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Research Article

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Building soil health: Lessons learned from seven field trials on the California Central Coast

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Abstract

California's Healthy Soils Program (HSP) funds demonstration projects to assess and showcase the impact of HSP practices in California agroecosystems. Here, we summarize findings from seven controlled field trials, each 2 to 3 years in length, and assess the potential of various HSP practices to improve soil health and mitigate climate change in California's Central Coast vineyards, orchards, cropland, and rangeland. The effect of compost application on soil health and carbon (C) sequestration varied between trials and was impacted by application rate, compost source, and soil properties. Reducing tillage intensity decreased yield in one of three project years and had limited effects on soil health and C sequestration in dryland forage, while no-till did not affect yield or winegrape quality in a biodynamic vineyard. Cover crops in two lemon orchards also showed few effects, likely due to low biomass production of rainfed cover crops during drought. We emphasize the importance of long-term assessments to quantify HSP practice effects and evaluate potential returns on investment across varying soils, environments, and agroecosystems, especially under climate change.

Since 2016, California's Healthy Soils Program (HSP) has allocated more than $162 million from cap-and-trade proceeds through California Climate Investments to improve soil health and sequester carbon (C). Program funding has supported both grower adoption of practices such as compost application, reduced tillage, and cover cropping, and demonstration projects evaluating these practices in California cropping systems.

By minimizing soil organic carbon (SOC) loss associated with tillage and adding organic C from external inputs and plant biomass grown *in situ*, HSP practices increase soil C storage and help mitigate climate change (Kögel-Knabner et al. 2023). However, soil microorganisms also produce the potent greenhouse gas (GHG) nitrous oxide (N_2O) (Butterbach-Bahl et al. 2013). For practices that affect nitrogen (N) cycling, such as fertilization, tillage, and irrigation, the balance between changes in SOC and N_2O emissions needs to be considered (Verhoeven et al. 2017).

California agriculture faces increasing challenges from climate change, including more frequent and severe drought and rising input costs. In addition to mitigating climate change, HSP practices can improve soil structure, fertility, and microbial activity (Lazcano et al. 2020). Soil health, defined as the soil's ability to provide these services, can help manage extreme weather, drought, fertilizer costs, and disease, all of which are expected to increase with climate change. Therefore, soil health management is a key strategy for both climate change mitigation and adaptation.

While many studies on HSP practices focus on cereal cropping systems in temperate climates (Karlen et al. 2019), California's Mediterranean climate and di-

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verse cropping systems require tailored solutions. To address this, we conducted seven field trials in California's Central Coast region. Here, we highlight lessons learned from these efforts. Note, it is not our intent to provide a comprehensive review of HSP practices or their global impacts, but rather to share region-specific experiences, outcomes, and take-home messages from field trials conducted in California's Central Coast.

Overview of studies

The seven trials included vineyards, rangeland, dryland forage systems, and lemon orchards, with soil health and C sequestration metrics monitored for 2 to 3 years following practice implementation. Sites were selected to represent major agroecosystems, soil types, and eligible HSP practices, with site-specific practices and measurements determined primarily by landowner interest (table 1). Four trials took place on commercial operations and three on the working lands of California Polytechnic State University, San Luis Obispo. Practices evaluated included compost application, reduced tillage, cover cropping, and biological amendments, with vermicompost, vermicompost extract, and mycorrhizal inoculants only eligible for demonstration projects. Site characteristics and measured soil health indicators are summarized in tables 1 and 2. All trials were located in San Luis Obispo County, except for trial 3, which took place in Santa Cruz County.

Compost application: Source, rate, timing, placement, and soil characteristics matter

Compost source

When applying compost, the source, rate, timing, and placement need to be considered. Trial 1 compared dairy manure compost and vermicompost from similar feedstocks in a vineyard. After 2 years of practice adoption, vermicompost treatments showed higher organic matter, C, N, and C:N ratio, but lower pH, phosphorus (P), potassium (K), and sodium (Na) content compared to dairy manure compost under the vine, where compost was applied (Luck 2022). Manure-based compost is a viable alternative to synthetic P and K fertilizers, though excessive P can cause environmental degradation and excessive K can harm soil structure (Pernes-Debuyser and Tessier 2004; Sharpley et al. 1994). Compost chemical composition can vary, so evaluating test reports is recommended. Details on chemical composition of compost used in trials in this study are provided in previously published work (Luck 2022; Wilson et al. 2025; Wong et al. 2023).

