Soil health practices have different outcomes depending on local soil conditions

Soil organic matter can vary dramatically in different environments, regardless of good soil management practices. A new framework that considers regional soil types can help guide investments in soil health and help understand what can be achieved.

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Abstract

The amount of soil organic matter is a critical indicator of soil health. Applying compost or manure, growing cover crops, reducing tillage, and increasing crop diversity may increase soil organic matter. However, soil organic matter can vary dramatically in different environments, regardless of management practices. This calls for a framework to recommend place-based soil health practices and evaluate their outcomes. We used a new framework that groups soil survey data into seven regions in California's Central Valley and Central Coast. These regions either have performance limitations, such as root restrictive horizons, salinity, and shrink-swell behavior, or have relatively homogeneous, coarse-to-loamy soils ideal for agriculture. These inherent conditions affect a soil's response to practices designed to improve soil health. Looking at vineyards as an example, we find significant soil organic matter contrasts between soil health regions but not among contrasting management approaches within a given region. We also show that conservation practices improve or help maintain soil health in several long-term experiments, but inherent soil properties and types of cropping systems affect outcomes.

Soil is not an inert medium but contains an unfathomable array of life — a teaspoon of soil contains billions of organisms, each with a specific role in the ecosystem. Soil health — the soil's capacity to function as a complex living ecosystem (Doran and Zeiss 2000) — provides benefits to agriculture, such as storing and releasing nutrients and water for crop growth, and also has large-scale benefits, such as purifying water that percolates through the soil on its way to streams and groundwater. Soil also stores immense quantities of carbon dioxide (CO_2) in solid form. Measuring at a depth of 0–79 inches (in; 0–2 meters [m]), the global reservoir of soil organic carbon (SOC) is estimated at 2.4 times the carbon in atmospheric CO_2 (Batjes 2016). This means that soil health is relevant to greenhouse gas reduction.

The carbon sequestered in soil is an essential building block of the tiny decomposed bits of plant material and microorganisms that make up soil organic matter (SOM), comprising 50% to 60% of SOM by mass (Pribyl 2010). The terms SOC and SOM are used interchangeably in this study, because soil surveys and most agronomic soil testing laboratories report SOM, while soil science studies report SOC as the more accurately measurable component of SOM (table 1).

A view of the complex landscape where diverse soil types are found in the Napa wine-growing region. *Photo*: Kerri Steenwerth, USDA-ARS

TABLE 1. Glossary of terms

Term	Definition
Soil health	Soil's capacity to function as a living ecosystem. Health cannot be measured directly but can be inferred from multiple *soil health indicators*.
Soil health indicators	A subset of semi-dynamic soil properties often related to *soil organic matter* that reflect *soil health* status but are also constrained by *soil forming factors* that give rise to *inherent soil properties*. The science of soil health indicators is an active area of research and subject to change, especially in regard to biological soil health indicators.
Soil forming factors	Five factors responsible for natural formation of soils and their *inherent soil properties*: (1) climate (long-term trends in precipitation and temperature), (2) parent material (kind of material from which a soil is formed), (3) relief (terrain slope, shape and the relative position in a landscape), (4) time (duration a given landscape is stable for soil forming processes to affect soil development) and (5) organisms (e.g., grasslands and forests have differing effects on soil formation).
Inherent soil properties	Soil features such as *soil texture* and restrictive horizons arising from *soil forming factors* that determine how a soil behaves physically and chemically, also influencing soil biological characteristics. Some inherent soil properties are *soil health indicators*, such as *soil salinity*, *soil pH*, and *soil organic matter*, which are more dynamic and readily influenced by agricultural management.
Soil texture	The soil particle size distribution, typically summarized by the percentage of sand, silt and clay-sized particles or as a textural class (e.g., sandy loam). Soil texture is linked to a number of key *soil health indicators*, such as *soil organic matter* and *aggregate stability*, but is practically impossible to change by agricultural management. In the *soil health regions framework*, soil texture distinguishes a number of regions from one another and is also linked to *shrink-swell* behavior in California.
Soil salinity	A dynamic *soil health indicator* referring to the amount of dissolved ions in soil solution, such as calcium, magnesium, potassium and sodium. *Soil salinity* restricts plant water uptake and the specific type of dissolved ions affect the extent to which soil particles bind to one another into *stable soil aggregates*. In the *soil health regions framework*, salt-affected regions are naturally more saline as a result of several *soil forming factors* but can be influenced by practices such as irrigation and leaching.
Soil pH	A dynamic *soil health indicator* referring to the relative soil acidity or alkalinity. Very acidic or alkaline soil pH restricts crop nutrient availability. In the *soil health regions framework*, salt-affected regions tend to be highly alkaline as a result of *soil forming factors*, but soil pH can be noticeably influenced by practices such as amendments, irrigation and leaching.
Soil organic matter (SOM)	A dynamic, widely validated *soil health indicator* consisting of soil particles from once living tissues, including those of both plant and microbial origins. SOM spans a large size range from bits of partially decomposed crop residue to complex organic molecules often bound to the surface of clay particles. SOM is 50% to 60% carbon (*soil organic carbon*) and can also be influenced by agricultural management such as tillage, cover cropping, and compost application but is also noticeably linked to *soil forming factors* in the *soil health regions framework*. SOM is roughly estimated in agronomic soil testing from "loss on ignition" analyses (correcting for soil moisture loss).
Soil organic carbon (SOC)	Carbon atoms in the SOM molecular structure are called SOC. The term is used interchangeably in this paper when citing studies where SOC was measured directly as a proxy for SOM, because the laboratory method to determine SOC is more accurate and reproducible than the method to determine SOM. SOC is reported two different ways: (1) as a "concentration" on a soil mass basis (g SOC g^{-1} soil) and (2) as a "stock" on a soil volume basis (kg SOC m^{-3}), which also requires measurement of soil bulk density (kg soil m^{-3} soil).
Restrictive horizons	Soil layers (horizons) arising from *soil forming factors* that restrict plant root growth and water percolation through the soil. In the *soil health regions framework*, hardpans (duripans) and abrupt increases in percentage clay with depth (claypans) are most common and distinguish several regions.
Shrink-swell	The tendency of soils with a large content of a particular kind of clay particle, common in California, to shrink when dry and expand when wet. Shrink-swell soils are difficult to cultivate and not recommended for production of many crops, although they do tend to have relatively high *SOM* levels.
Stable soil aggregates	The ability of primary soil particles (sand, silt and clay) bound together in clumps to resist disruptive forces such as rainfall and wind. *Aggregate stability* protects SOM from microbial decomposition, prevents soil erosion, and promotes a soil environment more conducive to water and air movement.
Soil health regions framework	A conceptual framework that groups many soils into fewer groups with similar *inherent soil properties* and associated *performance limitations* to agriculture. Soil health regions tend to be, but are not necessarily, geographically contiguous, as a result of soil forming factors. Regions were defined in this study using *K-means clustering* of the Soil Survey Geographic (SSURGO) database and were shown to be distinct from USDA-NRCS Soil Taxonomy (Devine et al. 2021).
Performance limitations	Soil properties that limit use of soil for crop production. In the *soil health regions framework*, *soil salinity, restrictive horizons*, and *shrink-swell* properties are *performance limitations* that distinguish regions. The difference in performance limitations among regions is highlighted by contrasting Stories Indices, a soil productivity rating developed for California (O'Geen et al. 2008).
K-means clustering	An unsupervised machine learning method of data analysis to mathematically identify groups of data points into a defined number of groups called clusters.

