of Fresno County, California, Western Part. Washington, D.C.: USDA NRCS. p 1159. www.waterboards.ca.gov/water-rights/water_issues/programs/bay_delta/california_waterfix/exhibits/docs/dd_jardins/part2/ddj_264.pdf

Bagnall DK, Morgan CLS. 2021. SLAKES and 3D Scans characterize management effects on soil structure in farm fields. Soil Till Res 208:1–8. https://doi.org/10.1016/j.still.2020.104893

Barrios E. 2007. Soil biota, ecosystem services and land productivity. Ecol Econ 64(2):269–85. https://doi.org/10.1016/j.ecolecon.2007.03.004

Blanco-Canqui H, Laird DA, Heaton EA, et al. 2020. Soil carbon increased by twice the amount of biochar carbon applied after 6 years: Field evidence of negative priming. GCB Bioenergy 12(4):240–51. https://doi.org/10.1111/gcbb.12665

Blanco-Canqui H. 2021. No-till technology has limited potential to store carbon: How can we enhance such potential? Agr Ecosys Environ 313:107352. https://doi.org/10.1016/j.agee.2021.107352

Bowles TM, Jackson LE, Loeher M, Cavagnaro TR. 2016. Ecological intensification and arbuscular mycorrhizas: A meta-analysis of tillage and cover crop effects. J Appl Ecol 54(6):1785–93. https://doi.org/10.1111/1365-2664.12815

Bunter W. 1990. The line-transect method of measuring crop residue cover. USDA Soil Conservation Service, California Technical Notes Agronomy 50. http://efotg.sc.egov.usda.gov/references/public/CA/Agronomy_Tech_Note_50.pdf (accessed March 1, 2020).

Cai A, Hun T, Ren T, et al. 2022. Declines in soil carbon storage under no-tillage can be alleviated in the long run. Geoderma 425:116028. https://doi.org/10.1016/j.geoderma.2022.116028

Crabtree B. 2010. Search for sustainability in dryland agriculture. www.no-till.io/resources/SearchSustainability/Search_for_Sustainability_with_No-Till_Bill_in_Dryland_Agriculture_1.6.pdf

Crovetto C. 1996. Stubble over the Soil: The Vital Role of Plant Residue in Soil Management to Improve Soil Quality. Madison, WI: American Society of Agronomy. 247 p. www.echocommunity.org/en/resources/67d42a6b-e2f4-42f6-a53d-446df9bcdbba

Cusser S, Bahlai C, Swinton SM, et al. 2020. Long-term research avoids spurious and misleading trends in sustainability attributes of no-till. Glob Change Biol 26(6):3715–25. https://doi.org/10.1111/gcb.15080

DeClerck F, Singer M. 2003. Looking back 60 years, California soils maintain overall chemical quality. Calif Agr 57(2):38–41. https://doi.org/10.3733/ca.v057n02p38

Don A, Rödenbeck C, Gleixner G. 2013. Unexpected control of soil carbon turnover by soil carbon concentration. Environ Chem Lett 11(4):407–13. https://doi.org/10.1007/s10311-013-0433-3

Doetterl S, Stevens A, Six J, et al. 2015. Soil carbon storage controlled by interactions between geochemistry and climate. Nat Geosci 8(10):780–3. https://doi.org/10.1038/ngeo2516

Francaviglia R, Renzi G, Ledda L, Benedetti A. 2017. Organic carbon pools and soil biological fertility are affected by land use intensity in Mediterranean ecosystems of Sardinia, Italy. Sci Total Environ 599-600:789–96. https://doi.org/10.1016/j.scitotenv.2017.05.021

Franzluebbers AJ. 2010. Will we allow soil carbon to feed our needs? Carbon Manag 1(2):237–51. https://doi.org/10.4155/cmt.10.25

Franzluebbers AJ. 2018. Short-term C mineralization (aka the flush of CO2) as an indicator of soil biological health. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 13(17). https://doi.org/10.1079/PAVSNNR201813017