Compost rate

Compost effects increased with rate but varied by soil and implementation. In Trial 2 (vineyard), annual compost applications ranged from 0 to 6 dry tons/acre, reflecting typical regional rates. Rates greater than 6 tons/acre raise grower concern for excessive vigor (C. Decock, personal communication with growers). Permanganate oxidizable C (POXC), an early indicator of soil C change (Christy et al. 2023; Hurisso et al. 2016; Woodings and Margenot 2023), increased with compost application rate, suggesting compost may be building soil C, even though total SOC was not detectably changed by the end of the trial (Wong et al. 2023). In Trial 3 (rangeland), a one-time compost application at 0, 10, 20, and 30 dry tons/acre showed significant improvements in soil health (soil C, POXC, water holding capacity [WHC], aggregation) at higher rates and on the older marine terrace with finer soil texture and more pedogenic development, but no effects on the younger terrace with sandier soil (Wilson et al. 2025). This indicates that compost effects depend on soil properties. In Trial 1 (vineyard), which evaluated the effects of diminishing rates over time, compost significantly increased soil organic matter (SOM), nitrate-N, P, and K in the second year (Luck 2022), but these effects disappeared when rates dropped to 1 dry ton/acre, suggesting that 2 dry tons/acre/year is necessary for measurable benefits (C. Decock, unpublished data).

Compost timing and placement

Timing of compost application varies among growers. We chose fall, so winter rains could move surface-applied compost into the soil. Depending on the C:N ratio of the compost, net mineralization or immobilization of N will occur, usually within the first month (Korsaeth et al. 2002). Mineralized N from low C:N ratio compost applied early in the season may contribute to the crop's N requirement (Lloyd et al. 2022).

Compost can be banded or broadcast, then incorporated or left on the surface. In Trial 2, surface applied compost increased POXC to a depth of 2 feet across all application rates in a vineyard under long-term no-till management, suggesting incorporation isn't necessary for deeper soil impacts. Broadcasting in Trial 2 showed effects in both the vine and drive row, while banding had limited effects to under-vine areas in Trial 1. Though roots grow well into the drive row (Smart et al. 2006), impacts of drive row soil health on vine performance are not well understood.

Tillage intensity: Optimize to balance benefits and tradeoffs

Tillage effects on soil health and C sequestration were evaluated in Trials 4 and 5. Trial 4, conducted in a dryland forage field, compared reduced tillage — using a single pass of an OPTIMIZER system (disk blades, reels, chisels, rollers) — to a control involving an average of four passes for seedbed preparation. While reduced tillage showed no significant impact on soil health indicators, it resulted in lower yields in the second of three growing seasons (fig. 1).

Table 1. Overview of seven controlled field trials, including practices or treatments assessed, study duration, crop type, topsoil texture class, and soil health indicators and outcome metrics measured in each study.

