The Positive Influence of Compost and Cover Crops on Key Soil Health Indicators in Nut Orchards

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Abstract

Sustainable management practices in nut orchards are crucial for enhancing soil health and minimizing environmental impacts associated with conventional production. Over three years, this study evaluated the effects of stacked soil health practices in five nut orchards (almonds and walnuts) in California. Experimental plots received annual applications of 19 Mg/ha of yard waste and manure compost, along with cover crops at a rate of 13.8 kg/ha, while conventionally managed plots served as controls. Compost and cover crops significantly improved all soil health indicators by year three. Microbial biomass carbon (MBC) increased significantly by 573 ± 98% in alleys and 307 ± 100% in berms, while microbial biomass nitrogen (MBN) showed significant increases of 487 ± 95% in alleys and 55 ± 14% in berms. Permanganate oxidizable carbon (POXC) rose significantly by 133 ± 23%. Short-term carbon mineralization rates were 70 ± 5% higher, reflecting enhanced soil biological activity likely from increased POXC. Cation Exchange Capacity (CEC) significantly increased by 25.7 ± 14.5% in alleys and 48 ± 16.9% in berms. Soil extractable ammonium (NH_4^+) levels increased rapidly following compost application, remaining significantly elevated for five months before aligning with control plots, whereas soil extractable nitrate (NO^3-) levels did not significantly change. By the end of the study, the average percent increase in soil organic carbon (SOC) storage with the stacked practices was 102 ± 21%, resulting in an average SOC content of 60.7 Mg C ha^{-1} across sites. The pH in compost + cover crops plots decreased slightly from 7.1 in 2021 to 6.8 in 2024, with an average change of -0.3 ± 0.3. Electrical conductivity (EC) increased significantly with an average rise of 445.3 ± 311.2 µS/cm. Improvements in wet aggregate stability were also significantly improved, with large macroaggregates increasing by 2.1 ± 0.5%, medium macroaggregates by 1.3 ± 0.2%, and small macroaggregates by 8.4 ± 2%. These findings underscore the critical role of compost and cover crops in enhancing soil health within conventional nut orchard management, independently from site factors such as soil type and management. The increase in SOC storage highlights the potential of orchard soils to serve as a significant carbon sink while supporting agricultural sustainability and resilience to climate change.

Key Finding:

1. Soil health in degraded conventional orchard soils can be rapidly improved through the combined application of compost and cover crops.
2. By the third year, soil carbon storage showed significant enhancement, positioning these sites as valuable targets for climate mitigation efforts through carbon sequestration.
3. The addition of organic matter effectively stimulated microbial processes within these systems, promoting increased nutrient cycling rates and greater availability of plant available nitrogen.

Introduction

Ecological-based management of nut orchard systems can play a key role in supporting ecosystem services and climate mitigation (Fenster et al., 2021; Timberlake et al., 2022; Weier et al., 2024). Environmental concerns related to conventional nut orchard production include water use, hazardous pesticides and herbicides, soil compaction, and nitrate leaching to groundwater (Baram et al., 2016;

Fulton et al., 2019; Zhan & Zhang, 2014). Since soil health is crucial for supporting ecosystem services that benefit both human and ecological systems, there is an increasing need to quantify the effects of integrated soil health practices. Compost application and the planting of cover crops has been identified as practices with individual and synergistic benefits to soil health. The application of compost provides essential nutrients and organic matter, increasing stable aggregates and water-holding capacity, while cover crops reduce soil erosion, decrease compaction, and provide additional nutrients through biological nitrogen fixation (Hodson et al., 2021; Repullo-Ruibérriz de Torres et al., 2021). Both of these practices independently have been documented to enhance the biological, chemical, and physical components of soil health in orchards (Kutos et al., 2023; Scavo et al., 2022). However, more research is needed to assess the effectiveness of these applications when integrated as "stacked" practices, along with the continued use of chemical fertilizers and irrigation, in nut orchard systems.

Compost, made from organic materials such as food waste, yard waste, and livestock manure, is a nutrient-rich soil amendment. It contains essential macronutrients, micronutrients, and organic matter all of which are crucial for plant growth and the provisioning of soil services (Ho et al., 2022). In many agricultural ecosystems, compost increases water-holding capacity and enhances soil structure, resulting in improved root growth, nutrient uptake, reduced soil erosion, and better soil moisture retention, which is particularly important in California's dry climate (Goldan et al., 2023; Ho et al., 2022). Compost also boosts biological activity, as the organic matter component serves as an energy source for soil microorganisms, fostering a diverse and active microbiome (Lazcano et al., 2022). This microbial life is essential for nutrient cycling, breaking down organic matter into forms that plants can readily absorb, thus enhancing soil fertility (Gougoulias et al., 2014). The increased biological activity also contributes to disease and pest suppression and promotes a healthy soil food web, supporting beneficial organisms that further improve soil structure and plant health (M. W. Brown & Tworkoski, 2004; van Bruggen & Semenov, 2000). Additionally, compost has been documented to increase C sequestration, thereby aiding in climate mitigation(Just et al., 2023; Kutos et al., 2023; Wang et al., 2022). This is especially important in perennial agricultural systems, as orchards are often grown for over 20 years, extending the time between major soil disturbances which release large quantities of CO_2 (Cai & Chang, 2020). Almond and walnut soils in this region exhibit relatively low soil C stocks, averaging 36 ± 0.9 Mg C · ha^{-1} in the 0-30 cm depth (Cooper et al., In review). The observed low soil C stocks in these orchards present an opportunity for enhanced C storage through soil health management practices such as compost and (Demestihas et al., 2017).

Cover crops, grown between tree rows, provide benefits such as soil erosion control, nutrient cycling, aeration, and weed suppression (Bechara et al., 2018; Haring & Hanson, 2022; Koudahe et al., 2022). Incorporating ground cover and minimizing soil disturbances in permanent crop systems such as orchards can increase microbial biomass, which is essential for forming stable, chemically diverse soil organic C and improving soil health (Ingels et al., 2005; Steenwerth & Belina, 2008; Vukicevich et al., 2019; Whitelaw-Weckert et al., 2007; Bastida et al., 2021; McClelland et al., 2021). Some cover crop species can also fix atmospheric nitrogen, into plant-available forms and provide inputs of organic matter via root turnover (Ordóñez-Fernández et al., 2018; Repullo-Ruibérriz de Torres et al., 2021). In orchards, cover crops can be used for pollinator habitat while addressing soil issues like compaction and low infiltration (Mallinger et al., 2019).

Almonds (*Prunus dulcis*) and walnuts (*Juglans regia)* are the two most common and lucrative nut orchard systems in California, where approximately 80% of the world's almonds and 75% of the world's walnuts are produced (CDFA, 2022). Almond orchards account for the majority of land use in California nut orchards, covering 555,633 bearing hectares (ha) and producing 1.27 T of almonds, resulting in the highest-grossing crop at $3.5 billion per year (California Almond Board, 2020; CDFA, 2023). Walnuts cover 155,800 ha of bearing land, producing 635,029 T and grossing about $473 million per year (CDFA, 2023). While most research is highly focused on almonds, it is crucial to test regenerative practices on other common nut crops in California, as these practices are beneficial across crop types (Lazcano et al., 2022; Scavo et al., 2022). Especially since nut orchards, comprising of almonds, walnuts, and pistachios, comprise over 1 million hectares across California. These lands offer a huge potential for improve soil health with the co-benefits of carbon storage via carbon sequestration, helping California to achieve it's climate mitigation goals.

Almond production in California has grown rapidly over the past two decades. This growth has been accompanied by a corresponding increase in the use of chemical fertilizers to provide essential nutrients such as nitrogen, phosphorus (P), and potassium (K) (CDFA Ag Stats, 2022). The most critical of these nutrients is nitrogen, as it plays a crucial role in tree health and productivity. Nitrogen deficiencies can lead to inadequate protein synthesis and reduced photosynthetic capacity, resulting in decreased growth and nut yield (Zayed et al., 2023). Conversely, excess nitrogen can cause dense vegetative growth at the expense of reproductive development, making trees more susceptible to pests and diseases (Sperling et al., 2019). Beyond the orchard, excessive application rates of nitrogen can also lead to nitrate (NO_3^-) contamination of groundwater and surface water, leading to water pollution and adversely affecting drinking water quality (Haynes, 2022). Additionally, NO_3^- pollution can lead to environmental concerns such as the eutrophication of lakes and rivers (Bijay-Singh & Craswell, 2021; Smolders et al., 2010), and contributes to nitrous oxide, a potent greenhouse gas (Liu et al., 2023). Tighter nitrogen cycling within the soil-plant system is essential to maintaining a balance that supports tree health and production while minimizing the ecological impacts of excess reactive nitrogen in the environment (Tully & Ryals, 2017).

Under conventional management, biological and physical soil health indicators are typically negatively impacted by the continuous use of chemical fertilizers, as well as the ground floor management that removes or prevents vegetation and compacts soil. A key issue is that when one or more of the soil health conditions are lacking, a "leaky" nitrogen cycle can occur, where excessive reactive nitrogen is often lost in gaseous and aquatic forms (Fowler et al., 2013). To mitigate nitrogen losses in orchard agroecosystems, various management practices have been suggested, such as the addition compost and cover crops to the current fertilizer management protocols(Castellano-Hinojosa et al., 2023; Lawrence & Melgar, 2023). Cover cropping can reduce NO_3^- leaching by minimizing soil erosion, nutrient runoff, and enhancing soil organic matter content, thereby improving water-holding capacity and reducing leaching (Ordóñez-Fernández et al., 2018). Slow-release fertilizers like compost can regulate NO_3^- leaching due to their biochemical characteristics (Hepperly et al., 2009; Kramer et al., 2006; Xu et al., 2020). These practices can enhance nitrogen cycling while buffering trees against nitrogen-related stress (Drinkwater & Snapp, 2007).

This study investigates the combined effects of compost and cover crops on soil health indices in five commercial orchards in California, comprising four almond orchards and one walnut orchard, over four growing seasons (Figure 1). We hypothesize that the addition of compost and cover crops will improve the biological, chemical, and physical properties of soil health across these orchards, regardless of soil type or prior management practices.

Given the highly degraded state of soil organic carbon at the start of the study, we expect that organic matter inputs from compost and cover crops will rejuvenate the soil system and enhance soil carbon storage. Furthermore, we propose that integrating these practices will optimize the soil nitrogen cycle by enhancing key processes such as nutrient cycling, organic matter decomposition, and soil structure formation. This integration is also expected to foster a more favorable soil environment for microbial activity, regulate soil pH, and ultimately improve the overall functionality and health of these highly productive perennial agroecosystems.

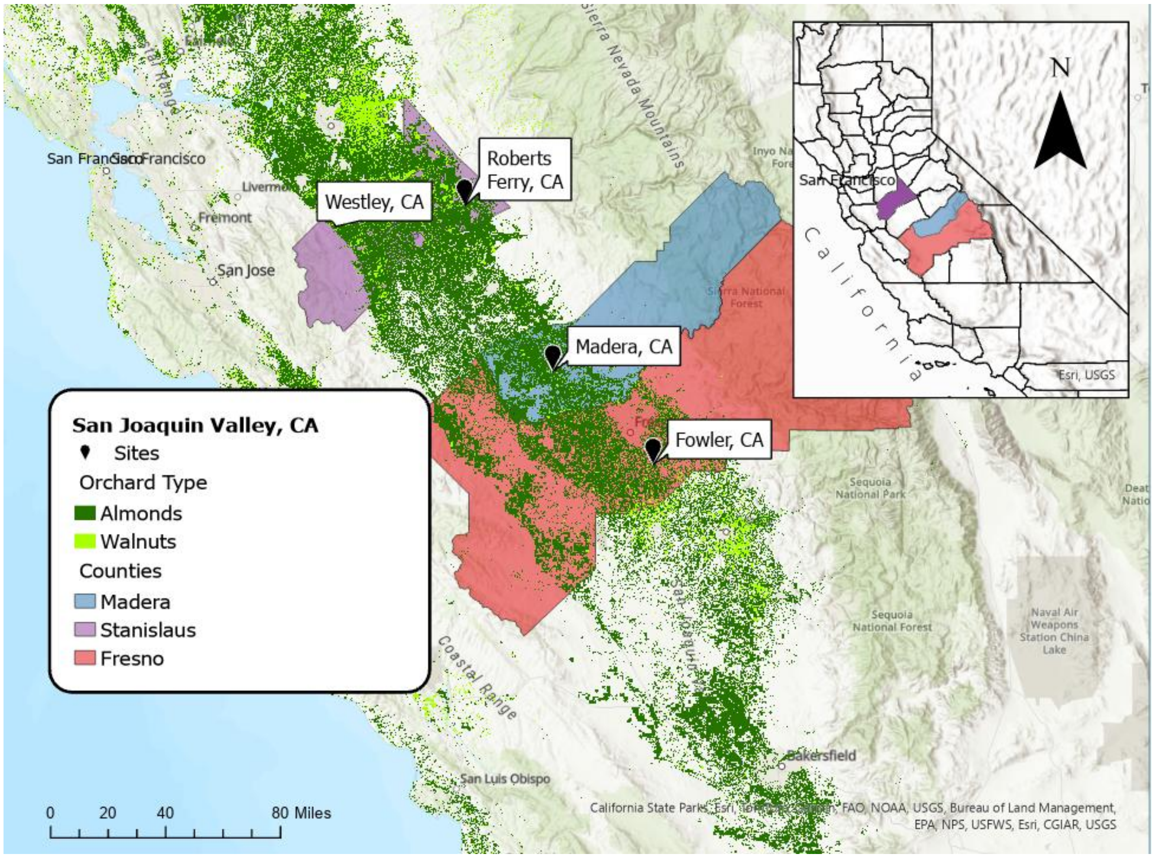


Figure 1. Map of site locations, with overlay of current acreage of walnut and almonds along the Central Valley.