Soil core collected to measure bulk density in the subsoil of a vineyard alley in the Napa Valley. *Photo*: Kerri Steenwerth, USDA-ARS

SOM serves many functions, from making it easier for the soil to absorb water and nutrients to fueling the microorganisms themselves. Like measuring blood pressure as an overall indicator of human health, measuring SOM is one indicator of soil health. Yet, blood pressure won't tell you if you have cancer or Alzheimer's disease — health is too complicated. Similarly, soil health indicators (table 1) are affected by other soil properties, including the soil's texture, pH, salinity and depth.

Given the complexity of soils, it has been challenging to develop accurate soil health analyses that work across diverse landscapes and climates in order to validate soil health practices (Fine et al. 2017). Much of this challenge is because of the inherent variability of soil properties. A national-scale analysis of SOC at a depth of 0–6 in (0–15 centimeters [cm]) showed significant average differences by U.S. geographic region, soil texture, and soil type, with different effects of conservation practices on SOC depending on these factors (Nunes et al. 2020). The same need for context exists in California.

SOM levels are ultimately a balance between inputs (crop residues) and outputs (decomposition by microbes). Both processes are affected by agriculture. A re-sampling of soil (0–10 in; 0–25 cm) first sampled from California agricultural lands in the 1940s and 1950s showed an average increase in total SOC 60 years later, yet the average change across the 125 sites varied from a 10% decline to an increase of more than 200% depending on the region (De Clerck et al. 2003). Increasing trends in SOM in some landscapes could be related to conversion to intensive agriculture across the same time span, which would have increased annual biomass inputs to those soils.

From 2016 to 2019, the California Department of Agriculture's (CDFA) Healthy Soils Program (HSP) distributed $41.5 million to growers to implement practices such as applying compost and cover cropping, with pre- and post-project SOM monitoring required (CDFA 2020). The HSP complements existing USDA-NRCS (Natural Resources Conservation Service) programs funding similar soil conservation practices. The challenge of evaluating soil health is especially great in California, where globally important agricultural production occurs across a dizzying combination of soil-forming factors (table 1): sandy Sierra Nevada glacial outwash, widespread ancient river terraces with root restrictive horizons like claypans and hardpans, salt-affected soils developed in drier climates and poorly drained landscape positions, and shrink-swell soils where clays have settled in vast basins from repeated slow-moving floods (Graham and O'Geen 2016).

To better understand regional soil patterns in California, the USDA-NRCS Soil Survey Geographic (SSURGO) database was grouped into regions of "soil health identity" in California sharing similar inherent soil properties (Devine et al. 2021). Using this recently published framework, the main objective of this study was to examine effects of practices that improve or maintain soil health in different regions. We apply this framework to existing datasets, to guide development of place-based strategies and expectations.

Seven soil health regions

K-means cluster analysis (table 1) was used to identify seven soil health regions within Central California coastal valleys and the entire Central Valley (13,873,131 acres; 5,614,257 hectares) from a suite of SSURGO properties linked to soil health. This approach to grouping data identified regions distinct from the USDA-NRCS Soil Taxonomy (Devine et al. 2021). Soil health regions occur either with or without performance limitations to agriculture (table 1).

Soil health regions are either ideal for agriculture (with coarse-to-loamy, homogeneous soil profiles) or they have agricultural performance limitations (e.g., problematic salinity, root restrictive horizons, and/or shrink-swell behavior). Soils without performance limitations, found in regions 1 and 2, accounted for 45% of the study area; they have deep, homogeneous profiles formed from more recent alluvial deposits with no major soil chemistry challenges to crop growth (figs. 1 and 2). Their suitability for agriculture is highlighted by a high Storie Index (table 2), which is a soil productivity rating developed specifically for California (O'Geen et al. 2008). Regions 1 (coarse with no restrictions) and 2 (loamy with no restrictions) are distinguished from one another by several properties related to soil textural differences (table 2).