Trial ID and reference	Practices/treatments (study duration)	Crop/land use type	Topsoil texture	Measured soil health indicators
Trial 1 (Luck 2022)	Compost, vermicompost, and vermicompost extract vs. control (3 years)	Wine grape	Sandy loam	SOM, TC, soil nutrient content, PLFA, N_2O, CO_2, yield
Trial 2 (Wong et al. 2023)	0, 2, 4, and 6 dry ton compost per acre (2 years)	Wine grape	Sandy loam	TC, POXC, MinC, aggregation, WHC, N_2O, CO_2, leaf tissue nutrient content, yield
Trial 3 (Damaschino 2024; Wilson et al. 2025)	One-time application of 0, 10, 20, and 30 dry ton compost per acre; 2 marine terraces (3 years)	Rangeland	Gravely sandy loam, loam	TC, POXC, MinC, aggregation, N_2O, CO_2, yield
Trial 4 (C. Decock, unpublished data)	Reduced till vs. conventional till; compost vs. no compost (3 years)	Dryland forage	Clay	SOM, TC, MinC, aggregation, Soil nutrient content, PLFA, soil hardness, infiltration, VWC, yield, forage quality
Trial 5 (Lazcano et al. 2022a)	No till vs. conventional till; grazing vs. mowing (2 years)	Wine grape	Clay loam	TC, POXC, MinC, aggregation, WHC, MBC, N_2O, CO_2, yield, grape quality
Trial 6 (C. Decock, unpublished data)	Legume and non-legume cover crop vs. control (2 years)	Lemon	Silty clay loam	TC, POXC, MinC, aggregation, Soil nutrient content, N_2O, CO_2, leaf tissue nutrient content, nematode abundance
Trial 7 (Rodriguez-Paiatsyka et al. 2025)	Cover crop and cover crop inoculated with mycorrhizae vs. control (3 years)	Lemon	Clay	TC, POXC, MinC, aggregation, soil nutrient content, PLFA, NLFA, N_2O, CO_2, leaf tissue nutrient content

All trials were in the California Central Coast region.
CO_2 = carbon dioxide, MBC = microbial biomass carbon, MinC = mineralizable carbon, N_2O = nitrous oxide, NLFA = neutral lipid fatty acid, PLFA = phospholipid fatty acid, POXC = permanganate oxidizable carbon, SOM = soil organic matter, TC = total carbon, VWC = volumetric water content, WHC = water holding capacity.

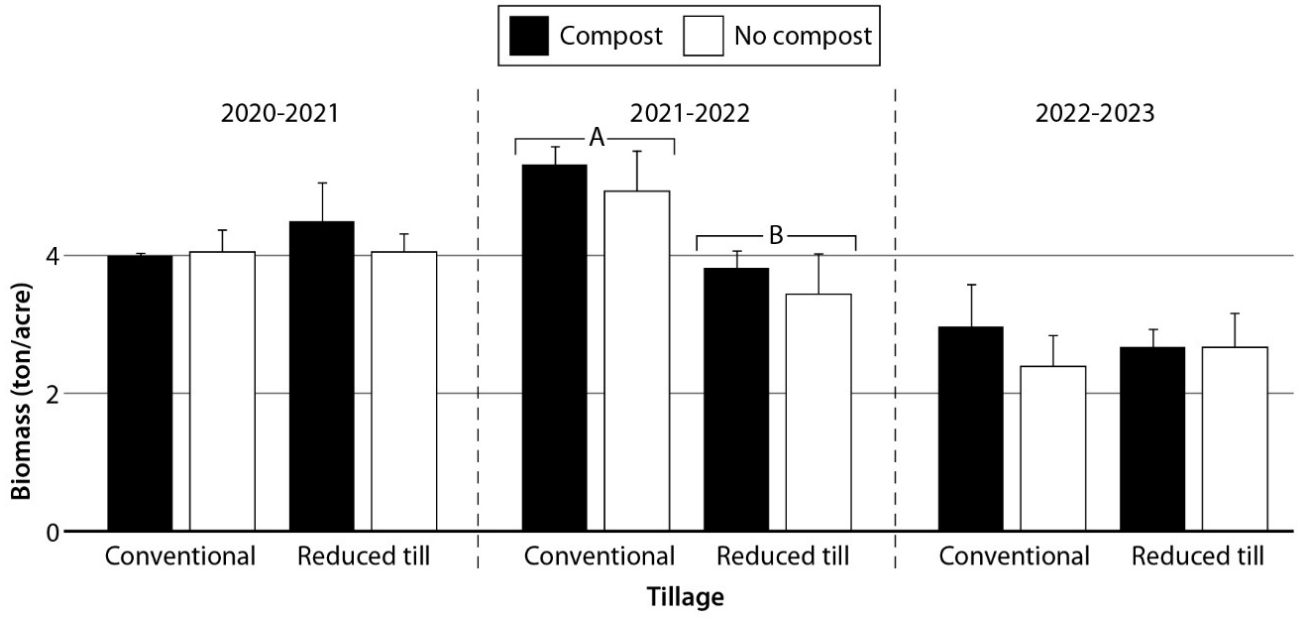


Fig. 1. Biomass production (ton dry mass/acre) in the 2020–2021, 2021–2022, and 2022–2023 season at Trial 4 (dryland forage). Different uppercase letters indicate significant differences between tillage treatments ($P < 0.05$).