Materials and Methods

Study Sites

To investigate the effects of annual compost application and cover crop seeding to soil health indicators, a four-year study was conducted in four almond and one walnut orchards along California's San Joaquin Valley (Figure 2), hereafter referred to as “Almond 1”, “Almond 2”, “Almond 3”, “Almond 4”, and “Walnut”. The San Joaquin Valley, historically the ancestral homeland of the Tejon, Kitanemuk, Yokuts, and Chamash indigenous peoples of California, is situated south of the Sacramento-San Joaquin River Delta and is drained by the San Joaquin River.

Table 1. Site information for the orchards within our study from 2021 to 2024 in the Central Valley of California.

Location	Site	Soil Order	Soil Series	Soil Texture	Variety	Age	Management	Irrigation
Westley, CA	Almond 1	Inceptisol	Zacharias	Fine-loam	Nonpareil & Monteray	6	Conventional	Drip
Westley, CA	Almond 2	Inceptisol	Zacharias	Fine-loam	Nonpareil & Monteray	6	Conventional	Drip
Madera, CA	Almond 3	Mollisols	Visalia	Fine Sandy-loam	Nonpareil & Monteray	12	Conventional	Micro-sprinkler
Roberts Ferry, CA	Almond 4	Entisol	Hanford	Coarse-loam	Nonpareil & Monteray	15	Organic	Micro-sprinkler
Fowler, CA	Walnuts	Entisol	Hanford	Coarse-loam	Chandler & Serr	15	Conventional	Flood

The San Joaquin Valley has a Mediterranean climate characterized by cool, wet winters and hot, dry summers. Mean annual temperatures in this region are approximately 16-14°C. The mean high temperature reaches approximately 30°C, while the mean low temperature is around 12°C (NOAA, 2021). Mean annual precipitation is 13 – 25 cm, with most precipitation occurring between November and April, with typically no rainfall during the summer dry months.

Experimental Design

A replicated field design was employed, with two large plots (approximately 5 ha) established at each of the five orchard sites to represent conventional and compost + cover crop management practices. Within each plot, three replicate transects were designated, and three trees were tagged for sampling within each transect. To account for spatial variability, two sampling locations were selected adjacent to each of the three trees within each replicate: one in the alleyway and one on the berm. The “stacked” soil health management consisted of three annual applications of compost and cover crops. Both conventional and treatment plots were managed the same within each site regarding foliar spray, pesticides, fungicides, irrigation, and in-line fertigation.

Cover crops were seeded in the alleys in November of 2021 2022, and 2023 at a rate of 13.8 kg/ha. A seed drill was used for the planting of the cover crops across the sites, and drilled the seeds to a max depth of 3 cm. The cover crop mix selected was soil building mix sourced from Project *Apis m.* This mix contains 30% Triticale (x Triticosecale), 35% Bell Beans, (*Vicia faba*), 28% Peas (*Pisum sativum* or *P. arvense*), 5% Diakon Radish (*Raphanus sativus*), 1% Canola (Brassica rapa), and 1% Common Yellow Mustard (*Sinapis alba*). The mix contains brassicas, legumes, and grains to address soil issues such as compaction and erosion, while fixing nitrogen and providing weed suppression. This mix also delivers a late source of nectar for pollinators. Weeds and cover crops were mowed within the months of March and April and again August prior to harvest. No additional water was used to aid in the germination of the cover crops.

An organic-rich compost made from feedstocks of manure and green waste (AllGro® by Synagro, CA, USA) was applied as a surface dressing across berms and alleys at a rate of 19 Mg/ha on a dry weight basis in March of 2022, May of 2023, and April of 2024. Compost timing was dependent on weather and compost availability. One site, Almond 3, delayed compost additions in 2023, and 2024 to November, due to harvest timing. Compost was applied to the alleys and the berms evenly, using a compost/manure spreader. The compost had an average organic C content of 27 ± 1%, and a total organic nitrogen content of 3.3 ± 0.05 % (C:N ratio of 8:1) with a pH of 7.7, and a bulk density of 2.8 g/cm^2. The amendment of compost added approximately 5.13 Mg C/ha, and 0.5 Mg nitrogen/ha to the soils in each application.

Soils were sampled to 0-10 and 10-30 cm depths to capture the zone of root activity in orchards. A suite of biological, chemical, and physical soil health indicators was measured prior to treatment application and for three years following treatment application. The frequency of sampling varied by indictor type from daily (e.g. soil volumetric water content) to monthly (e.g. soil inorganic nitrogen) to annually (e.g. soil carbon) depending on the temporal variability and projected rate of change of each indicator.

Soil compositing entailed subsampling 35 g from each replicate at the 0-10 cm depth, generating a composite sample (~100 g) for every replicate transect. Including the alley and berm locations for both control and treatment plots at each site (n=6). The composited samples underwent analysis for soil pH and EC, water holding capacity, microbial respiration, permanganate oxidizable carbon (POXC), and wet aggregate stability. Soil C and nitrogen samples were not composited, and analyses were run on the full replication across sites.

Soil moisture and physical soil properties

Soil probes (Drill & Drop, TriScan SDI-12, Sentek, SA, AUS) were installed within each replicate of the plots. These drill-and-drop probes, which utilize capacitance-based technology and site-specific calibrations, were installed and maintained by the agriculture management company SEMIOS (Modesto, CA). The sensors were buried to a depth of 1 meter and measured soil moisture, salinity, and temperature every 10 cm along the depth profile. Readings for these measurements were collected every 5 minutes and averaged to provide daily mean, minimum, maximum, and standard error for each sensor.

Soil texture was determined at each plot via the hydrometer method (Gee & Bauder, 1986) prior to treatment application. Briefly, for each depth increment, 40 g of air-dried 2 mm sieved soil was mixed with 100 mL of sodium hexametaphosphate solution, let sit for 10 minutes, then mixed with an electric mixer for 5 minutes, then added to a glass sedimentation cylinder and brought to up a total volume of 1,000 mL. At the 30 second, 1 minute, 90 minutes, and 24-hour mark, a hydrometer was used to measure the density of the liquid, and the corresponding liquid temperature was recorded. Afterwards, the measurements were then used to calculate the fractions of sand, silt, and clay via equations that were corrected for temperature.

Chemical Soil Health Indicators

Soil pH and electrical conductivity were analyzed prior to treatment and annually for three years of treatment. A 10 ± 0.1 g sieved soil g of soil was mixed with 20 ml of deionized water and then placed on an orbital shaker for 30 min. The soil slurry dilutions (1:2) were let to equilibrate uncapped for 10 minutes, then a calibrated pH meter (Mettler Toledo SS20, OH, USA) and EC meter (Mettler Toledo SS30, OH, USA) were used to measure pH and EC.

Cation exchange capacity (CEC) was analyzed on a subset of samples of alley and berm for sites all years. Soil samples were air-dried, sieved to 2 mm, and analyzed for CEC using the barium chloride method (Rible et al., 1960) at the University of California, Davis Analytical Lab Four deionized water rinses are used to remove excess barium. A known quantity of calcium is then exchanged for barium and excess solution calcium is measured. CEC is determined by the difference in the quantity of the calcium added and the amount found in the resulting solution. The method has a detection limit of approximately 2.0 cmol kg^{-1}.

All samples, and all depths, were analyzed for soil total C and nitrogen. Soil samples were air-dried, sieved at 2 mm, and pulverized by hand with a mortar and pestle. Carbonate presence was based on effervesce after addition of 4 nitrogen HCl to soil. No sites exhibited a response to the test for carbonates, thus all soil C data presented here consist solely of organic C. Soil C and nitrogen concentrations were measured on an Elemental Analyzer (ECS 4010 CHNS-O, Costech, CA, USA) coupled to a continuous flow isotope ratio mass spectrometer (Delta-V Plus, Thermo Fischer Scientific, CA, USA) at the Stable Isotope Ecosystem Laboratory of University of California, Merced.

Soil C content was calculated using the equivalent soil mass method (ESM). The ESM method uses soil mass, volume, and the percent soil C and then uses a cubic spline of reference mass layers that is site-specific (Wendt & Hauser, 2013). The ESM method uses soil mass, and volume, and soil C concentration and then uses a cubic spline of reference mass layers that was site specific (Wendt & Hauser, 2013). To calculate soil C content, we used an R script developed by Von Haden et al. (2020). Soil C and nitrogen contents were calculated independently by berm and alley locations. Cumulative soil C and nitrogen content by site was calculated using an area-weighted approach to account for the unequal land coverage of the berms and alleys. As berms account for approximately one-quarter of the area with an orchard, and alleys the remaining three quarters, the soil C storage measured at each location was multiplied by each fraction of coverage and then summed to get a more accurate account of soil C storage in the orchards.

The potentially available ammonium (NH_4+) and nitrate (NO_3-) in the top 0-10cm of soil was assessed monthly in each replicate of control and treatment plots at all sites, except for Almond 4, from January 2022 to August 2024. 20 g of fresh sieved soil samples were weighed, shaken in 75 ml of 2 M potassium chloride (KCl) for 1 h, and filtered through Whatman 1 filter papers. Filtrate was analyzed for NO_3^- and NH_4^+ by microplate-colorimetric techniques using the vanadium-chloride method and salicylate-nitroprusside method, respectively (Mulvaney et al., 1996). The absorbance was read at 540 nm for NO_3^- and 650 nm for NH_4^+ on a microplate reader (BioTek Gen5 Microplate Reader, Agilent Technologies, CA, USA), then corrected to concentration from the standard curve equation.

Biological Soil Health Indicators

To assess microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) content, analyses were conducted on berm and alley locations within three out of nine replicates in both control and treatment plots within the 0-10 cm depth range, which represents the primary zone for microbial activity. Soil samples were taken each year in January, and extracted within 24 h of sampling using the chloroform fumigation method (Vance et al., 1987). Extractants were stored at -4 °C until ready for analysis. The thawed extractant was diluted to a ratio of 4:1 sample to deionized water. Soils were run with blanks and standards on a total organic carbon analyzer (TOC-L) (Shimadzu Scientific, Japan) in the Environmental Analytical Lab at the University of California, Merced. MBC and MBN were corrected with a standard curve of known concentrations for total nitrogen and total organic C. We used an extraction efficiency factor of (keC) of 0.45 for MBC and 0.55 for MBN (keN) (Beck et al., 1997).

Permanganate Oxidizable C *(POXC)* was analyzed on the composited samples once prior to treatment, and yearly for three years. We used the method described by (Weil et al., 2023). Briefly, 2.5 ± 0.01 g air-dried sieved soil was added to 20 mL of 0.2 M potassium permanganate ($KMnO_4$) and deionized water and then were shaken for 2 minutes then let settled for 10 minutes. After settling, 0.5 mL of supernatant was transferred from the centrifuge tube, diluted with 49.5 mL of deionized water, and then 200 µL of the supernatant was read on a microplate reader at 550 nm (Agilent BioTek Gen5 Microplate Reader, Agilent Technologies, Santa Clara, CA, USA) . Sample absorbance was then corrected with known concentrations of $KMnO_{4,}$ and included the milligrams of C oxidized by 1 mole of MnO_4 (9,000 mg C/mol) and reported as mg $KMnO_4$ reduced per kg soil.