By contrast, soils with performance limitations (55% of the study area: regions 3–7) are all characterized by lower Storie Indices. Region 3 (18% of the study area) and region 4 (5% of the study area) are moderately deep to a restrictive layer, moderately acid to slightly alkaline, moderately well-drained, and

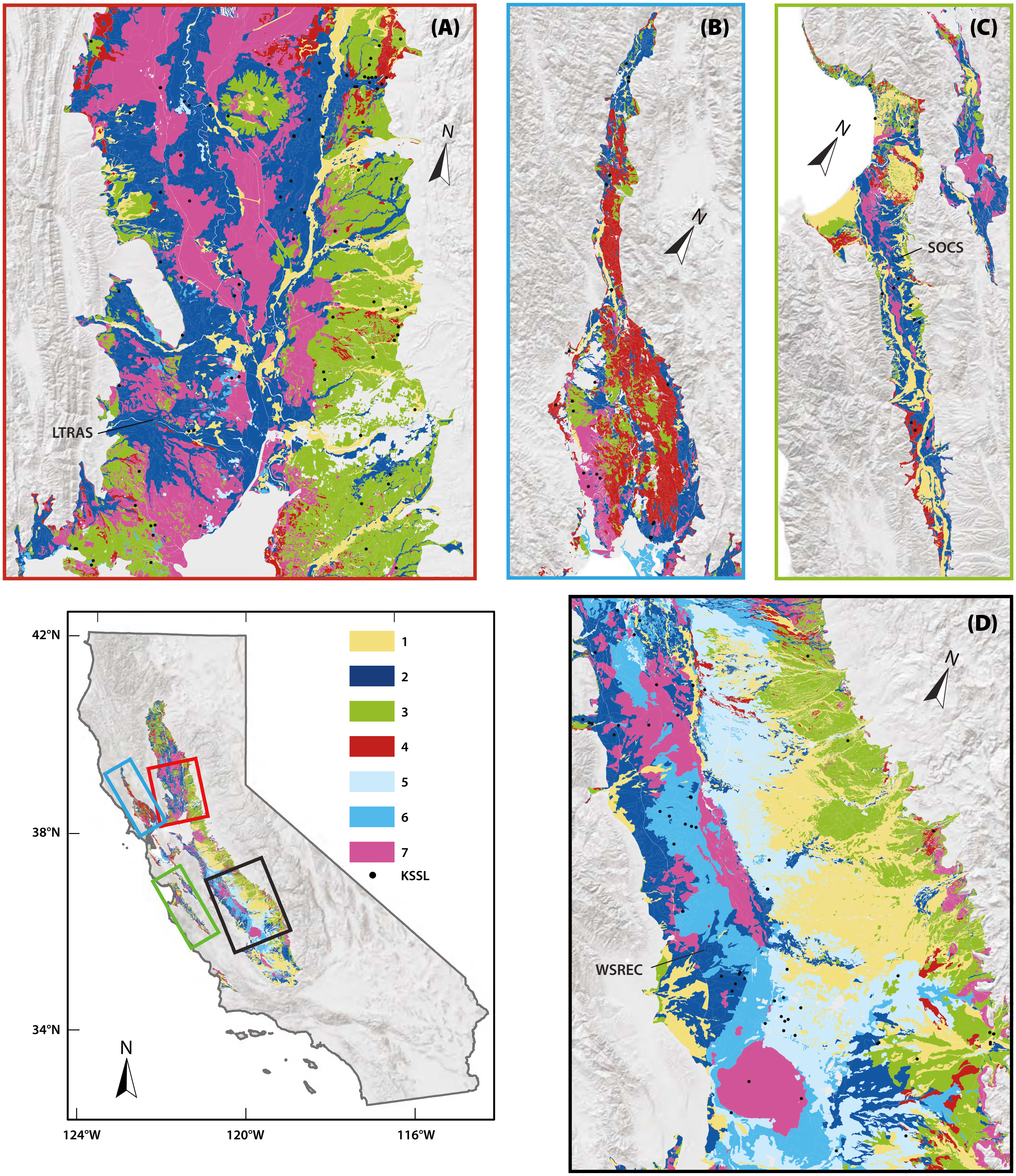

FIG. 1. Seven California soil health regions identified from cluster analysis of 10 soil properties derived from USDA-NRCS SSURGO (Soil Survey Geographic) data, highlighting the following: (A) southern Sacramento Valley, (B) Napa and Sonoma valleys (including adjacent hillsides), (C) Salinas, Santa Clara and Pajaro valleys and (D) central and southern San Joaquin Valley. Locations of Kellogg Soil Survey Laboratory (KSSL) points and three soil health experiments are depicted: the Long Term Research in Agricultural Sustainability (LTRAS), Salinas Organic Cropping Systems (SOCS) and UC West Side Research and Extension Center (WSREC). Soil health regions: 1 = Coarse with no restrictions, 2 = loamy with no restrictions, 3 = low organic matter (OM) with restrictive horizons, 4 = high OM with restrictive horizons, 5 = coarse-loamy salt-affected, 6 = fine salt-affected and 7 = shrink-swell.