Table 2. Soil health indicators and outcome metrics, including measurement method and interpretation.

	Abbreviation	Indicator/metric	Measurement method	Interpretation
Chemical	SOM	Soil organic matter	Loss on ignition	Stores C and nutrients, supports soil structure and soil biota
	Soil nutrient content	Macronutrients, micronutrients	Standard procedures for western regions	Available plant nutrients to guide nutrient management
Biological	POXC	Permanganate oxidizable carbon	Reaction with potassium permanganate	Management sensitive carbon fraction that may be an indicator of plant-mediated soil processes
	MinC	Mineralizable carbon	Burst of CO_2 upon rewetting	Microbial activity or soil respiration
	MBC	Microbial biomass carbon	Fumigation-extraction	Abundance of soil microorganisms
	PLFA	Phospholipid fatty acids	Extraction with solvents, quantification by gas chromatography	Biomarker for abundance and diversity of soil microbial groups
	NLFA	Neutral lipid fatty acids	Extraction with solvents, quantification by gas chromatography	Biomarker for abundance of arbuscular mycorrhizal fungi
	Nematode abundance	Abundance of functional feeding groups of soil nematodes	Baermann funnel extraction and microscopy	Abundance and functional capacity of beneficial soil nematodes
Physical	Aggregation	Aggregate size distribution	Wet sieving	Measure of soil structure. Aggregates also help stabilize soil carbon
	VWC	Volumetric water content	Soil moisture probe	The amount of water measured in the soil at sampling, by volume
	WHC	Water holding capacity	Soil moisture retention curve	The amount of water soil can hold against gravitational force, by mass
	—	Soil hardness	Penetrometer	Reflects the ease or difficulty for roots to penetrate the soil
	—	Infiltration	Minidisk infiltrometer	Good infiltration reduces runoff and erosion and can increase water availability to the plant
Plant health	—	Leaf tissue nutrient content	Nitric acid digestion and elemental analysis	Indicates nutrient deficiencies experienced during plant growth
	—	Yield	Varies by crop; representative of grower harvest method	Reflects plant productivity and economic value
	—	Crop quality	Winegrapes: anthocyanins and phenolics; forage: standard feed analysis	Reflects value of the crop
GHG budget	TC	Total C	Dry combustion	Includes organic carbon and inorganic carbon (carbonates). Both contribute to C sequestration
	N_2O	Nitrous oxide emissions	Static flux chambers, analysis on gas chromatograph	Potent greenhouse gas predominately emitted from soil. Management-induced emission reductions are warranted
	CO_2	Carbon dioxide emissions	Static flux chambers, analysis on gas chromatograph	Reflects microbial activity and the loss of C from soil through respiration. To build soil C, cumulative annual CO_2 emissions should be less than net C inputs.

Not all indicators and metrics are measured in all studies (see table 1).

Trial 5, in a biodynamic vineyard, compared no-till to the grower's practice of biannual tillage using a three-point offset disk. No-till had no significant effect on grape yield or quality (Lazcano et al. 2022a), but it slightly reduced CO_2 fluxes during the rainy season, especially in year 1, suggesting reduced carbon loss if carbon inputs were comparable between treatments. Although total soil C stocks remained unchanged, no-till increased POXC stratification, with higher concentrations in the topsoil.

The yield impacts of reduced or no-till practices vary across crops and regions, ranging from penalties to neutral or positive effects (Allam et al. 2021; Pittelkow et al. 2015). However, potential savings in labor and fuel costs may offset yield declines (Kim et al. 2006). Given the variability in tillage responses, optimizing practices often requires multiple trial iterations tailored to specific crop systems and environments (Mitchell et al. 2016; 2009). While this study observed minimal benefits of reduced or no-till to soil health and C sequestration within the first 2 to 3 years of practice adoption, long-term no-till adoption has shown positive outcomes in tomato-cotton rotations in California's San Joaquin Valley (Mitchell et al. 2024).