Short-term C mineralization of soils was measured on composited soil samples prior to treatment and the three years following. A Picarro multi-gas analyzer and Soil Flux Processor (G2508, Picarro, CA, USA) was used to measure the flux of microbial respiration after a wetting event for 4 days. For the lab study, 30 g air dried, sieved soil were placed into half-pint jars, with specialized chamber lids. The chamber lid is fitted with two 1/4" tube fittings (Swagelok, Solon, OH) each connected to an inlet or outlet 1/4" tube with sample air flowing at a rate of 275 ml min^{-1}. Briefly, the baseline was determined on the dry fluxes that were measured the day 0 of the study. The next day deionized water was added to achieve 60% water holding capacity (WHC). The maximum WHC of each soil was determined prior to the study for each site by calculating the volume of water retained after 1h (no drips) via a percolation method with a funnel, filter paper, and drainage setup. Concentrations of CO_2, N_2O, and CH_4 were measured for 5-minute intervals for each sample. After taking a measurement, gas concentrations were allowed to return to ambient concentrations before the next measurement. Gas fluxes (nmol m^{-2} s^{-1}) were calculated in the Picarro Soil Flux Processor program using the exponential model developed by Hutchinson and Mosier to account for nonlinear changes in headspace concentration, and cumulative flux concentrations were calculated with linear line. The cumulative flux over the four days was calculated by trapezoidal interpolation between measurement dates.

Physical Soil Health Indicators

Wet aggregate stability was analyzed on composited samples prior to treatment and three years after. Air dried soils were processed by the wet sieving method using a RO-TAP RX-29 mechanical shaker (W.S Tyler, Ohio). 20 gs of air-dried and sieved soil (4.75 mm) was placed onto the topmost of three sequentially arranged sieves of 2.00, 1.00, and 0.25 mm and shaken at 45 revolutions per minute for 5 min. Subsequently, the wet stable aggregate (WSA) fractions (large macroaggregates (4.75–2.00 mm = Lma), medium macroaggregates (2.00–1.00 mm = Mma), small macroaggregates (1.00–0.25 mm = Sma), and microaggregates, including silt and clay (<0.25 mm = Mia), were obtained, weighed, and expressed in a percentage (%) to the initial sample weight.

The bulk density for each soil sample was determined using the dimensions of the custom steel cores for our study. They had a diameter of 8 cm, and the height of the cores was adjusted based on the sampling depth (either 10 cm or 30 cm). The volume of each core was calculated using these dimensions. To account for soil moisture content, a subsample of soil was air-dried, and then used to correct the bag of soil. The moisture-corrected dry soil mass was then divided by the core volume to calculate the bulk density, expressed in grams per cubic centimeter (g/cm^3).

Statistical Analysis

All analyses were conducted using R Statistical Software (v4.4.2; R Core Team, 2021). The primary independent variable was management practice, categorized as either Conventional or Compost + Cover Crops, while various soil health indices served as numeric response variables. The study followed a longitudinal design, with repeated measurements collected over three years to capture temporal variations and evaluate the impact of soil health practices. For each response variable, normality was assessed using the Shapiro-Wilk test. If the variable failed to meet normality assumptions, transformations (log, natural log, or square root) were applied. Transformed variables that achieved normality were analyzed using parametric tests, while those that remained non-normal were analyzed with non-parametric approaches. Response variables that met the assumptions of parametric testing (EC, pH, POXC, and mineralized CO_2) were analyzed using linear mixed models (LMMs). These models included Site as a random effect to account for variability between sites. Fixed effects included management, location (Alley vs. Berm), soil depth, and year, as well as their interactions. Significance of fixed effects for LMM models was tested using Type II ANOVA (Girden, 1992). For variables that could not be transformed to meet parametric assumptions, generalized linear mixed models (GLMMs) were employed to account for their distribution characteristics. GLMMs were fitted using the glmer function from the lme4 package (Bates et al., 2015), specifying Site as a random effect. The significance of fixed effects was tested using Type II Wald Chi-square tests via the Anova function in the car package (Fox & Weisberg, 2019). Pairwise comparisons for both models were conducted using the emmeans package (Lenth, 2021) to identify significant differences between management practices across years, locations (Alley vs. Berm), and soil depths. The emmeans analysis provided contrasts with estimates, standard errors, z-values, and p-values to highlight significant effects.

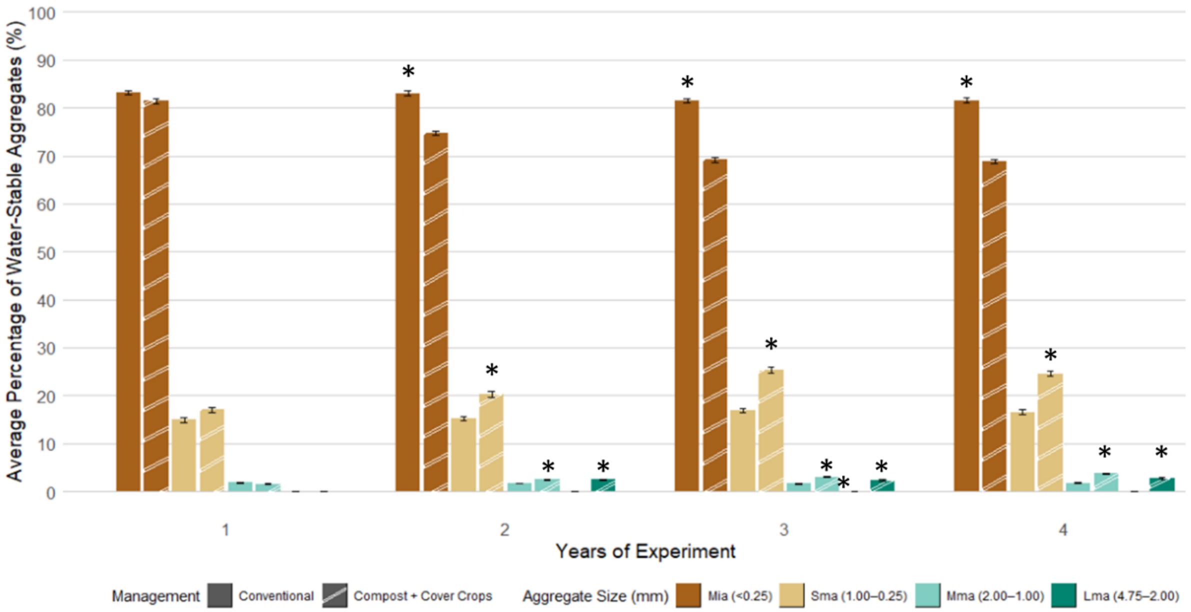
Results

Physical

Table 2. Physical properties of bulk density (BD) and wet stable aggregates (WSA), organized by management plots of conventional (C) and compost + cover crops (T), and depth (cm) for the location of alley and berm for the four years of sampling.