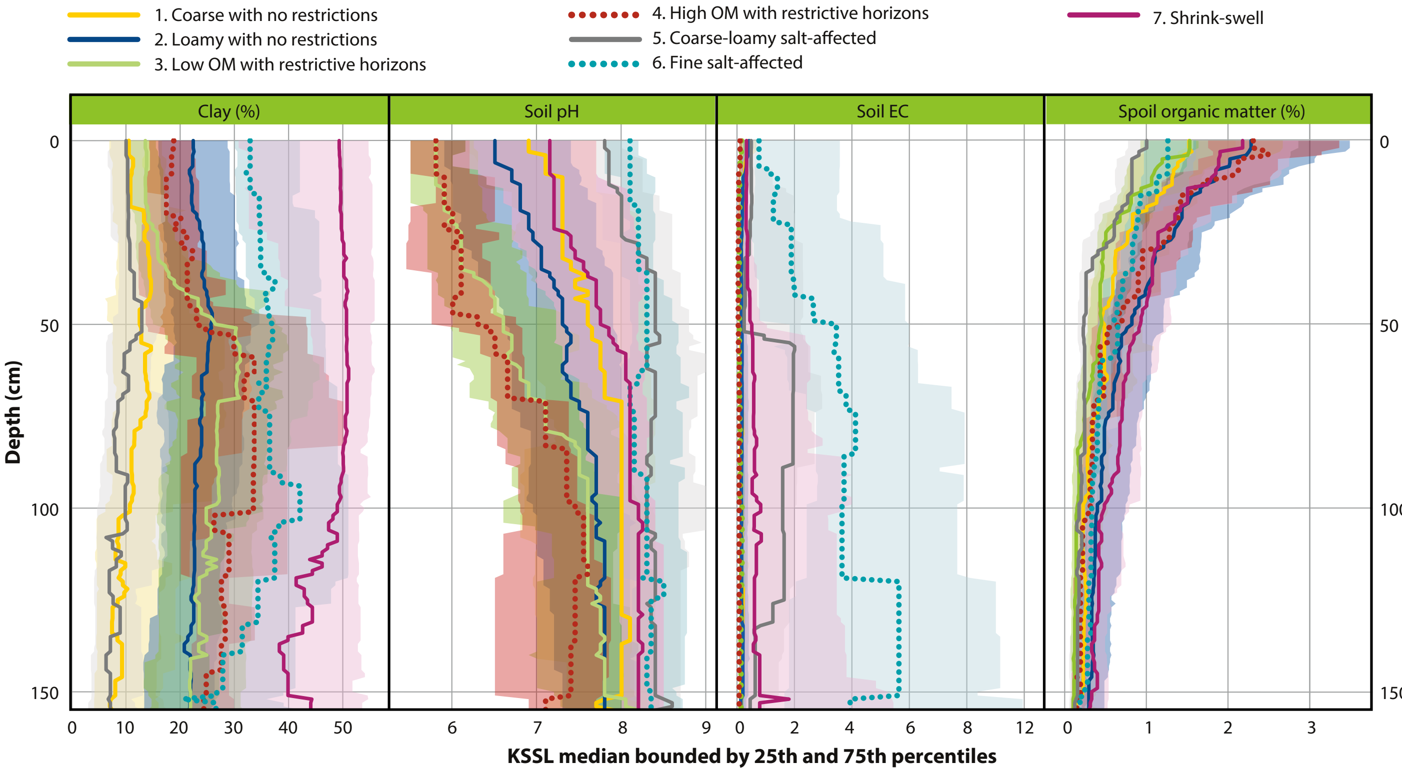

FIG. 2. Inherent soil properties differ by soil health region based on 369 validation locations from the Kellogg Soil Survey Laboratory (KSSL) database, emphasizing the need for a regional soil health approach. Most data was available in loamy with no restrictions (n = 109), low organic matter (OM) with restrictive horizons (n = 85), and shrink-swell (n = 64) regions. Fewer points were available in coarse with no restrictions (n = 41), fine salt-affected (n = 28), coarse-loamy salt-affected (n = 27), and high OM with restrictive horizons (n = 15) regions. Soil organic matter (SOM) was estimated by multiplying soil organic carbon concentrations by the van Bemmelen factor (1.72). Solid lines are KSSL medians and shaded areas in the same color are 25th and 75th percentile values at 1-cm depth intervals.

TABLE 2. Spatially weighted medians and interquartile range (in parentheses) of USDA-NRCS SSURGO (Soil Survey Geographic) 0–30 cm data by soil health region mapped in figure 1

Soil health region	Sand	Silt	Clay	OM	LE	CEC	pH	EC	Ksat	Storie Index
			%			*mEq 100 g^{-1}*	*1:1 H_2O*	*dS m^{-1}*	*μm s^{-1}*	
1	68 (7)	20 (5)	13 (4)	0.7 (0.2)	1.5 (0.1)	8.0 (3)	7.0 (1.2)	0.5 (1.0)	28 (10.3)	81 (30)
2	35 (10)	37 (9)	25 (8)	1.5 (1.1)	3.6 (2.5)	19 (8)	7.3 (1.1)	1.0 (0.8)	6.1 (6.2)	77 (25)
3	47 (24)	35 (19)	17 (5)	0.8 (0.5)	1.5 (0.4)	12 (6)	6.3 (0.6)	0 (0.7)	9 (0.6)	29 (20)
4	38 (6)	37 (3)	25 (6)	2.0 (1.5)	3.0 (3.0)	17 (5)	6.3 (0.6)	0 (0.6)	9 (3.8)	28 (28)
5	59 (27)	23 (19)	16 (10)	0.7 (0.3)	1.5 (1.5)	11 (5)	8.4 (0.6)	6.5 (5.0)	9 (12.6)	34 (34)
6	26 (11)	31 (10)	41 (16)	0.8 (0.5)	7.1 (2.5)	30 (9)	8.2 (0.6)	6.4 (5.0)	0.9 (1.5)	23 (27)
7	17 (14)	29 (9)	50 (6)	1.8 (0.5)	8.0 (3.2)	38 (7)	7.5 (1.2)	1.0 (0.6)	0.9 (0.4)	33 (26)

Productivity increases from non-agricultural (< 20) to prime farmland (> 80) along the Storie Index.

Soil health regions: 1 = Coarse with no restrictions, 2 = loamy with no restrictions, 3 = low OM with restrictive horizons, 4 = high OM with restrictive horizons, 5 = coarse-loamy salt-affected, 6 = fine salt-affected and 7 = shrink-swell.

OM = organic matter, LE = linear extensibility (shrink-swell), CEC = cation exchange capacity, EC = electrical conductivity.

formed from alluvial deposits on stream terraces, alluvial fans above current floodplains, or residuum in uplands. Permeability can be slow as a result of the restrictive layer.

Specifically, region 3 has low-to-moderate clay content (spatially weighted mean [μ] = 18%) and low SOM (μ = 1.0%) in the surface layer and is most widespread on the Central Valley's eastern margins on terraces formed from granitic deposits. Region 4 has moderate clay content (μ = 25%) and high SOM (μ = 2.5%) in the surface layer and occurs mostly in the wetter, northern half of the study area, such as shallow soils in cropped foothills near the Napa and Sonoma Valleys, where the climate has favored higher levels of SOM accumulation. The soils also occur on dissected high terraces along the eastern Central Valley margins (Graham and O'Geen 2016).

Region 5 (9% of the study area) and region 6 (7% of the study area) are salt-affected and distinguished by alkaline (pH > 8) chemistry; they often have layers that restrict drainage and roots. Region 5 has low-to-moderate clay (μ = 18%) and low SOM (μ = 0.8%), occurring almost exclusively in the drier, southern half of the study area along the San Joaquin River. Region 6 soils have high clay content (μ = 42%), typically with high shrink-swell capacity and low permeability but with relatively low SOM (μ = 1.2%). They occur mostly in the southern half of the study area alongside region 5.