Cover cropping: Species selection, growing conditions, and termination strategy interact

Trials 6 and 7 assessed the effects of cover crops in lemon orchards. Both trials compared the grower practice (control with no cover crop) with a triticale cover crop planted in the alley rows. Trial 6 also included a cereal-legume mix panted in the alley rows. No cover crops were planted under or around the trees. In Trial 6, alley rows were kept weed-free with the use of herbicides in the control treatment, while in Trial 7, resident vegetation — primarily *Malva* spp. — was allowed to grow in the control alley rows (Rodriguez-Paiatsyka et al. 2025).

Over 2 years, cover crops had no significant effects on tree nutrition, soil C, N_2O emissions, abundance of specific nematode feeding groups, or other measured soil health parameters (figs. 2 and 3, table 3, and unpublished data). These limited impacts may reflect low biomass from drought, poor legume germination (likely from soil compaction, mulch interference, and moisture stress), and the short duration of the trial. Additionally, weeds in the Trial 7 control treatment may have masked cover crop benefits, as some studies suggest that weeds can deliver similar ecosystem services (Yvoz et al. 2021).

Impacts of cover crops on C sequestration and soil health are known to depend on species selection, productivity, growing season, and termination strategy (McClelland et al. 2021; Moukanni et al. 2022; Wauters et al. 2023). Cereal-legume mixes offer multiple benefits: legumes fix atmospheric nitrogen and, when combined with cereals, promote C sequestration through greater biomass production and enhanced microbial C efficiency (Moukanni et al. 2022). However, legumes may also increase N_2O emissions (Basche et al. 2014). In addition, our data and a small side experiment (C. Decock, unpublished data) suggest triticale is more drought tolerant and better suited to compacted or poorly prepared soils than legumes.

Cover crops can be terminated using herbicides, by mowing, rolling/crimping, or grazing, each with or without tillage. Trial 5 compared mowing to sheep grazing in a vineyard. While grazing did not alter POXC or plant-available N, the combination of grazing and tillage led to higher soil nitrate levels and occasional increases in daily N_2O fluxes, which emphasizes the need to align termination strategies with management goals.

A concern in perennial systems is the potential competition for nutrients and water. In our lemon orchard trials, cover crops had no significant effect on soil or leaf nutrient concentrations, and most nutrients remained within acceptable ranges for citrus. Some studies suggest cover crops can enhance exchangeable cations and micronutrients via chelation and pH reduction (Demir et al. 2019; Sharma et al. 2018), but long-term effects in Central Coast citrus systems remain unclear. Water dynamics were not monitored in our trials. However, recent work shows that winter cover crops have minimal impact on soil moisture and evapotranspiration in California specialty crops (DeVincentis et al. 2022).

Although HSP practices showed limited short-term effects, consistent differences in soil health indicators between tree/vine and alley rows point to strong legacy effects of long-term management. In vineyard Trials 1 and 2, where compost was the primary treatment and cover cropping was well established, greater soil health in alley rows likely reflects cumulative vineyard floor management (Luck 2022; Wong et al. 2023). Similarly, in the lemon orchards, higher soil health in alley rows (fig. 3), including greater populations of predominantly beneficial nematodes and greater microbial biomass (Trial 7; Rodriguez-Paiatsyka et al. 2025), may be attributed to a long history of mulch application. These results underscore the importance of long-term practice adoption and the need to account for spatial variability in sampling design to accurately assess soil health outcomes.

Biologicals: A complicated market

Biological products are increasingly promoted as soil health management tools. Agricultural biologicals encompass a diverse range of products with varying modes of action, which makes broad conclusions about their effects on soil health challenging (Abbott et al. 2018). In this study, we evaluated two biological products: arbuscular mycorrhizal fungi (AMF) inoculum and vermicompost extract.