Site	**Plot**	**Indice**		**Depth**	**2021**		**2022**		**2023**		**2024**	
					Alley	*Berm*	*Alley*	*Berm*	*Alley*	*Berm*	*Alley*	*Berm*
Almond 1	C	**BD**		10	1.63 ± 0.02	1.63 ± 0.02	1.26 ± 0.06	1.27 ± 0.07	1.26 ± 0.06	1.1 ± 0.05	1.64 ± 0.04	1.4 ± 0.07
				30	1.47 ± 0.06	1.47 ± 0.04	1.21 ± 0.07	1.17 ± 0.08	1.33 ± 0.04	1.26 ± 0.03	1.64 ± 0.02	1.4 ± 0.02
	T			10	1.36 ± 0.02	1.36 ± 0.03	0.94 ± 0.08	1.04 ± 0.05	1.06 ± 0.08	1.04 ± 0.05	1.21 ± 0.03	1.18 ± 0.04
				30	1.34 ± 0.08	1.34 ± 0.02	1.36 ± 0.07	1.27 ± 0.06	1.27 ± 0.04	1.21 ± 0.05	1.71 ± 0.02	1.42 ± 0.01
	C	**WSA**	2 mm	10	2.4 ± 0.13	2.7 ± 0.33	2.5 ± 0.01	2.3 ± 0.12	3 ± 0.01	3 ± 0.03	3 ± 0.01	3 ± 0.03
			1 mm		0.7 ± 0.13	0.8 ± 0.12	0.4 ± 0.01	0.5 ± 0.03	0.7 ± 0.03	0.3 ± 0.01	0.7 ± 0.03	0.3 ± 0.02
			0.25 mm		0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0.01	0 ± 0	0 ± 0.01	0 ± 0
			< 0.25 mm		26.9 ± 0.26	26.5 ± 0.45	27.1 ± 0.02	27.2 ± 0.2	26.3 ± 0.04	26.7 ± 0.04	26.3 ± 0.05	26.7 ± 0.04
	T		2 mm		2.3 ± 0.05	2.3 ± 0.19	2.9 ± 0.05	2.8 ± 0.03	3.4 ± 0.03	5.2 ± 0.31	3.4 ± 0.03	5.2 ± 0.31
			1 mm		0.5 ± 0.05	0.4 ± 0.12	0.7 ± 0.05	0.9 ± 0.03	1 ± 0.03	0.9 ± 0.03	1.1 ± 0.03	1 ± 0.02
			0.25 mm		0 ± 0	0 ± 0	2.3 ± 0.12	0.6 ± 0.04	2.2 ± 0.07	0.3 ± 0.05	2.9 ± 0.13	0.5 ± 0.07
			< 0.25 mm		27.2 ± 0.01	27.3 ± 0.21	24.1 ± 0.12	25.7 ± 0.08	23.4 ± 0.08	23.7 ± 0.3	22.6 ± 0.11	23.3 ± 0.37
Almond 2	C	**BD**		10	1.79 ± 0.02	1.79 ± 0.07	1.36 ± 0.08	1.26 ± 0.13	1.26 ± 0.06	1.1 ± 0.05	1.64 ± 0.02	1.4 ± 0.02
				30	1.51 ± 0.01	1.51 ± 0.02	1.54 ± 0.06	1.39 ± 0.07	1.64 ± 0.06	1.48 ± 0.06	1.64 ± 0.01	1.4 ± 0.07
	T			10	1.29 ± 0.02	1.29 ± 0.04	1.03 ± 0.07	1 ± 0.06	1 ± 0.03	1.06 ± 0.06	1.21 ± 0.05	1.18 ± 0.02
				30	1.55 ± 0.03	1.55 ± 0.02	1.19 ± 0.07	1.09 ± 0.06	1.22 ± 0.05	1.21 ± 0.03	1.71 ± 0.02	1.42 ± 0.04
	C	**WSA**	2 mm	10	2.4 ± 0.13	2.7 ± 0.34	2.6 ± 0.02	2.3 ± 0.12	3 ± 0.01	3 ± 0.03	3 ± 0.01	3 ± 0.03
			1 mm		0.8 ± 0.18	0.8 ± 0.12	0.4 ± 0.01	0.5 ± 0.03	0.7 ± 0.03	0.3 ± 0.01	0.7 ± 0.03	0.3 ± 0.01
			0.25 mm		0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0.01	0 ± 0
			< 0.25 mm		26.8 ± 0.32	26.5 ± 0.45	27 ± 0.03	27.2 ± 0.09	26.3 ± 0.04	26.7 ± 0.04	26.3 ± 0.04	26.7 ± 0.03
	T		2 mm		2.3 ± 0.05	2.3 ± 0.19	2.8 ± 0.06	2.8 ± 0.03	3.4 ± 0.03	4.8 ± 0.03	3.4 ± 0.03	4.8 ± 0.03
			1 mm		0.5 ± 0.07	0.4 ± 0.08	0.7 ± 0.04	0.9 ± 0.03	1 ± 0.03	0.9 ± 0.03	1.1 ± 0.04	1 ± 0.03
			0.25 mm		0 ± 0	0 ± 0	2.2 ± 0.06	0.4 ± 0.09	2.2 ± 0.07	0.3 ± 0.04	2.9 ± 0.14	0.6 ± 0.06
			< 0.25 mm		27.2 ± 0.03	27.3 ± 0.2	24.3 ± 0.05	25.9 ± 0.11	23.4 ± 0.08	24 ± 0.04	22.6 ± 0.15	23.6 ± 0.06
Almond 3	C	**BD**		10	1.3 ± 0.02	1.3 ± 0.02	1.25 ± 0.04	1.15 ± 0.02	1.24 ± 0.02	1.21 ± 0.04	1.3 ± 0.12	1.42 ± 0.03
				30	1.5 ± 0.02	1.5 ± 0.04	1.42 ± 0.05	1.31 ± 0.06	1.39 ± 0.06	1.27 ± 0.02	1.31 ± 0.03	1.42 ± 0.04
	T			10	1.49 ± 0.01	1.49 ± 0.02	1.29 ± 0.2	0.98 ± 0.03	1.01 ± 0.05	0.92 ± 0.04	1.24 ± 0.02	1.2 ± 0.03
				30	1.39 ± 0.02	1.39 ± 0.03	1.2 ± 0.05	1.05 ± 0.02	1.17 ± 0.03	1.05 ± 0.03	1.14 ± 0.03	1.32 ± 0.01
	C	**WSA**	2 mm	10	5 ± 0.39	4 ± 0.21	4.3 ± 0.02	4 ± 0.01	5.5 ± 0.15	3.8 ± 0.08	4.3 ± 0.02	4 ± 0.01
			1 mm		0.3 ± 0.01	0.8 ± 0.04	1.3 ± 0	0.8 ± 0.01	0.9 ± 0	0.6 ± 0	1.2 ± 0.09	0.8 ± 0.01
			0.25 mm		0 ± 0	0 ± 0	0 ± 0.01	0 ± 0	0 ± 0	0 ± 0	0 ± 0.01	0 ± 0
			< 0.25 mm		24.7 ± 0.4	25.3 ± 0.23	24.4 ± 0.03	25.1 ± 0.02	23.6 ± 0.15	25.6 ± 0.08	24.5 ± 0.11	25.1 ± 0.02
	T		2 mm		7 ± 0.04	6.3 ± 0.04	7.2 ± 0	5.8 ± 0	7.7 ± 0.18	7.6 ± 0	7.2 ± 0	5.8 ± 0
			1 mm		0.9 ± 0.06	0.5 ± 0.17	0.6 ± 0.01	0.6 ± 0.03	1.2 ± 0.23	1.2 ± 0.07	1.9 ± 0.21	2 ± 0.26
			0.25 mm		0 ± 0	0 ± 0	0 ± 0.02	0.1 ± 0.01	0.9 ± 0.29	1 ± 0.09	0.5 ± 0.24	0.5 ± 0.13
			< 0.25 mm		22 ± 0.1	23.2 ± 0.14	22.2 ± 0.04	23.5 ± 0.03	20.3 ± 0.68	20.2 ± 0.16	20.5 ± 0.26	21.7 ± 0.38
Almond 4	C	**BD**		10	1.47 ± 0.09	1.47 ± 0.02	1.49 ± 0.08	1.29 ± 0.08	1.35 ± 0.09	1.45 ± 0.08	1.82 ± 0.02	1.37 ± 0.02
				30	1.56 ± 0.12	1.56 ± 0.06	1.46 ± 0.11	1.39 ± 0.13	1.56 ± 0.09	1.54 ± 0.07	1.67 ± 0.08	1.6 ± 0.03
	T			10	1.44 ± 0.02	1.44 ± 0.02	1.28 ± 0.09	1.23 ± 0.09	1.21 ± 0.05	1.1 ± 0.03	1.2 ± 0.05	1.33 ± 0.02
				30	1.5 ± 0.07	1.5 ± 0.04	1.41 ± 0.09	1.44 ± 0.1	1.42 ± 0.07	1.3 ± 0.07	1.51 ± 0.01	1.44 ± 0.05
	C	**WSA**	2 mm	10	5 ± 0.39	4 ± 0.21	4.3 ± 0.02	4 ± 0.01	5.5 ± 0.15	3.8 ± 0.08	4.3 ± 0.02	4 ± 0.01
			1 mm		0.3 ± 0.01	0.8 ± 0.04	1.3 ± 0	0.8 ± 0.01	0.9 ± 0	0.6 ± 0	1.2 ± 0.09	0.8 ± 0.01
			0.25 mm		0 ± 0	0 ± 0	0 ± 0.01	0 ± 0	0 ± 0	0 ± 0	0 ± 0.01	0 ± 0
			< 0.25 mm		24.7 ± 0.4	25.3 ± 0.23	24.4 ± 0.03	25.1 ± 0.02	23.6 ± 0.15	25.6 ± 0.08	24.5 ± 0.11	25.1 ± 0.02
	T		2 mm		7 ± 0.04	6.3 ± 0.04	7.2 ± 0	5.8 ± 0	7.7 ± 0.18	7.6 ± 0	7.2 ± 0	5.8 ± 0
			1 mm		0.9 ± 0.06	0.5 ± 0.17	0.6 ± 0.01	0.6 ± 0.03	1.2 ± 0.23	1.2 ± 0.07	1.9 ± 0.21	2 ± 0.26
			0.25 mm		0 ± 0	0 ± 0	0 ± 0.02	0.1 ± 0.01	0.9 ± 0.29	1 ± 0.09	0.5 ± 0.24	0.5 ± 0.13
			< 0.25 mm		22 ± 0.1	23.2 ± 0.14	22.2 ± 0.04	23.5 ± 0.03	20.3 ± 0.68	20.2 ± 0.16	20.5 ± 0.26	21.7 ± 0.38
Walnut	C	**BD**		10	1.58 ± 0.02	1.58 ± 0.06	1.44 ± 0.1	1.59 ± 0.06	1.32 ± 0.07	1.03 ± 0.1	1.34 ± 0.04	1.3 ± 0.02
				30	1.74 ± 0.07	1.74 ± 0.02	1.65 ± 0.07	1.41 ± 0.07	1.28 ± 0.03	1.38 ± 0.04	1.91 ± 0.02	1.61 ± 0.05
	T			10	1.33 ± 0.02	1.33 ± 0.03	1.08 ± 0.04	1.06 ± 0.11	1.06 ± 0.03	1.09 ± 0.05	1.13 ± 0.03	1.36 ± 0.02
				30	1.6 ± 0.01	1.6 ± 0.02	1.44 ± 0.12	1.41 ± 0.15	1.18 ± 0.04	1.13 ± 0.04	1.77 ± 0.02	1.55 ± 0.01
	C	**WSA**	2 mm	10	9.3 ± 0.33	9.2 ± 0.38	9.5 ± 0	9.2 ± 0.33	9.3 ± 0.33	10.3 ± 0.32	9.3 ± 0.33	10.3 ± 0.32
			1 mm		0.1 ± 0.01	0.1 ± 0.01	0.1 ± 0.01	0.1 ± 0.01	0.1 ± 0	0.1 ± 0	0.1 ± 0	0.1 ± 0
			0.25 mm		0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0.01
			< 0.25 mm		20.6 ± 0.32	20.7 ± 0.37	20.4 ± 0.01	20.7 ± 0.34	20.6 ± 0.33	19.5 ± 0.32	20.6 ± 0.33	19.5 ± 0.32
	T		2 mm		9 ± 0.31	9.2 ± 0.22	10.3 ± 0.32	9.9 ± 0.34	10.6 ± 0.07	12.1 ± 0.01	10.6 ± 0.07	12.1 ± 0.01
			1 mm		0.1 ± 0.02	0.2 ± 0.06	0.4 ± 0.1	0.3 ± 0.03	0 ± 0.01	0.1 ± 0.01	0.1 ± 0.03	0.2 ± 0.01
			0.25 mm		0 ± 0	0 ± 0	0.2 ± 0.03	0.2 ± 0.02	0 ± 0.01	0.1 ± 0.01	0.1 ± 0.02	0.4 ± 0.26
			< 0.25 mm		20.9 ± 0.32	20.6 ± 0.26	19.2 ± 0.33	19.6 ± 0.35	19.3 ± 0.07	17.7 ± 0.03	19.2 ± 0.07	17.3 ± 0.25

Bulk density at the onset of the study ranged from a low of 1.29 g cm^3 to a high of 1.79 g cm^3 in the 10 cm depth, the 30 cm depth ranged from a low of 1.34 g cm^3 to a high of 1.73 g cm^3 (Table 4) By the end of the study, the average bulk density of the compost + cover crops plots in the 10 cm depth were 1.22 g cm^3, and 1.5 g cm^3 for the 30 cm depth. The analysis found that all factors in the study significantly influence BD, Year (F= 117, *p* <0.01), Management (F= 187, *p* <0.01), and Depth (F= 106, *p* <0.01), and Location i.e. berm or alley (F = 18, *p* <0.01). There was a significant decrease in BD for the 10 cm depth across sites from the baseline to the final sampling was 0.15 g cm^3, whereas there was a slight increase in in the 30 cm depth of 0.03 g cm^3.



* = *p* < 0.05 diff. Conv. & Comp. Cover Crops

Figure 2. The percentage (%) of average wet aggregate stability (WSA) averaged across sites over the four years of the study. Management is denoted by patterns, with plain bars representing conventional plots and crosshatching representing plots with compost and cover crops. This figure displays averages across berm and alley locations. The asterisk (*) indicates a significant difference between conventionally managed sites and those with compost and cover crops..

Wet aggregate stability in the compost + cover crop treated plots increased over time, characterized by a shift towards larger aggregates (Table 2). Specifically, Small Macroaggregates (Sma) increased by 8.4 ± 2 %, followed by gains in Large Macroaggregates (Lma) by 2.1 ± 0.5 % and Medium Macroaggregates (Mma) by 1.3 ± 0.2 %. Conversely, Microaggregates (Mia) decreased by 11.7 % in the treatment plots over the study period. Management, sample location (alley/berm) and year exerted significant influences on these changes (*p* < 0.05), as illustrated in Figure 2. There were significant differences in aggregate stability observed between sample locations (alley vs. berm), with berms having a higher level of stable aggregates across size classes (p =0.03).

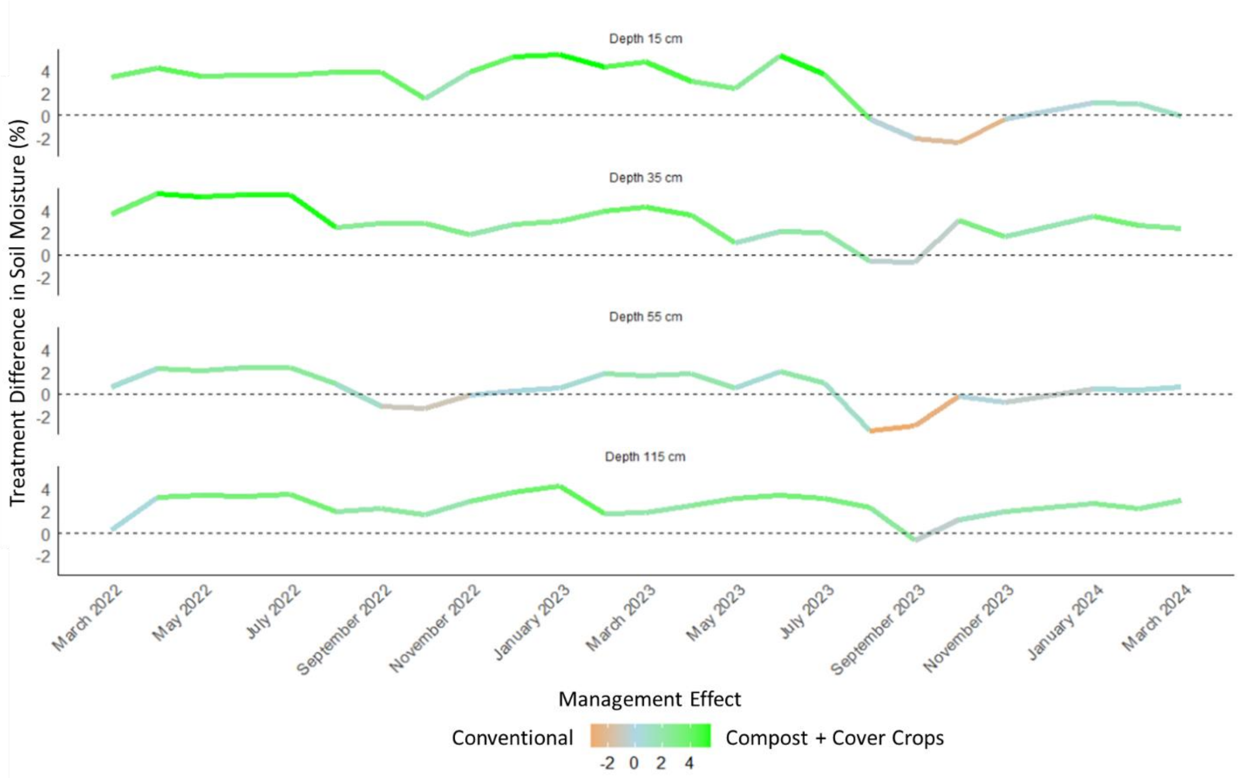


Figure 3. Volumetric water content % for the months of August and September across years 2, 3, and 4 for the four sites. The line represents the treatment difference between management plots of compost + cover crops and conventional, across all sites in the study from March 2022 to March 2024. When the line is above zero, it denotes an increase in soil moisture for the compost + cover crops plots.