Haddaway NR, Hedlund K, Jackson LE, et al. 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environ Evidence 6(30). https://doi.org/10.1186/s13750-017-0108-9

Hamza MA, Anderson WK. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil Till Res 82(2):121–45. https://doi.org/10.1016/j.still.2004.08.009

Humphrey V, Berg A, Clais P, et al. 2021. Soil moisture-atmosphere feedback dominates land carbon uptake variability. Nature 592(1):65–72. https://doi.org/10.1038/s41586-021-03325-5

Jackson LE, Wheeler SM, Hollander AD, et al. 2011. Case study on potential agricultural responses to climate change in a California landscape. Climatic Change 109:407–27. https://doi.org/10.1007/s10584-011-0306-3

Kelly C, Fonte SJ, Shrestha A, et al. 2021. Winter cover crops and no-till promote soil macrofauna communities in irrigated, Mediterranean cropland in California, USA. Appl Soil Ecol 166:104068. https://doi.org/10.1016/j.apsoil.2021.104068

Kladivko EJ. 2001. Tillage systems and soil ecology. Soil Till Res 61(1-2):61–76. https://doi.org/10.1016/S0167-1987(01)00179-9

Klocke NL, Currie RS, Aiken RM. 2009. Soil water evaporation and crop residues. ASABE 52(1):103–10. https://doi.org/10.13031/2013.25951

Kravchenko AN, Robertson GP. 2011. Whole-profile soil carbon stocks: The danger of assuming too much from analysis of too little. Soil Sci Soc Am J 75(1):235–40. https://doi.org/10.2136/sssaj2010.0076

Lal R. 2020. Regenerative agriculture for food and climate. J Soil Water Conserv 75(5): 123A–124A. https://doi.org/10.2489/jswc.2020.0620A

Lindwall CW, Sonntag B. 2010. *Landscapes Transformed: The History of Conservation Tillage and Direct Seeding*. University of Saskatchewan: Knowledge Impact in Society. 233 p.

Liptzin D, Norris CE, Cappellazi SB, et al. 2022. An evaluation of carbon indicators of soil health in long-term agricultural experiments. Soil Biol Biochem 172:108708. https://doi.org/10.1016/j.soilbio.2022.108708

Luo Z, Wang E, Sun OJ. 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agr Ecosyst Environ 139(1-2):224–31. https://doi.org/10.1016/j.agee.2010.08.006

Marks JNH, Lines TEP, Penfold C, Cavagnaro, TR. 2022. Cover crops and carbon stocks: How under-vine management influences SOC inputs and turnover in two vineyards. Sci Total Environ 831:154800. https://doi.org/10.1016/j.scitotenv.2022.154800

Martinez-Mena M, Lopez J, Almagro M, et al. 2008. Effect of water erosion and cultivation on the soil carbon stock in a semiarid area of South-East Spain. Soil Till Res 99(1), 119–29. https://doi.org/10.1016/j.still.2008.01.009

Miller, CMF, Fadel, JG, Heguy, JM, et al. 2018. Optimizing accuracy of protocols for measuring dry matter and nutrient yield of forage crops. Sci Total Environ 624:180–8. https://doi.org/10.1016/j.scitotenv.2017.11.203

Mitchell JP, Singh PN, Wallender WW, et al. 2012a. No-tillage and high-residue practices reduce soil water evaporation. Calif Agr 66(2):55–61. https://doi.org/10.3733/ca.v066n02p55

Mitchell JP, Carter L, Munk D, et al. 2012b. Conservation tillage systems for cotton advance in the San Joaquin Valley. Calif Agr 66(3):108–15. https://doi.org/10.3733/ca.v066n03p108

Mitchell JP, Shrestha A, Horwath WR, et al. 2015. Tillage and cover cropping affect crop yields and soil carbon in the San Joaquin Valley, California. Agron J 107:588–96. https://doi.org/10.2134/agronj14.0415