Region 7 (16% of the study area) has the most finely textured soils (μ = 51% clay) with shrink-swell clays but without pronounced alkalinity (μ = 7.4 pH) or salt-affected chemistry, holding a substantial amount of SOM (μ = 1.9%). This widespread region occurs throughout the Central Valley and Central Coast valleys but some coarser-textured soils are intermixed. Even though the framework was developed using surface soil properties (0–12 in; 0–30 cm) and depth to restrictive horizons, soil properties differed by region through full soil profiles according to Kellogg Soil Survey Laboratory (KSSL) data (fig. 2). Thus, the soil health implications of each region's properties can be expected to extend through the full rooting zone.

A soil profile from soil health region 3 showing a root-restrictive horizon between 30 cm and 50 cm relative to the black tape measure. *Photo:* Toby O'Geen

Vineyard organic matter varies

The seven-region framework was used to analyze vineyard alley SOM as influenced by soil health region and management practices such as establishing perennial groundcover and conservation tillage. In 2011, 102 locations were sampled and analyzed for SOC (0–39 in; 0–1 m) across 34 vineyard blocks in Napa-Sonoma and Lodi grape-growing regions (Burns et al. 2015, 2016; Yu et al. 2017, 2019) and then converted to SOM using the van Bemmelen factor (1.72) for comparison to soil survey data.

The dataset showed significant SOM contrasts between soil health regions but not among contrasting management approaches within a given region (fig. 3). Finer-textured soil health regions (2, 4 and 7) had significantly higher SOM than coarser-textured regions (1 and 3), demonstrating that SOM is as much an inherent property determined by a site's unique environmental conditions as it is affected by management.

Interestingly, within region 2, where most sampled vineyards were located, SOM showed no clear difference across contrasting management practices (fig. 3), even though, for example, soil bacterial communities tended to vary by management practices in this region (Burns et al. 2016). The mean surface SOM (0–4 in; 0–10 cm) difference under perennial groundcover in vineyard alleys and several contrasting management approaches was notable and promising but not statistically significant.

Vineyard regions with root restrictive horizons (claypans and hardpans) showed steeper SOM declines with depth (fig. 3). Limitations to root elongation into deeper soil affect the supply of biomass inputs necessary to build deeper SOM stocks. These restrictions are typically removed through deep tillage, a common practice before planting. But restrictive horizons may be unaffected if tillage was poorly implemented. Moreover, claypans re-form over time. Even with mixing or shattering, residual pan fragments would likely be slow to accumulate new SOM, if any. For example, clay-rich aggregates from a region 3 subsoil were shown to have protected, millennia-old SOC, but this deep SOC was vulnerable to rapid microbial decomposition upon disturbance (Ewing et al. 2006), warranting caution about deep tillage practices.

Overall, the vineyards reported widespread practices of soil health management. All alleys had annual or perennial cover, 71% of sampled alleys were in blocks where growers had applied compost, and 40% practiced no-till. Effects of these practices are likely reflected in the SOM statistics: In each soil health region, median Napa-Lodi vineyard estimated SOM (0–12 in; 0–30 cm) was > 75th percentile relative to the median SSURGO SOM, whereas median KSSL SOM was closer to median SSURGO SOM, with the exception of region 1 (coarse and no restrictions) (table 3). Indeed, a retrospective sampling study found a doubling of SOC in the "wine country" (eight sites in Napa and Sonoma counties) from 1945 to 2001 (De Clerck et al. 2003). This supports the idea that widespread soil health management approaches (including irrigation) may have broadly increased SOM in California vineyards.

Soil regions affect results

The soil health regions framework was used to contextualize several long-running agricultural experiments