Volumetric Water Content (VWC).

There was a significant effect of management (Compost + Cover Crops vs Conventional), depth, season (Spring, Summer, Fall, Winter), and site on volumetric water content (%). The management approach demonstrated a significant effect on water content (F = 19129.64, $p < 0.001$). Depth also significantly affected volumetric water content (F = 8550.015, $p < 0.001$), showing considerable variation across soil depths. Similarly, the season had a significant effect on water content (F = 24747.74, $p < 2.2e-16$), suggesting that volumetric water content varies significantly by season with higher levels in Spring and Winter.

The interaction effects were also significant. The interaction between management and depth was significant ($F = 1489.530$, $p < 2.2e-16$), indicating that the effect of management type on water content varies with depth. The trend was that the uppermost of the soil profile, the 0-35 depth, was higher with the compost + cover crops, and the deepest soils i.e. 115cm. The interaction between management and season was significant ($F = 611.271$, $p < 2.2e-16$), suggesting that the management effect on water volume differs across seasons, while the interaction between depth and season was highly significant ($F = 1439.552$, $p < 2.2e-16$), showing that seasonal effects on water content vary by depth. Treatment (Compost + Cover Crops) consistently exhibited higher volumetric water content compared to Control (Conventional Management) across all seasons. In Fall, the estimate was 0.75 ($p < 0.0001$), indicating significantly higher water content in the Treatment. In Spring, the estimate was 1.95 ($p < 0.0001$). In Summer, the estimate was 1.97 ($p < 0.0001$), and in Winter, the estimate was 1.93 ($p < 0.0001$).

Chemical

pH, EC, soil C & N concentrations, and soil C content results.

Table 3. Chemical soil properties for the four years of the study, organized by alley and berm locations and management plots of conventional (C) and compost + cover crops (T).

Site	Plot	Indice	2021		2022		2023		2024	
			Alley	*Berm*	*Alley*	*Berm*	*Alley*	*Berm*	*Alley*	*Berm*
Almond 1	C	pH	7.2 ± 0	6.39 ± 0.03	7.13 ± 0.06	7.81 ± 0.02	6.88 ± 0.09	5.64 ± 0	7.34 ± 0	6.98 ± 0.02
	T		7.65 ± 0.01	7.07 ± 0	6.91 ± 0.03	6.81 ± 0.04	7.14 ± 0.01	6.78 ± 0	6.9 ± 0.02	6.78 ± 0.01
	C	EC	269.75 ± 0.38	702.2 ± 6.99	633.75 ± 0.26	654.55 ± 0.26	165.15 ± 0.14	166.25 ± 0.03	188.75 ± 0.09	245.9 ± 0.29
	T		472.6 ± 5.43	467.7 ± 16.57	677.7 ± 0.12	955.9 ± 0.81	315.95 ± 0.26	780.5 ± 0.52	591.25 ± 0.61	1595 ± 4.62
	C	CEC	26.2	23.3	24.8	15.9	23.7	23.7	20.3	20.5
	T		24.4	23.8	25.5	256	25.1	25.8	26.1	28.6
Almond 2	C	pH	7.08 ± 0.01	7.14 ± 0.01	7.37 ± 0.01	7.29 ± 0.01	7.19 ± 0.01	7.26 ± 0.01	7.53 ± 0.03	7.96 ± 0
	T		7.58 ± 0.02	7.31 ± 0.01	6.89 ± 0.01	7.04 ± 0.01	7.22 ± 0	6.57 ± 0.01	7.07 ± 0.01	6.82 ± 0.01
	C	EC	486.55 ± 4.13	749.4 ± 9.58	633.23 ± 0.58	654 ± 0.61	165.17 ± 0.15	166.17 ± 0.09	188.57 ± 0.2	245.93 ± 0.29
	T		436.65 ± 6.38	424.15 ± 2.11	676.73 ± 0.97	954.57 ± 1.56	315.73 ± 0.34	780.07 ± 0.68	589.77 ± 1.6	1596.33 ± 4.81
	C	CEC	22.5	24.5	20.7	20.3	21.2	15.4	16.6	20.5
	T		24.4	23.8	25.7	25.9	23.8	26.8	25.3	26.8
Almond 3	C	pH	6.43 ± 0.03	6.56 ± 0.06	6.71 ± 0.03	6.64 ± 0	7.32 ± 0.03	7 ± 0.02	6.98 ± 0.02	7.41 ± 0.01
	T		7.39 ± 0.05	6.74 ± 0.03	6.09 ± 0.03	6.24 ± 0	7.09 ± 0	6.58 ± 0.01	6.43 ± 0.01	6.29 ± 0.03
	C	EC	851.95 ± 8.63	851.95 ± 8.63	235.07 ± 0.23	1122.43 ± 479.27	241.97 ± 3.51	84.98 ± 0.49	216.87 ± 30.66	167.1 ± 0.56
	T		673.4 ± 1.67	2294 ± 0.58	2703.67 ± 5.49	7965 ± 39	3000.13 ± 1.05	2319.67 ± 0.33	1968.33 ± 10.74	2162.33 ± 6.12
		CEC	12.3	10.6	10.2	15.3	13.7	11.4	16.1	15.1
			16.4	13.8	14.4	14.4	16.5	24.9	18.5	26.9
Almond 4	C	pH	6.8 ± 0.03	6.54 ± 0.03	6.55 ± 0.01	7.01 ± 0.01	7 ± 0.01	6.59 ± 0.22	6.8 ± 0.01	7.09 ± 0.08
	T		7.15 ± 0	6.43 ± 0.07	6.78 ± 0.01	5.92 ± 0.01	6.42 ± 0.13	6.85 ± 0.32	7.01 ± 0.08	6.81 ± 0.1
	C	EC	96.46 ± 0.42	98.25 ± 22.95	223.77 ± 0.13	529.17 ± 396.92	171.2 ± 0.15	107.47 ± 0.03	68.59 ± 0.1	134.7 ± 0.87
	T		68.59 ± 0.1	134.7 ± 0.87	224.83 ± 7.12	300.43 ± 0.44	943.6 ± 1.15	560.37 ± 0.54	326.07 ± 0.73	406.47 ± 0.28
	C	CEC	8.8	9.1	7.5	6.6	9.7	7.5	9.5	9.7
	T		7.8	8.6	9.2	4.8	12	11	14.2	11.1
Walnut	C	pH	7.28 ± 0.01	7.68 ± 0.02	7.18 ± 0.01	7.48 ± 0.04	7.44 ± 0.08	6.75 ± 0.01	6.33 ± 0	6.6 ± 0.02
	T		6.96 ± 0.04	7.16 ± 0.01	6.71 ± 0.01	6.8 ± 0.01	6.38 ± 0.01	7.1 ± 0.01	7.42 ± 0	6.91 ± 0.03
	C	EC	389.15 ± 1.82	209.65 ± 0.03	258.73 ± 0.35	150.87 ± 0.32	176.57 ± 0.23	80.22 ± 0.22	221.73 ± 0.38	142.77 ± 0.28
	T		433.3 ± 0.46	136.05 ± 0.49	710.57 ± 1.25	262.93 ± 0.49	322.2 ± 0.35	159.83 ± 0.03	622.27 ± 0.15	136.6 ± 0.1
	C	CEC	12.6	9.3	10	7.1	13.1	8.1	13	7.3
	T		12.1	5.3	13.8	6.9	14.1	9	14.9	9.7

The average pH in Conventional plots increased from 6.9 in 2021 to 7.1 in 2024, resulting in an average increase of 0.2 ± 0.3 (Table 3). In contrast, the average pH in compost + cover crops plots decreased, from 7.1 in 2021 to 6.8 in 2024, with an average difference of -0.3 ± 0.3. There was a significant interaction effect of management and year on pH, with year 1 (p <0.05) and year 3(p =0.04), both having a significant decrease in the management plots compared to control. There was not a significant difference between alley and berm locations. Electrical conductivity (EC) decreased in Conventional plots over time, with an average reduction of 313.6 ± 114.5 µS/cm from 2021 to 2024. In contrast the compost + cover crops plots had a significant positive effect on EC with an average increase 445.3 ± 311.2 µS/cm by year three (p < 0.05), There was a significant interaction effect of management and year, with year 12 (p = 0.015) and year 3(p < 0.01), both having a significant increase in the management plots compared to control.

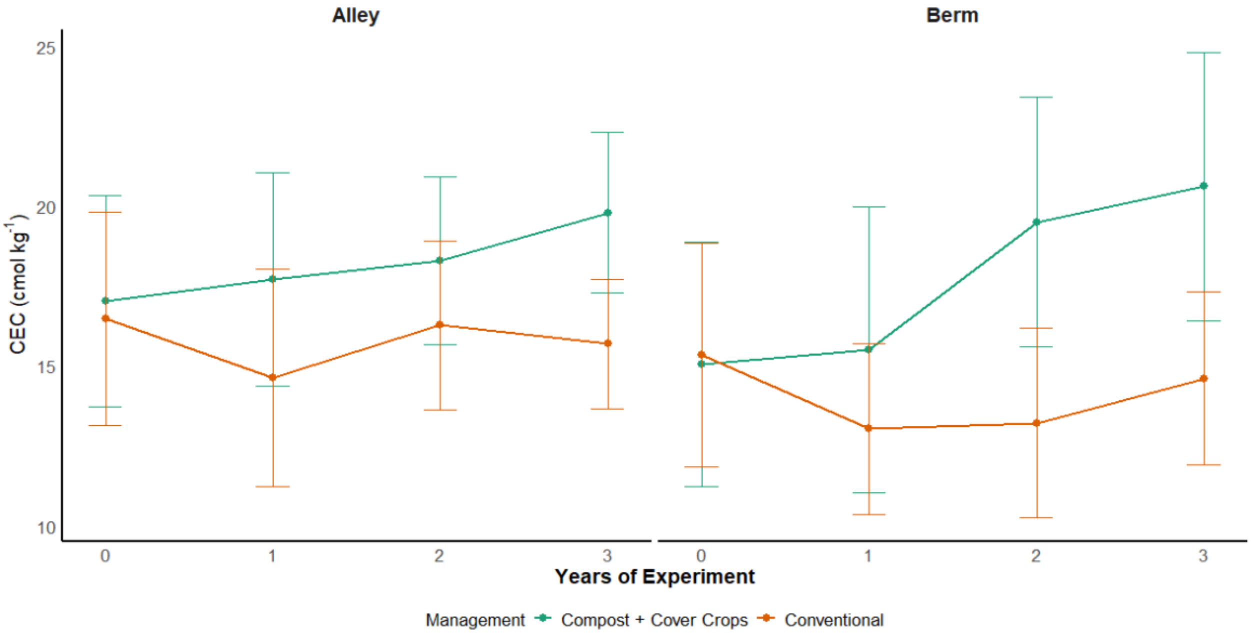


Figure 4. Cation Exchange Capacity (CEC) cmol kg^{-1} *for all sites. Color represents compost + cover crops management as green, and conventional as orange.*

Soil CEC across sites at the beginning of the study was highly variable, ranging from a low of 12 cmol kg^{-1} to a high of 25 cmol kg^{-1} (Table 3). The GLMM revealed a significant main effect of Date 2024 (Z=0.047) indicating a significant increase in CEC in 2024 compared to the baseline year. A Type II Wald Chi-square test showed significant effects of Management ($\chi2=20.40$, df=1, $p<0.001$), Location ($\chi2=10.09$, df=1 , $p<0.001$), and Date ($\chi2=15.73$, df=3, $p<0.001$) on CEC. A significant interaction between Management and Date ($\chi2=9.83$, df=3, $p=0.02$) indicated that the effect of Management varied across years with an increase over time with the management of compost + cover crops (Figure 4). In 2021, there was no significant difference in CEC between the Compost + Cover Crops and Conventional management practices (estimate = -0.0162, SE = 0.0755, z = -0.214, p = 0.8304). However, in 2022, CEC was significantly higher under Compost + Cover Crops compared to Conventional management (estimate = 0.1546, SE = 0.0755, z = 2.048, p = 0.0406). This trend continued in 2023 (estimate = 0.2606, SE = 0.0755, z = 3.451, p = 0.0006) and 2024 (estimate = 0.2835, SE = 0.0755, z = 3.757, p = 0.0002), with Compost + Cover Crops consistently showing significantly higher CEC values compared to Conventional management. By year three, there was an average increase of 25.7 ± 14.5% for the alleys CEC and 48 ± 16.9% for the berms for plots receiving compost + CC, whereas conventional plots saw a small increase in the alleys of 1.3 ± 9.2 % and a decrease in berms of 0.16 ± 11.7 %.