Mitchell JP, Shrestha A, Dahlberg JA, et al. 2016. Prospect of no-till planting of sorghum with and without cover cropping in the San Joaquin Valley. Crop, Forage & Turfgrass Management 2(1):1–3. https://doi.org/10.2134/cftm2015.0208

Mitchell JP, Shrestha A, Mathesius K, et al. 2017. Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA. Soil Till Res 165:325–35. https://doi.org/10.1016/j.still.2016.09.001

Mitchell JP, Reicosky DC, Kueneman EA, et al. 2019. Conservation agriculture systems. CAB Reviews 14, No. 001. 25 p. https://doi.org/10.1079/PAVSNNR201914001

Newton P, Civita N, Frankel-Goldwater L, et al. 2020. What is regenerative agriculture? A review of scholar and practitioner definitions based on processes and outcomes. Frontiers in Sust. Food Sys 4. https://doi.org/10.3389/fsufs.2020.577723

Nielsen DC, Unger PW, Miller PR. 2005. Efficient water use in dryland cropping systems in the Great Plains. Agron J 97(2):364–72. https://doi.org/10.2134/agronj2005.0364

Norris CN, Bean M, Cappellazzi SB, et al. 2020. Introducing the North American project to evaluate soil health measurements. Agron J 112(4):3195–215. https://doi.org/10.1002/agj2.20234

Ogle SM, Alsaker C, Baldock J, et al. 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Sci Rep 9(1):11665. https://doi.org/10.1038/s41598-019-47861-7

Peiretti R, Dumanski J. 2014. The transformation of agriculture in Argentina through soil conservation. International Soil Water Conserv Res 2(1):14–20. https://doi.org/10.1016/S2095-6339(15)30010-1

Pittelkow CM, Liang X, Linquist BA, et al. 2015. Productivity limits and potentials of the principles of conservation agriculture. Nature 517(7534):365–8. https://doi.org/10.1038/Nature13809

Poeplau C, Don A. 2015. Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. Agri Ecosyst Environ 200:33–41. https://doi.org/10.1016/j.agee.2014.10.024

Powlson DS, Stirling CM, Jat M, et al. 2014. Limited potential of no-till agriculture for climate change mitigation. Nat Clim Change 4:678–83. https://doi.org/10.1038/nclimate2292

Powlson DS, Stirling CM, Thierfelder C, et al. 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agr Ecosys Environ 220:164–74. https://doi.org/10.1016/j.agee.2016.01.005

Pribyl DW. 2010. A critical review of the conventional SOC to SOM conversion factor. Geoderma 156(3-4):75–83. https://doi.org/10.1016/j.geoderma.2010.02.003

Ranaivoson L, Naudin K, Ripoche A, et al. 2017. Agro-ecological functions of crop residues under conservation agriculture. A review. Agron Sustain Dev 37(4):26. https://doi.org/10.1007/s13593-017-0432-z

Rasse DP, Rumpel C, Dignac MF. 2005. Is soil carbon mostly root carbon? Mechanisms for a specific stabilisation. Plant Soil 269(1):341–56. https://doi.org/10.1007/s11104-004-0907-y

Reicosky DC. 2015. Conservation tillage is not conservation agriculture. J Soil Water Conserv 70(5):103–7. https://doi.org/10.2489/jswc.70.5.103A

Reicosky DC, Archer DW. 2007. Moldboard plow tillage depth and short-term carbon dioxide release. Soil Till Res 94(1):109–21. https://doi.org/10.1016/j.still.2006.07.004

Reicosky DC, Kassam A. 2021. Conservation agriculture: Carbon and conservation centered foundation for sustainable production. In *Advances in Soil Science, Soil Organic Matter and Feeding the Future: Environmental and Agronomic Impacts.* Lal R (ed.). Boca Raton, FL: Taylor & Francis Group, LLC. p 428.