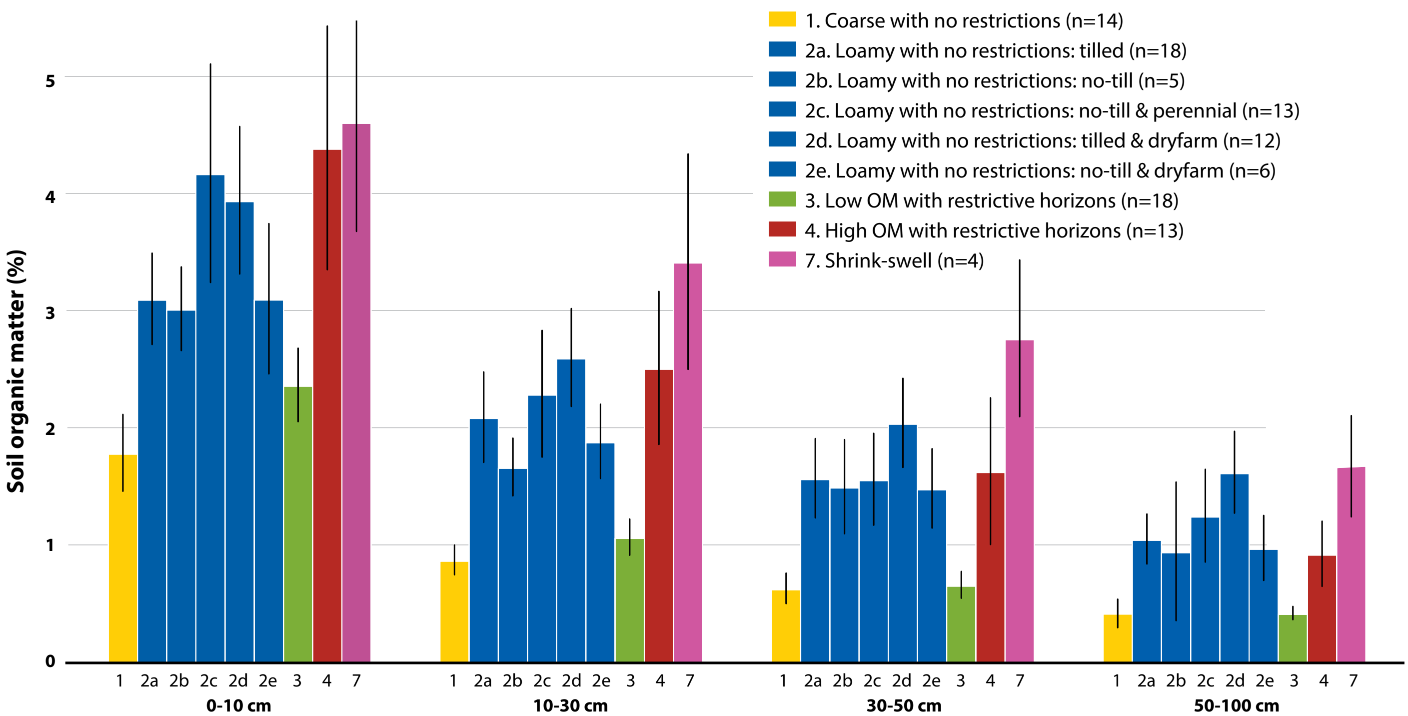

FIG. 3. Relatively high soil organic matter (SOM) levels more clearly differ by soil health region across Napa-Lodi vineyards. Height of bars show mean SOM concentration in alleys between vine rows across four soil health regions and four soil depth intervals (0–10, 10–30, 30–50 and 50–100 cm). SOM is presented by management type in region 2 (loamy and no restrictions). Perennial refers to perennial groundcover in alleys. All points sampled in region 2, region 4 (high OM with restrictive horizons) and region 7 (shrink-swell) were in Napa. All points sampled in region 3 (low OM with restrictive horizons) and 9 of 14 points sampled in region 1 (coarse with no restriction) were in Lodi. Error bars denote 95% confidence intervals for means, so non-overlapping error bars indicate a statistically significant contrast. SOM was estimated by multiplying soil organic carbon concentrations by the van Bemmelen factor (1.72).

TABLE 3. Expected 0–12 in (0–30 cm) soil organic matter (SOM) statistics by soil health region according to USDA-NRCS Soil Survey Geographic (SSURGO) data, points sampled in Napa-Lodi vineyard alleys, and the Kellogg Soil Survey Laboratory (KSSL) data

Soil health region	10th	25th	50th	75th	90th	Napa-Lodi	KSSL
	SSURGO SOM percentiles					*SOM at 50th percentile*	
1. Coarse with no restrictions	0.25	0.58	0.72	0.75	2.00	1.07	1.07
2. Loamy with no restrictions	0.66	0.94	1.50	2.00	3.27	2.35	1.65
3. Low OM with restrictive horizons	0.44	0.69	0.75	1.21	2.00	1.49	1.13
4. High OM with restrictive horizons	0.82	1.35	2.00	2.84	6.38	2.90	1.76
5. Coarse-loamy salt-affected	0.04	0.50	0.70	0.75	2.00	NA	0.70
6. Fine salt-affected	0.42	0.70	0.75	1.23	3.00	NA	1.01
7. Shrink-swell	0.90	1.49	1.82	2.02	3.50	4.03	1.66

Napa-Lodi and KSSL samples were analyzed for soil organic carbon (SOC) and multiplied by the van Bemmelen factor (1.72) to estimate SOM.

in California, including the UC Davis Long Term Research in Agricultural Sustainability (LTRAS, also known as the Russell Ranch Century Experiment) in Davis in region 2 (loamy with no restrictions) (fig. 1A). Here, tomato-corn rotations tested in combination with winter cover crops and compost, and wheat-based systems tested in combination with irrigation and fertilizer, have been managed since 1993 (Wolf et al. 2017). Nineteen years of applying composted poultry manure (cumulative input of 18 T C ac^{-1}; 40 Mg C ha^{-1}), supplying 134–178 lb N ac^{-1} yr^{-1} (150–200 kg N ha yr), and cover cropping (cumulative input of 7 T C ac^{-1}; 15 Mg C ha^{-1}) increased SOC by statistically significant or notable levels (Tautges et al. 2019).

Specifically, the tomato-corn rotation with a winter cover crop showed a 22% increase in 0–6 in (0–15 cm) SOC concentration and an 11% increase in 6–12 in (15–30 cm) SOC. With compost and winter cover crops, soils showed a 44% increase in 0–6 in (0–15 cm) SOC, 30% increase in 6–12 in (15–30 cm) SOC, and 9% increase in 12–24 in (30–60 cm) SOC. With starting 0–12 in (0–30 cm) SOC at 0.90% (approximately 1.55% SOM), soils in the tomato-corn rotation had some apparent capacity for an increase in SOM (Kong et al. 2005) compared to what the region's soils typically stabilize (fig. 4; table 3).

This example offers a cautionary tale about the relationship between soil and climate. Just 15% of the additional carbon supplied by cover crop biomass and compost became part of SOM, meaning most of the surplus carbon was returned to the atmophere as CO_2 through microbial decomposition. This process may have accelerated by multiple annual tillage passes and a warm climate (MAT = 16.7°C; MAP = 559 millimeters [mm]). A concern is that if tillage disrupts soil aggregates, preventing the aggregates from protecting SOM from microbial decomposition, the decomposition process may release carbon into the atmosphere (table 1).

By contrast, across the wheat-based agroecosystems at Russell Ranch, this region 2 soil demonstrated its resistance to change: Cumulative differences in crop and cover crop residues across these treatments (equivalent up to 6.7 T C ac^{-1}; 15.1 Mg C ha^{-1}) produced no discernible changes in SOM over the 19-year period (fig. 4). This is even more remarkable considering that, as a C equivalent, cumulative wheat systems' residues were just 28% to 46% of the residues of the tomato-corn rotation without a cover crop (Tautges et al. 2019).

In the similarly warm but drier climate of the UC West Side Research and Extension Center (WSREC) experiment (MAT = 17.2°C; MAP = 185 mm), in region 2 (fig. 1D), 14 years of reduced tillage and cover cropping (with some supplemental winter irrigation during dry years) doubled SOC stocks (0–12 in; 0–30 cm) in a tomato-cotton rotation (Mitchell et al. 2017). But this remarkable SOC change is likely related to the initial soil conditions: SOC began at 0.51% (approximately 0.87% SOM) in 1999 (Mitchell et al. 2015), below the 25th percentile for this soil health region (fig. 4; table 3). Even in the conventional treatment with tillage and no cover crops, SOM increased by 50% (fig. 4). This example highlights the value of this system of identification of soil regions with expected values, for the purpose of establishing targets and evaluating potential outcomes. In this instance, reducing tillage and using cover crops in relatively low-SOM soils sequestered carbon and improved soil health indicators such as water infiltration and aggregate stability (Mitchell et al. 2015), while reducing dust emissions (Baker et al. 2015). This is relevant to millions of acres of crops in California where tillage is frequent and the historical norm (Mitchell et al. 2016).