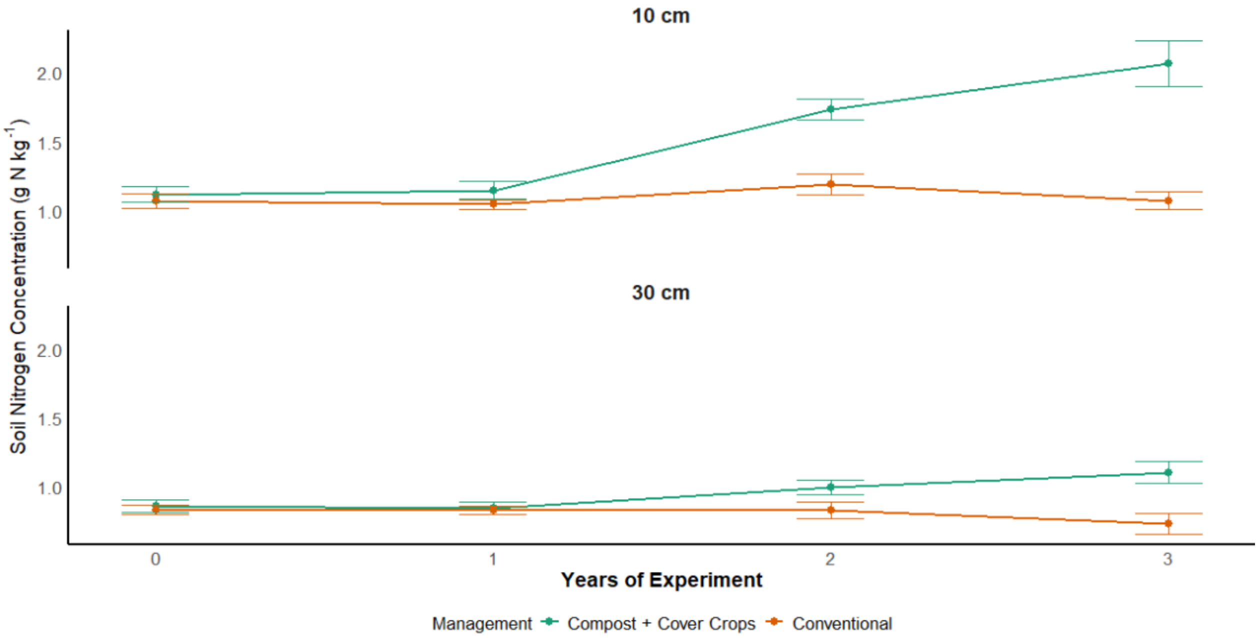


Figure 5. Soil N concentration (N / kg dry soil) averaged across the 5 sites of the for the baseline, and the 3 years of the study. Color represents compost + cover crops management as green, and conventional as orange. Depth is denoted by line type, solid as the 10 cm depth, and dashed as the 30 cm depth. Error bars are the mean ± the standard error.

Total soil nitrogen concentration (g N kg^{-1}) was evaluated at baseline across different sites at depths of 10 cm and 30 cm (Figure 5). At the 10 cm depth, total nitrogen concentration ranged from 0.54% to 1.44%, with an average of 0.89 ± 0.08%. At the 30 cm depth, total nitrogen concentration ranged from 0.61% to 1.35%, with an average of 0.89 ± 0.04%. Several factors significantly influenced soil nitrogen concentration throughout the study. Year had a notable effect ($\chi2=57.7$,df=3, $p<0.001$, management ($\chi2=45.6$,df=1, $p<0.001$), and depth ($\chi2=257.4$,df=1, $p<0.001$). Significant interactions were found between year and management ($\chi2=36.3$, ,df=3, $p<0.001$), year and depth ($\chi2=32.4$,df=3, $p<0.001$. Pairwise comparisons between management practices (Compost + Cover Crops vs. Conventional) were conducted for each year and depth, with results presented on the log-transformed scale. At 10 cm depth, no significant differences were observed in 2021 and 2022 ($p = 0.6$ and $p = 0.1$, respectively). However, Compost + Cover Crops resulted in significantly higher nitrogen content in 2023 ($p < 0.0001$) and an even greater difference in 2024 ($p < 0.0001$). At 30 cm depth, no significant differences were detected in 2021 and 2022 ($p = 0.3$ and $p = 0.1$, respectively). Significant increases in nitrogen content under Compost + Cover Crops were observed in 2023 ($p = 0.003$) and 2024 ($p < 0.0001$). These results indicate that the impact of Compost + Cover Crops on nitrogen content became more pronounced in later years, with consistent differences at both depths by 2023 and 2024. For the compost + cover crops plots, the percent increase in soil nitrogen concentration from 2021 to 2024 was 84.7% ± 15.6% at the 10 cm depth and 28.2% ± 10.5% at the 30 cm depth. In contrast, for the conventional plots, the percent increase in soil nitrogen concentration from 2021 to 2024 was 0.1% ± 7.5% at the 10 cm depth and a decrease of -11.9% ± 9.6% at the 30 cm depth.

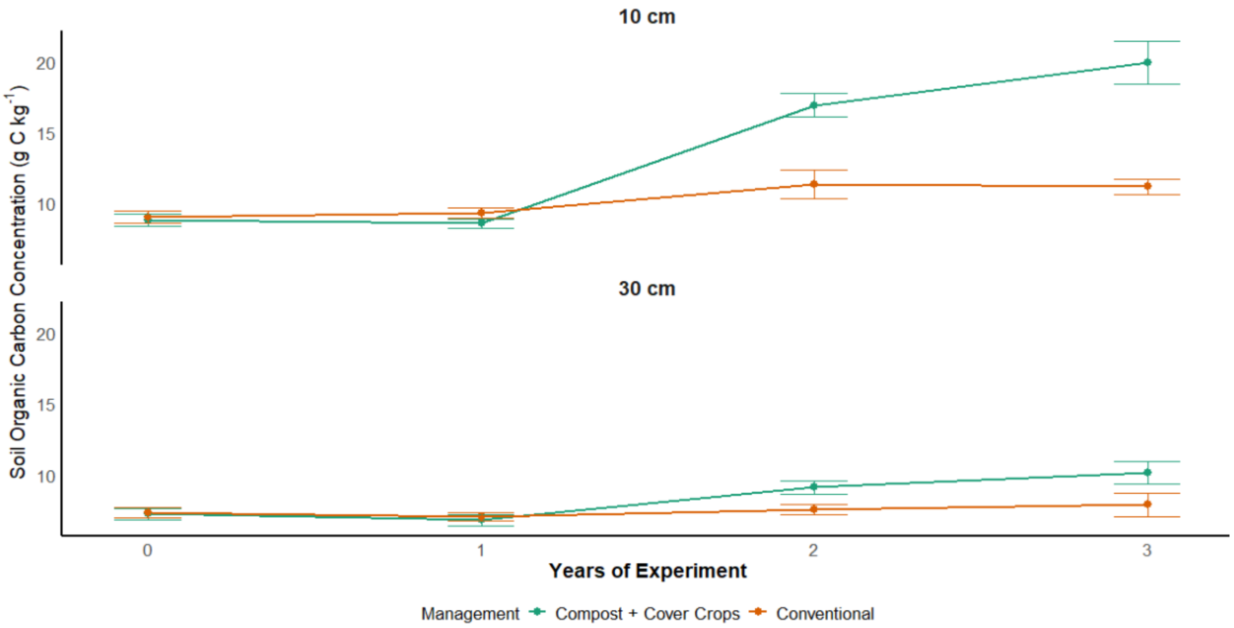


Figure 6. Average soil C concentration (g C kg $^{-1}$) of soils across sites in the study through time. Color represents compost + cover crops management as green, and conventional as orange. Depth is denoted by line type, solid as the 10 cm depth, and dashed as the 30 cm depth. Error bars are the mean ± the standard error.

Total soil organic C concentration was evaluated across different sites at depths of 10 cm and 30 cm throughout the study (Figure 6). At baseline measurements, the 10 cm depth had soil organic C concentrations (g C kg) ranging from 4.6% to 11%, with an average of 7.6 ± 0.7%. At the 30 cm depth, soil organic C concentrations ranged from 5.4% to 11%, with an average of 6.5 ± 0.6%. Management practices had a highly significant effect on SOC ($\chi^2 = 16.6$, $p < 0.001$), while the sampling date and soil depth were also significant predictors ($\chi^2 = 155.4$, $p < 0.001$, and $\chi^2 = 233.3$, $p < 0.001$, respectively). Interactions between management and date ($\chi^2 = 38.4$, $p < 0.001$) and between date and depth ($\chi^2 = 48.4$, $p < 0.001$) were significant. The three-way interaction between management, date, and depth approached significance ($\chi^2 = 7.56$, $p = 0.056$), suggesting a potential complex interplay among these factors. By 2023, significant differences emerged, with Compost + Cover Crops showing higher SOC than Conventional management at both 10 cm (estimate = 0.28, $p < 0.0001$) and 30 cm (estimate = 0.12, $p = 0.001$). In 2024, these differences persisted, with significant increases in SOC under Compost + Cover Crops at both 10 cm (estimate = 0.59, $p < 0.0001$) and 30 cm (estimate = 0.24, $p = 0.03$. By 2024, the average percent increase in soil organic C concentration at the 10 cm depth was 30.91 ± 11.50% under conventional management. In contrast, the compost + cover crops treatment resulted in a much higher average increase of 149.13 ± 60.13% (Supp. Table 1). At the 30 cm depth, conventional management showed a minimal increase of 0.99 ± 9.22%, while compost + cover crops increased to 62.59 ± 48.50%.

Supplemental Table 1. Total C (C Conc.) and N (N Conc.)concentrations (g kg^{-1}), and soil organic C (SOC Cont.) content (Mg ha^{-1})for the baseline, 2021, and the three years of the study until 2024. Plot represents management and is denoted by the colors used throughout the study, with conventional(C) as orange, and compost + cover crops (T) as green. Depth is measured in cm, and alley and berm represent the location of the soil sample.