In Trial 7 (lemon orchard), we inoculated a cover crop with AMF to facilitate colonization and applied AMF for 3 years, but did not observe impacts on bio-

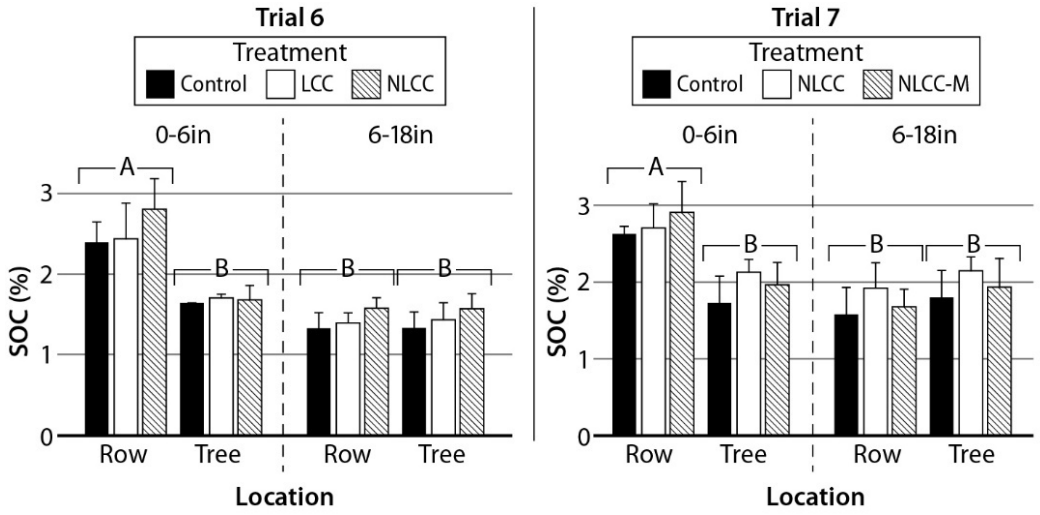


Fig. 2. Soil organic carbon (SOC, %) concentrations at the lemon orchards in the middle of the row and under the tree in the 0- to 6-inch and 6- to 18-inch depth increments for the control, cereal-legume cover crop mix (LCC), non-legume cover crop (NLCC), and non-legume cover crop inoculated with mycorrhizae (NLCC-M) treatments (left, Trial 6; right, Trial 7) 2 years post treatment establishment. Error bars represent standard errors (n = 3). Different uppercase letters indicate significant differences between depths and locations (P < 0.05).

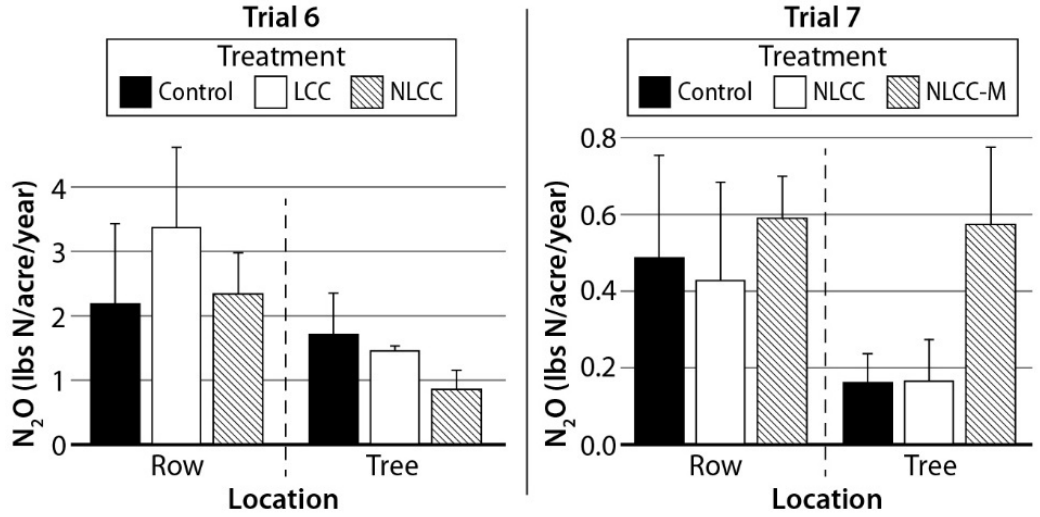


Fig. 3. Cumulative N_2O (kg N_2O-N ha^{-1} yr^{-1}) emissions at the lemon orchard trials (left, Trial 6; right, Trial 7) in year 1. Errors indicate standard errors (n = 3). There were no significant effects of location or treatment on cumulative N_2O emissions (P > 0.05). Note the difference in magnitude on the y-axis. Cumulative N_2O emissions are greater in Trial 6, where microjet sprinklers were used for irrigation, compared to Trial 7, in which drip irrigation was used.