The same crops tested at WSREC are also cultivated on many soils that have performance limitations (fig. 5). This includes the soilscape near WSREC (fig. 1), where soil health practices may have even greater impacts, for example, in salt-affected soils where SOM is typically lower or in shrink-swell soils where SOM storage capacity is greatest (table 3). This is especially relevant in region 5 (coarse loamy salt-affected), where approximately half of KSSL points showed electrical conductivity measurements below 2 dS m^{-1}, indicating low salinity (fig. 2). Even though these locations may have had salt-affected soils, they were likely reclaimed by relatively recent agricultural practices. Cover cropping could pay greater SOM dividends here, assuming availability of winter irrigation to subsidize productivity in this very dry climate.

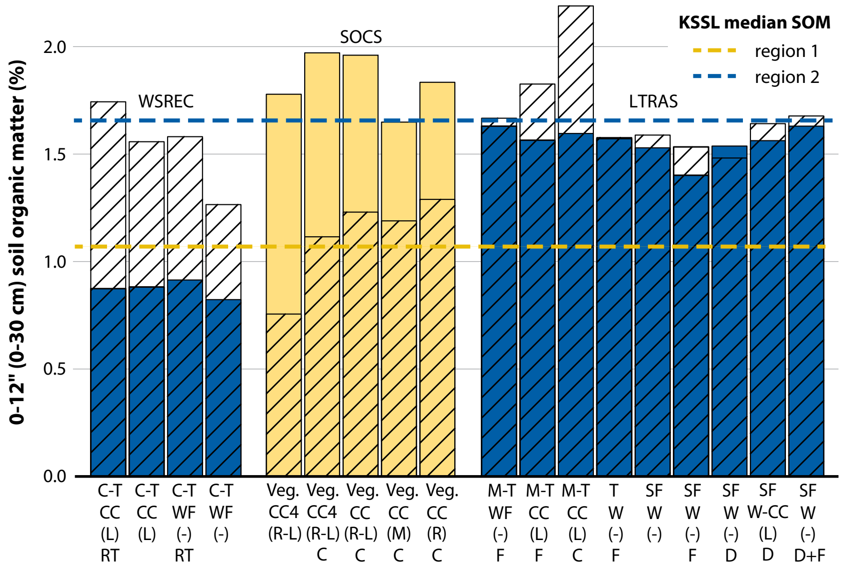

FIG. 4. Soil health practices appear to have consistent outcomes when seen through the lens of soil health regions. 0–12 in (0–30 cm) soil organic matter (SOM) at year 0 of treatment (solid bars, light yellow = soil health region 1 and brown = soil health region 2) and at last published sampling (transparent bars with 45° hash lines) at three long-term agroecosystem experiments: (1) the UC West Side Research and Extension Center (WSREC) 1999–2014, (2) Salinas Organic Cropping Systems (SOCS) 2003–2011 and (3) the Long Term Research in Agricultural Sustainability (LTRAS) 1993–2012. See figure 1 for exact locations. The horizontal dashed lines denote the median 0–12 in (0–30 cm) SOM for points sampled in soil health regions 1 and 2, as reported by the Kellogg Soil Survey Laboratory (KSSL) database. Below x-axis, the first line denotes summer crops: C-T is a cotton-tomato rotation, Veg. is a double crop of lettuce and broccoli or spinach, M-T is a maize-tomato rotation, T is tomatoes and SF is a summer fallow. Second line denotes winter crops: CC is an annual cover crop, CC4 is a cover crop grown every fourth year with winter fallows in between, WF is winter fallow, W is wheat and W-CC is a wheat–cover crop rotation. Third line denotes the type of cover crop: (L) is legume, (R-L) is a rye-legume mix, (M) is mustard, (R) is rye and (-) emphasizes no cover crops were grown. Fourth line denotes other practices: RT is reduced tillage, C is compost, D is rainfed only and F is fertilized. All treatments at WSREC were fertilized and all treatments at SOCS were fertilized following USDA organic standards. Soil organic matter (SOM) was estimated by multiplying soil organic carbon concentrations by the van Bemmelen factor (1.72). Soil organic carbon reported as stocks by White et al. (2020) and Mitchell et al. (2015) were converted to concentrations using bulk density data.

Good practices reduce organic loss

Meanwhile, a stark first-year loss of 13.4 T SOC ac^{-1} (30 Mg ha^{-1}) occurred at the USDA-ARS Salinas Organic Cropping Systems experiment ("Salinas experiment") in double-cropped vegetables (White et al. 2020). The Salinas experiment is located in a soil on the border