Site	Plot	Indice	Depth	2021		2022		2023		2024	
				Alley	*Berm*	*Alley*	*Berm*	*Alley*	*Berm*	*Alley*	*Berm*
Almond 1	C	N Conc.	10	1.5 ± 0.09	1.4 ± 0.06	1.1 ± 0.1	1 ± 0.05	1.1 ± 0.03	1.1 ± 0.09	1.2 ± 0.05	1 ± 0.09
			30	1.2 ± 0.11	1.1 ± 0.04	0.9 ± 0.07	1.1 ± 0.04	1 ± 0.04	1.1 ± 0.05	1.4 ± 0.42	0.9 ± 0.05
	T		10	1.6 ± 0.09	1.3 ± 0.1	1 ± 0.08	1 ± 0.07	1.8 ± 0.11	2.3 ± 0.31	1.9 ± 0.29	3.2 ± 0.34
			30	1.1 ± 0.11	1.1 ± 0.03	1.1 ± 0.12	1 ± 0.04	1.2 ± 0.09	1.3 ± 0.07	1.3 ± 0.17	1.4 ± 0.11
	C	C Conc.	10	12.2 ± 1.07	10.5 ± 0.82	9.7 ± 1	9.3 ± 0.52	9.5 ± 0.52	9.1 ± 0.88	12.1 ± 0.68	9.6 ± 1.09
			30	10.4 ± 1.05	8.9 ± 0.47	8.9 ± 1.19	10 ± 0.46	9.4 ± 0.93	10 ± 0.77	15.9 ± 4.99	8.6 ± 0.38
	T		10	12.2 ± 0.95	9.1 ± 0.78	8.3 ± 0.8	8.4 ± 0.49	17.7 ± 1.4	22.7 ± 4.12	17.3 ± 2.54	28.4 ± 2.82
			30	8.4 ± 0.85	8 ± 0.31	9.3 ± 1.05	8.2 ± 0.46	9.6 ± 0.71	11.4 ± 0.89	15.2 ± 4.65	14 ± 1.49
	C	SOC Cont.	10	15.9 ± 1.5	13.6 ± 1.1	12.5 ± 1.3	12 ± 0.7	15.7 ± 1.1	10.5 ± 0.5	15.7 ± 1.1	12.1 ± 1.7
			30	27.1 ± 1.9	24.6 ± 1.3	23.6 ± 3.5	26.6 ± 1.3	31.4 ± 1.8	27.4 ± 1.1	31.4 ± 1.8	37.5 ± 13
	T		10	15.9 ± 1.3	11.8 ± 1	11 ± 1.1	10.7 ± 0.6	22.1 ± 3.8	34.3 ± 2.7	22.5 ± 3.5	37.3 ± 3.7
			30	23.3 ± 2.9	23 ± 0.5	29.6 ± 4.8	21.4 ± 1.5	35.5 ± 3.7	31.6 ± 5	42.4 ± 12.4	36.3 ± 4.7
Almond 2	C	N Conc.	10	1.3 ± 0.07	1.2 ± 0.05	1.3 ± 0.04	1.3 ± 0.06	1.1 ± 0.03	1.1 ± 0.09	1.1 ± 0.06	1 ± 0.03
			30	1 ± 0.03	1.1 ± 0.05	1.1 ± 0.04	1.1 ± 0.05	0.9 ± 0.06	1 ± 0.02	1 ± 0.03	1 ± 0.11
	T		10	1.5 ± 0.04	1.3 ± 0.08	1 ± 0.06	1.1 ± 0.07	2.4 ± 0.33	1.9 ± 0.14	1.9 ± 0.29	3.2 ± 0.34
			30	1.1 ± 0.08	1.3 ± 0.07	0.8 ± 0.08	1 ± 0.05	1.7 ± 0.09	1.3 ± 0.09	1.3 ± 0.17	1.4 ± 0.11
	C	C Conc.	10	10.7 ± 0.58	9.6 ± 0.42	11 ± 0.51	12.8 ± 1.6	9.5 ± 0.52	9.1 ± 0.88	13.8 ± 1.24	11.9 ± 0.17
	T		30	8.3 ± 0.39	9.8 ± 0.74	9.2 ± 0.41	9.8 ± 0.44	8.2 ± 0.59	8.8 ± 0.3	10.3 ± 0.11	9.6 ± 1.09
	C		10	12.2 ± 0.49	10.8 ± 0.99	8.6 ± 0.59	9.3 ± 0.76	23.6 ± 3.96	19.3 ± 1.89	17.3 ± 2.54	28.4 ± 2.82
	T		30	9.3 ± 0.81	11.4 ± 0.69	7 ± 0.82	8.4 ± 0.68	15.6 ± 0.98	12.1 ± 0.97	11.9 ± 1.32	13.7 ± 1.16
	C	SOC Cont.	10	14 ± 0.7	11.9 ± 0.5	13.8 ± 0.7	15.9 ± 1.9	11.8 ± 0.6	10.5 ± 0.5	17.6 ± 1.7	15 ± 0.2
			30	26.9 ± 1.5	30.4 ± 2.7	28.2 ± 1.3	27.6 ± 1.8	25.1 ± 1.8	27.4 ± 1.1	35.7 ± 2.5	25.9 ± 1
	T		10	15.3 ± 0.6	13.6 ± 1.3	10.7 ± 0.6	11.4 ± 0.9	29.7 ± 4.5	23.9 ± 3.2	31.2 ± 6.3	38 ± 2.7
			30	28.9 ± 2.5	33.7 ± 2.4	20.1 ± 4.1	23.7 ± 3.2	37.7 ± 4	29.7 ± 5	34 ± 0.6	37.6 ± 3.6
Almond 3	C	N Conc.	10	0.8 ± 0.15	0.8 ± 0.13	1.4 ± 0.13	1.3 ± 0.09	1.4 ± 0.04	0.9 ± 0.01	1.5 ± 0.28	1.2 ± 0.08
			30	0.8 ± 0.09	0.8 ± 0.14	0.8 ± 0.05	0.9 ± 0.06	0.7 ± 0.02	0.6 ± 0.01	0.7 ± 0.1	0.6 ± 0.08
	T		10	1 ± 0.13	0.8 ± 0.25	1.5 ± 0.11	2.9 ± 0.29	2.2 ± 0.09	1.3 ± 0.06	1.6 ± 0.11	1.3 ± 0.02
			30	0.7 ± 0.11	0.6 ± 0.11	1 ± 0.05	1.2 ± 0.12	1 ± 0.1	1 ± 0.04	1 ± 0.14	1.5 ± 0.48
	C	C Conc.	10	8.1 ± 1.73	7.8 ± 1.57	10.7 ± 1.04	9.8 ± 0.87	15.5 ± 0.54	8.4 ± 0.1	11.4 ± 0.67	11.5 ± 1.31
	T		30	7.8 ± 0.72	8 ± 1.53	4.8 ± 0.39	6 ± 0.47	6.3 ± 0.14	5.7 ± 0.13	4.8 ± 0.12	5.9 ± 0.77
	C		10	8.4 ± 0.65	5.7 ± 1.37	9.7 ± 0.47	8.5 ± 0.37	21.8 ± 1.26	12 ± 0.86	18.9 ± 3.76	10.7 ± 0.3
	T		30	5.7 ± 1	4.9 ± 0.97	6.2 ± 0.34	7.5 ± 0.21	10 ± 1.12	8.9 ± 0.38	8.8 ± 1.16	9.6 ± 0.12
	C	SOC Cont.	10	10.4 ± 2.3	9.9 ± 2.1	13.7 ± 1.4	12.4 ± 1.1	20 ± 0.7	10.6 ± 0.1	17.8 ± 1.6	15.4 ± 0.2
			30	20.2 ± 1.9	21.1 ± 3.6	13.1 ± 1.1	14.9 ± 1.2	16.2 ± 0.7	14.5 ± 0.4	29.4 ± 2.3	23.4 ± 0.8
	T		10	10.8 ± 0.9	7.3 ± 1.8	12.3 ± 0.5	10.8 ± 0.5	27.3 ± 1.6	14.3 ± 0.5	31.8 ± 6.3	38.8 ± 2.7
			30	20.2 ± 2.5	14 ± 4	15.2 ± 0.8	18.9 ± 0.7	18.8 ± 3.8	20.2 ± 1.7	23.4 ± 1	34.1 ± 3
Almond 4	C	N Conc.	10	1 ± 0.07	1.2 ± 0.13	1.1 ± 0.1	0.9 ± 0.06	1.6 ± 0.05	1 ± 0.02	1.4 ± 0.3	1 ± 0.07
			30	0.6 ± 0.03	0.7 ± 0.03	0.6 ± 0.08	0.7 ± 0.05	1.2 ± 0.67	0.7 ± 0.03	0.6 ± 0.01	0.4 ± 0.18
	T		10	0.9 ± 0.09	0.9 ± 0.06	1.1 ± 0.09	0.9 ± 0.07	2 ± 0.14	1.2 ± 0.09	2.8 ± 0.33	1.6 ± 0.25
			30	0.6 ± 0.05	0.6 ± 0.04	0.7 ± 0.09	0.6 ± 0.05	0.8 ± 0.14	0.8 ± 0.07	0.8 ± 0.02	0.8 ± 0.05
	C	C Conc.	10	8.6 ± 0.74	9.8 ± 1.16	10.4 ± 0.95	8.2 ± 0.57	15.1 ± 0.66	10 ± 0.41	14.1 ± 3.47	9.4 ± 1.11
	T		30	5.1 ± 0.32	5.9 ± 0.29	5.9 ± 0.77	5.8 ± 0.27	7.5 ± 3.07	6.3 ± 0.32	5.4 ± 0.18	4 ± 1.98
	C		10	7.7 ± 0.95	7.7 ± 0.62	10.5 ± 0.93	7.9 ± 0.65	17.5 ± 1.37	11 ± 0.86	24.9 ± 2.84	15.5 ± 1.49
	T		30	5 ± 0.42	5.7 ± 0.31	5.5 ± 0.51	5.7 ± 0.43	7.6 ± 1.58	7.2 ± 0.5	7.1 ± 0.16	7.4 ± 0.41
	C	SOC Cont.	10	10.4 ± 0.9	11.9 ± 1.5	13.7 ± 1	10.2 ± 0.7	18.6 ± 0.9	12.1 ± 0.5	18.3 ± 4.8	11.3 ± 1.4
			30	18 ± 3.1	23.1 ± 2	19.2 ± 2.4	19.4 ± 1.5	27.1 ± 12.5	21.6 ± 1.5	24.5 ± 1.8	20.8 ± 0.6
	T		10	11.2 ± 0.2	9.2 ± 0.8	12.2 ± 1.2	9.3 ± 0.8	21.3 ± 1.9	13.9 ± 1.1	30.4 ± 3.6	19 ± 1.9
			30	12.7 ± 0.2	18.8 ± 1.6	15.1 ± 2	18.5 ± 1.4	23.2 ± 6.3	22.6 ± 1.8	21 ± 0.6	23.5 ± 1.7
Walnut	C	N Conc.	10	0.6 ± 0.05	0.6 ± 0.1	1.1 ± 0.07	0.6 ± 0.06	1 ± 0.14	1.3 ± 0.56	0.8 ± 0.1	0.5 ± 0.03
			30	0.5 ± 0.04	0.4 ± 0.04	0.4 ± 0.06	0.4 ± 0.02	0.5 ± 0.06	0.4 ± 0.01	0.3 ± 0	0.6 ± 0.12
	T		10	0.6 ± 0.03	0.4 ± 0.01	1.1 ± 0.07	0.6 ± 0.06	1.6 ± 0.15	0.5 ± 0.09	2 ± 0.12	1.4 ± 0.79
			30	1 ± 0.29	0.7 ± 0.12	0.8 ± 0.22	0.5 ± 0.08	0.7 ± 0.09	0.3 ± 0.02	0.8 ± 0.12	0.5 ± 0.22
	C	C Conc.	10	5 ± 0.56	4.9 ± 1.09	10.5 ± 1.09	4.8 ± 0.73	7.8 ± 0.92	15.9 ± 7.37	8.8 ± 1.33	9.2 ± 2.01
	T		30	4.2 ± 0.43	3.3 ± 0.37	4.3 ± 0.69	3.8 ± 0.22	5.3 ± 0.53	4.3 ± 0.17	7.3 ± 2.56	7.1 ± 1.3
	C		10	4.8 ± 0.45	3.1 ± 0.25	11 ± 1.05	4.8 ± 0.73	16.8 ± 1.56	5.4 ± 0.98	25.6 ± 4.43	14.5 ± 7.13
	T		30	9.9 ± 3.37	5.6 ± 1.3	7.5 ± 2.61	3.7 ± 0.67	6.8 ± 0.96	2.4 ± 0.3	7.2 ± 1.24	4.5 ± 1.42
	C	SOC Cont.	10	6.2 ± 0.6	5.4 ± 1.2	6.1 ± 0.5	5.3 ± 1.1	14.7 ± 2.2	19.7 ± 9.9	10.2 ± 1.5	10.7 ± 2.4
			30	13.5 ± 1.5	9.9 ± 0.9	12.3 ± 3.6	10.5 ± 1	8.7 ± 0.2	9.4 ± 2	21.3 ± 6.3	20.6 ± 3.4
	T		10	5.2 ± 0.6	7 ± 2.2	9.6 ± 2.9	14.6 ± 2	15 ± 0.4	18 ± 0.2	25.3 ± 3.9	26 ± 5.4
			30	10.7 ± 0.2	4.9 ± 1	12 ± 1.7	14 ± 4.1	16 ± 10	16.5 ± 5	17 ± 3	18.8 ± 3.7