markers for AMF abundance, cover crop growth, C sequestration, or plant nutrition (Rodriguez-Paiatsyka et al. 2025). Research showing positive AMF effects often involves controlled environments or assesses native AMF, not inoculation (Chen et al. 2018; Jeewani et al. 2021). In this field setting, high native AMF populations may have outcompeted the introduced strain. More research is needed to determine under what conditions AMF inoculation is effective.

In Trial 1, we evaluated the impact of vermicompost extract on C sequestration and soil health in an organically managed vineyard. No fertilizers or soil amendments were applied to the control treatment during the trial period. Applied through irrigation for 3 years, vermicompost extract showed no effects on GHG emissions, SOM, nutrient levels, or microbial community composition during the first two years (Luck 2022). In the third year, the vermicompost extract treatment showed a more uniform nitrogen and microbial distribution between the topsoil and subsoil, whereas these differed notably in the control (C. Decock, unpublished data). This suggests vermicompost extract may distribute microorganisms and nutrients more evenly within the root zone, though its impact on vine health remains uncertain.

Table 3. Abundance of soil nematode functional feeding groups in alleys and under trees in Trial 6 (lemon orchard) for the leguminous cover crops (LCC), non-leguminous cover crops (NLCC), and control treatments (n = 36).

Comparison	Bacterivores	Fungivores	Phytophagous	Omnivores	Predators
Treatment					
Control	28.21 ± 8.47	26.37 ± 12.61	28.52 ± 8.92	0.92 ± 0.66	1.16 ± 0.53
LCC	38.67 ± 19.26	9.19 ± 3.66	14.45 ± 5.17	0.91 ± 0.56	0.83 ± 0.56
NLCC	65.33 ± 25.10	16.42 ± 6.29	27.84 ± 11.30	1.08 ± 0.54	1.42 ± 1.29
Location					
Alley	78.69 ± 18.22 a	31.97 ± 8.35 a	37.39 ± 7.62 a	1.78 ± 0.60 a	0.88 ± 0.47
Under tree	9.44 ± 4.27 b	2.68 ± 1.56 b	9.82 ± 5.04 b	0.16 ± 0.11 b	1.40 ± 0.87

Mean nematode abundance (number of individuals per gram dry soil) ± standard errors are given. Lowercase letters indicate significant differences (P < 0.05).

Stacking practices

Most knowledge on soil health management comes from long-term trials that focused on single practices; such trials do not reflect the complexity of commercial crop production, where multiple practices are often combined in response to economic and environmental pressures (Ellis and Paustian 2024). Few studies assess the synergistic or antagonistic effects of stacked practices. In Trial 4, compost application in a dryland forage field increased P and K concentrations, but there was no added benefit from reduced tillage (fig. 1, unpublished data). In Trial 5, vineyard grazing increased N_2O fluxes under conventional tillage, but no-till mitigated this effect (Lazcano et al. 2022b). These findings highlight the need for more research into impacts of stacked practices, with a focus on optimizing resource use to align with diverse grower goals.

Implications and knowledge gaps

Overall, the results from seven controlled field trials show that short-term impacts on soil health were limited. On the other hand, where measured, no increases in N_2O emissions were detected, which highlights the practices' lack of environmental tradeoffs in the short term. Compost impacts varied by source, rate, timing, and soil properties, while cover crop impacts depended on species, management, and termination. Stacking practices did not consistently improve soil health and may have synergistic or antagonistic effects.

Our findings highlight the need for a systems-based approach tailored to crop, region, and grower needs. Crucially, improving soil health requires a long-term commitment, supported by long-term trials that assess benefits, tradeoffs, and return on investment, especially in the context of climate change.

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