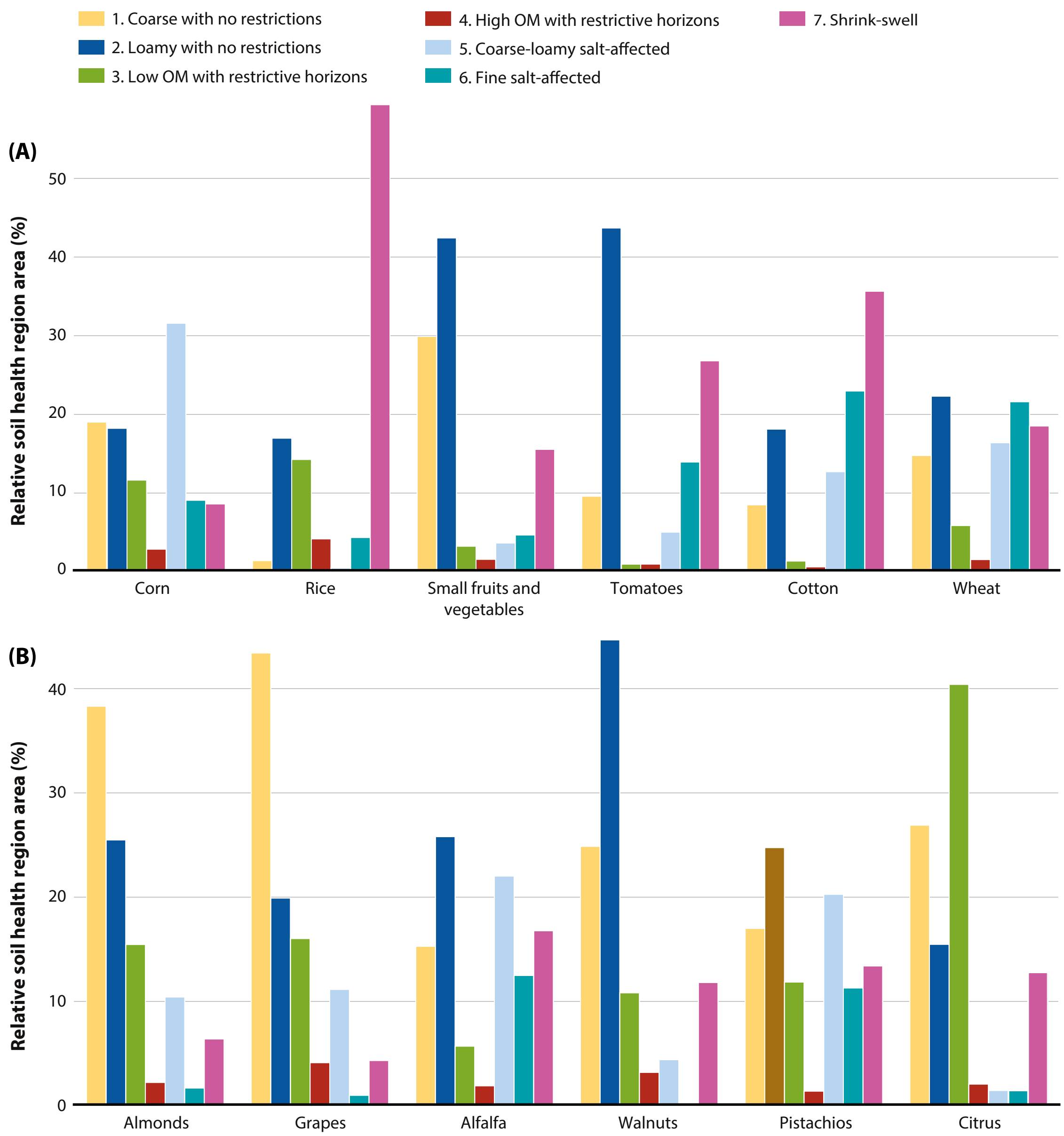

FIG. 5. Top six (by irrigated land area) annual (A) and perennial (B) crop types with proportions by seven soil health regions. Land use was identified by 2014 remote sensing (CDWR 2017), which classified 64% of the 5,274,720-ha study area.

of regions 1 (coarse with no restrictions) and 2 (loamy with no restrictions) (fig. 1C), but with site properties (70% sand, 22% silt and 8% clay) more in line with region 1. Thus, SOC is potentially very sensitive to extreme tillage disturbance such as that induced by the soil spader used at the Salinas experiment site. This loss possibly was enhanced by the site's coarse texture that favors rapid microbial decomposition of SOM, a soil characteristic common to much vegetable production (fig. 5).

Similar to WSREC, initial SOM values may have played a role in this outcome. With an estimated 1.85% SOM (0–12 in; 0–30 cm) at the start of the experiment, the coarse soils had relatively high SOM levels, near the 90th percentile of region 1 soils (fig. 4; table 3), perhaps enabled by low tillage intensity, multiple cover crops, compost applied prior to the experiment (Brennan and Boyd 2012), and the site's cooler coastal climate (MAT = 14.2°C; MAP = 344 mm). The initial SOM loss was then partly compensated by stabilization of 4.2 T SOC ac^{-1} (9.4 Mg ha^{-1}) out of the applied compost and an additional 1.5 T SOC ac^{-1} (3.4 Mg ha^{-1}) from annual cover cropping versus quadrennial cover cropping. However, this was just 19% to 24% of additional carbon supplied via compost and different annual cover crop mixes through 8 years, similar to the Russell Ranch results.

Soil health regions matter

The soil health concept has spurred awareness of soil as a living ecosystem, and has encouraged conservation practices, including (1) keeping the soil covered,

(2) increasing crop diversity, (3) reducing tillage and (4) adding biomass such as compost or manure to feed the soil and build soil organic matter.

California has spent millions to fund soil health practices through its Healthy Soils Program. How these practices can be practically integrated across diverse climates, crops and soils, with realistic expectations of benefits, remains largely unanswered. This study demonstrated the utility of a recently developed soil health regions framework to guide place-based soil health strategies and expectations. As scientists and growers learn more about the soils in their region, there will be a better and shared understanding of what can be accomplished in terms of improving soil health and which practices work best for soils within a region — each of which has unique, inherent properties.

Soil organic matter in California vineyards differed more by soil health region than by management practices. In three long-term annual cropping experiments, conservation practices showed promise for improving soil health (especially when starting from a relatively low level of soil organic matter) or helping to maintain soil health in intensively tilled systems when starting from a relatively high value.

The vineyard study demonstrates that the soil health regions framework can help growers understand the expected soil organic matter values for their location, an overall indicator of soil health.

While conservation practices improved or helped maintain soil health in several long-term experiments, inherent soil properties and cropping system affected the outcomes. This is relevant to identifying where California's Healthy Soil Program resources would best be allocated and also highlights that long-term commitment to practices may be necessary to create and maintain increased soil organic matter.

The framework also revealed how ongoing investment in long-term soil health research has largely focused on soils ideal for agriculture. Given that agricultural production often spans more challenging soils (fig. 5), it is a good idea to expand the focus of soil health research, especially since soil health practices may pay greater dividends across these unique regions. CA

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