Rieke EL, Bagnall DK, Morgan CLS, et al. 2022. Evaluation of aggregate stability methods for soil health. Geoderma 428:116156. https://doi.org/10.1016/j.geoderma.2022.116156

Rosenzweig ST, Fonte SJ, Schipanski ME. 2018. Intensifying rotations increases soil carbon, fungi, and aggregation in semi-arid agroecosystems. Agr Ecosyst Environ 258:14–22. https://doi.org/10.1016/j.agee.2018.01.016

SAS Institute Inc. 2002. SAS 9.1.3 Help and Documentation. Cary, NC: SAS Institute Inc. 2000–2004.

Schmidt MW, Torn MS, Abiven S, et al. 2011. Persistence of soil organic matter as an ecosystem property. Nature 478:49–56. https://doi.org/10.1038/nature10386

Schmidt RK, Gravuer AV, Bossange, et al. 2018. Long-term use of cover crops and no-till shift soil microbial community life strategies in agricultural soil. PLoS ONE 13(2):e0192953. https://doi.org/10.1371/journal.pone.0192953

Schmidt R, Mitchell J, Scow K. 2019. Cover cropping and no-till increase diversity and symbiotroph: Saprotroph ratios of soil fungal communities. Soil Biol Biochem 129:99–109. https://doi.org/10.1016/j.soilbio.2018.11.010

Schnitkey G, Paulson N, Zulauf C, et al. 2022. Nitrogen fertilizer prices and supply in light of the Ukraine-Russia conflict. farmdoc daily (12):45. https://farmdocdaily.illinois.edu/2022/04/nitrogen-fertilizer-prices-and-supply-in-light-of-the-ukraine-russia-conflict.html

Six J, Elliott ET, Paustian K. 2000. Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. Soil Biol Biochem 32(14):2099–103. https://doi.org/10.1016/S0038-0717(00)00179-6

Six J, Conant RT, Paul EA, Paustian, K. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241:155–76. https://doi.org/10.1023/A:1016125726789

[SSSA] Soil Science Society of America. 1996. *Glossary of Soil Science Terms.* Madison, WI: Soil Science Society of America.

Sun W, Canadell JG, Yu L, et al. 2020. Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. Glob Change Biol 26(6):3325–35. https://doi.org/10.1111/gcb.15001

Syswerda SP, Corbin AT, Mokma DL, et al. 2011. Agricultural management and soil carbon storage in surface vs. deep layers. Soil Sci Soc Am J 75(1):92–101. https://doi.org/10.2136/ssaj2009.0414

Tautges NE, Chiartas JL, Gaudin ACM, et al. 2019. Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils. Globl Change Biol 25(11):3753–66. https://doi.org/10.1111/gcb.14762

Upadhyaya S, Lancas K, Santos-Filho A, Raghuwanshi N. 2001. One-pass tillage equipment outstrips conventional tillage method. Calif Agr 55(5):44–7. https://doi.org/10.3733/ca.v055n05p44

[USDA NRCS] U.S. Department of Agriculture Natural Resources Conservation Service. 2012. Unlock the Secrets of the Soil. www.nrcs.usda.gov/sites/default/files/2022-12/NRCS-Basics-and-Benefits-Factsheet-2021-English.pdf

USDA NRCS. 2013. Soil Quality Test Kit Guide. Soil Quality Institute (ed.). www.nrcs.usda.gov/sites/default/files/2022-10/Soil%20Quality%20Test%20Kit%20Guide.pdf

Wall DH, Nielsen UN, Six J. 2015. Soil biodiversity and human health. Nature 528:69–76. https://doi.org/10.1038/nature15744

Wright S, Dubcovsky J, Jackson L, et al. 2015. Fresno County small grain variety performance trials. Small Grain News Tulare County 11(2). https://cetulare.ucanr.edu/newsletters/Small_Grain_News59266.pdf

Zhang X, Ferris H, Mitchell J, Liang W. 2017. Ecosystem services of the soil food web after long-term application of agricultural management practices. Soil Biol Biochem 111:36-43. https://doi.org/10.1016/j.soilbio.2017.03.017

Zhang YM, Rock CO. 2008. Membrane lipid homeostasis in bacteria. Nat Rev Microbiol 6:222–33. https://doi.org/10.1038/nrmicro1839