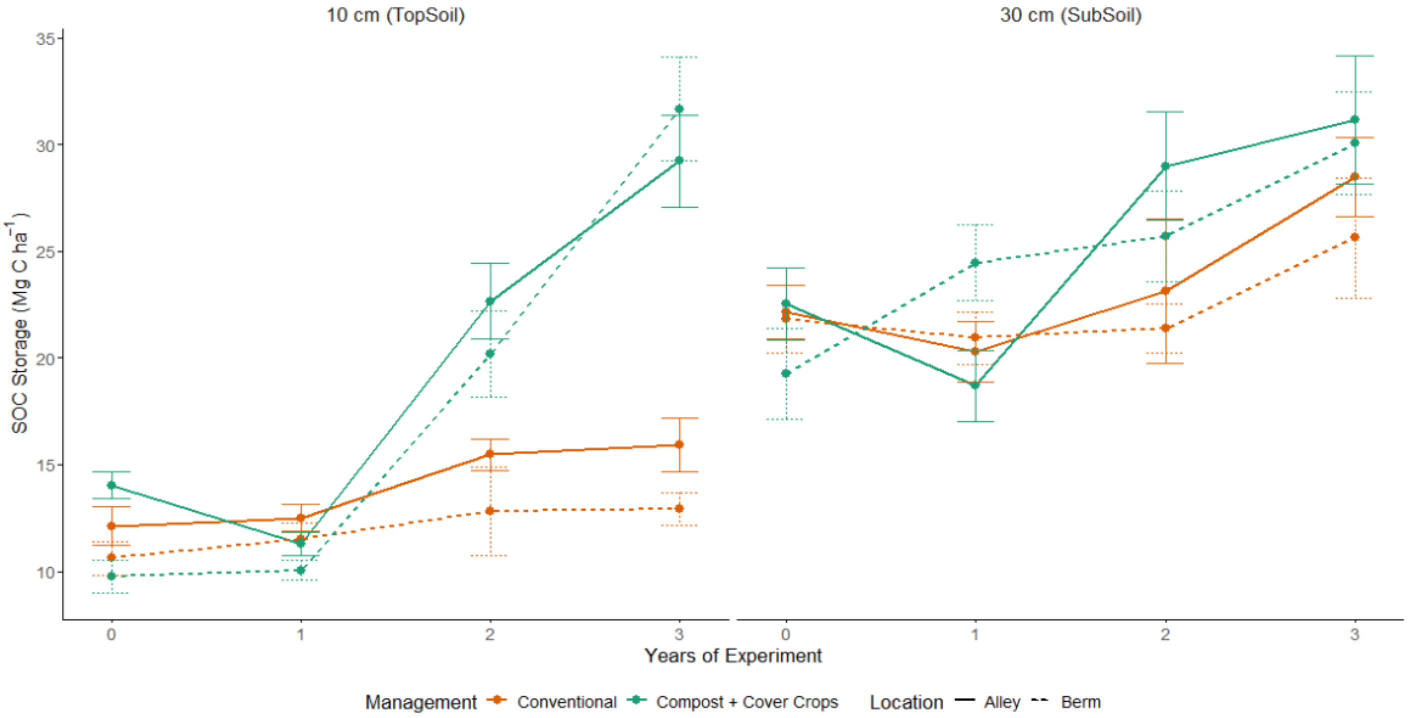


Figure 2. Soil organic carbon (SOC) storage by location of alley and berm and depth increments of 10 cm and 30 cm.

Soil organic C storage across sites varied across alley and berm, with lower values for the surface soils than the deeper depth. Berms were often lower, with an average of 10 ± 0.7 Mg C ha^{-1} for baseline soils in the 10 cm depth, and a 20 ± 2.1 Mg C ha^{-1} in the 30 cm depth. Alleys were slightly higher than berms, with an average in the 10 cm depth of 13 ± 1 Mg C ha^{-1}, and an average of 22 ± 1.3 Mg C ha^{-1}. There was a significant effect of management ($\chi^2 = 37.1$, $p < 0.001$), year ($\chi^2 = 206.1$, = $p < 0.001$) and depth ($\chi^2 = 371.6$, = $p < 0.001$) on SOC storage, along with significant three-way interaction ($\chi^2 = 26.7$, = $p < 0.001$). Pairwise comparisons (Comp. + Cover Crops – Conv.) with depth and management across years found that for the surface soils of 10 cm depth, there was a significant increase for year 2 (estimate:0.36, $p < 0.001$) and year 3 (estimate:0.76, $p < 0.001$). As for the deeper soils of 30cm, , there was a significant increase for year 1 (estimate:0.13, $p = 0.04$) and year 2 (estimate:0.31, $p < 0.001$).

There was a significant effect of compost and cover crops on the 10 cm depth soils across the alley and berms for year 2 and year 3. As for the 30 cm depth, there was not a significant effect at the 30 cm depth, but there was a trend of increased soil organic C storage in both alley and berm compared to conventional management.

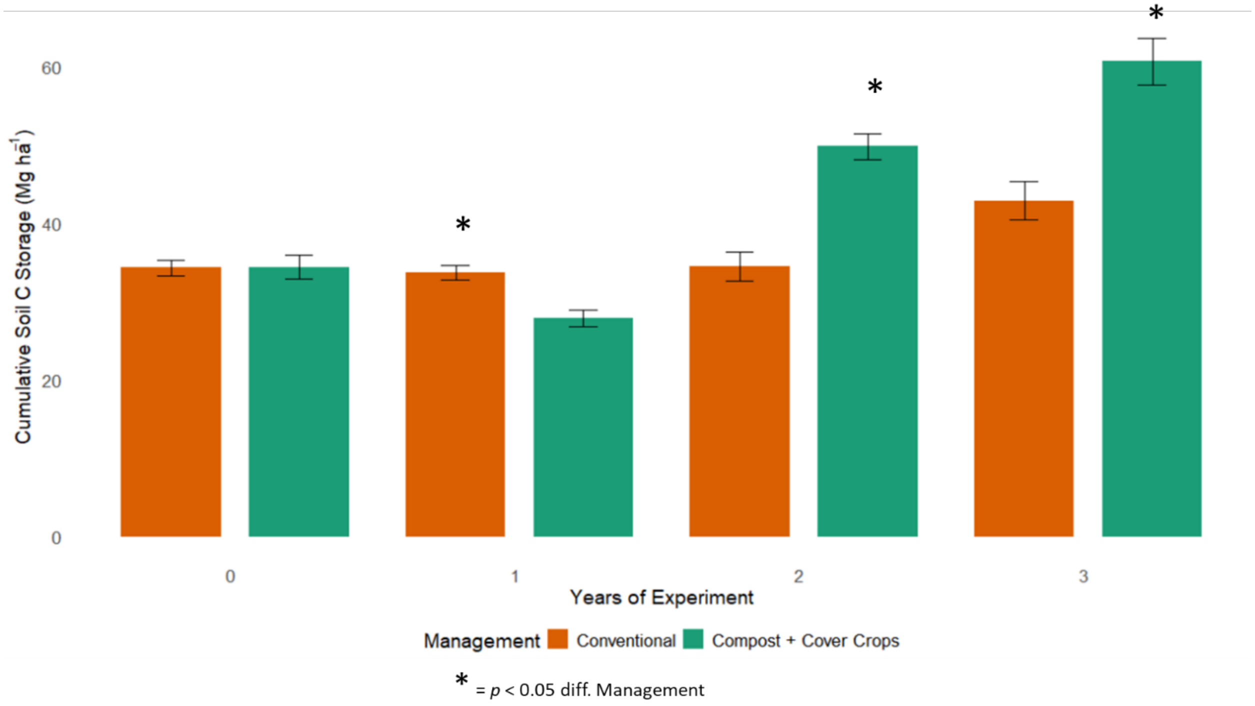


Figure 7. Cumulative soil C storage to the 0-30 cm depth, normalized to the ratio of alley and berms. Asterisks (*) indicate significant between management plots p < 0.05.

At the beginning of the study, baseline soils cumulative soil C storage to 30 cm ranged from a low of 18 ± 1.2 Mg C ha^{-1} to a high of 41 ± 1.8 Mg C ha^{-1}, reflecting high variability across sites and generally a soil C depletion. By the end of the study, after three years of applying compost and cover crops, the average percent increase in soil C storage was 102.2% ± 21.3%, more than double the 37.0% ± 9.7% increase observed in the conventional plots (Figure 7). Treatment plots resulted in an average soil C storage of

60.7 Mg C ha^{-1}, compared to 42.9 Mg C ha^{-1} in the conventional plots in the cumulative soil profile to 30 cm depth. Over the course of the study, soil C storage was significantly impacted by management (χ^2 = 6.4, $p = 0.01$), year (χ^2 = 187.4, $p < 0.001$), and there was also a significant interaction between the two (χ^2 = 62.9, $p < 0.001$). Pairwise comparisons found significant difference between Compost + Cover Crops and conventional within after the first year of the study, with a significant decrease in the treatment plots (estimate:-0.17, $p = 0.001$). The trend shifted to positive increases in cumulative SOC storage for year 2 (estimate:0.32, p <0.0001) and year 3 (estimate:0.41, p <0.0001.

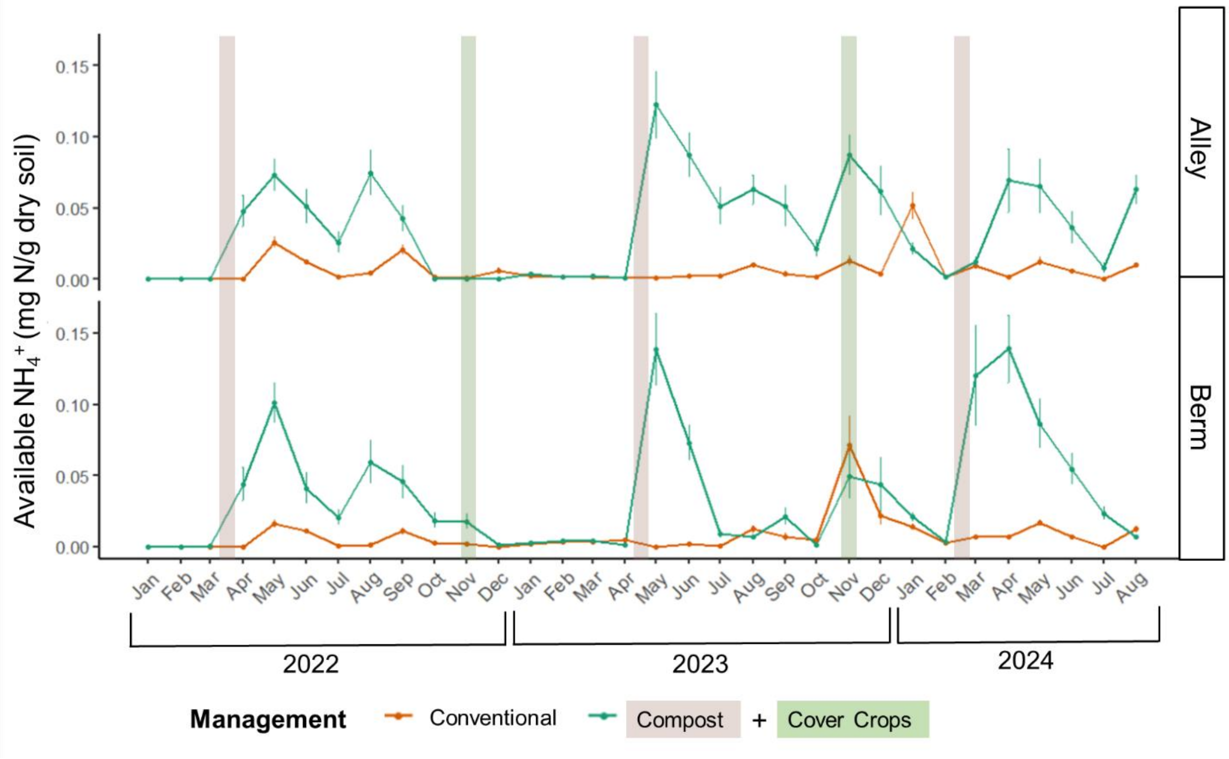


Figure 8. Average available ammonium (NH_4^+) across sites for the months of the study after the application of compost and cover crops. Brown and green highlights represent the application of compost or the planting of compost throughout the study.

Following the application of compost, the treatment plots showed a rapid increase in NH$_4^+$ availability compared to the conventionally managed plots throughout all three years of the study (Figure 8). After the first application, the average increase in NH$_4^+$ availability was 0.06 (± 0.02) mg nitrogen/g dry soil. By the second year, this increase more than doubled to 0.17 (± 0.05) mg nitrogen/g dry soil, and in the third year, it stabilized at 0.15 (± 0.05) mg nitrogen/g dry soil. A strong trend of increased NH_4^+ availability was observed in both the berm and alley areas throughout the growing season when compost was applied in the spring. Notably, the alleys sustained this increase longer than the berms, with an average duration of 5 ± 2 months, compared to 3 ± 1 months in the berms. The analysis of deviance for NH_4 concentrations revealed significant effects of several predictors. Management practices had a highly significant influence on NH_4 levels ($X^2 = 284.9$, $p < 0.001$). Sampling dates ($X^2 = 1332.4$, $p < 0.001$) and their interaction with location ($X^2 = 388.21$, $p < 0.001$) were also significant, indicating temporal and spatial variability in NH_4 availability. The interaction between management and date was significant ($X^2 = 1047.43$, $p < 0.001$), suggesting that the effects of management practices varied over time. Additionally, the three-way interaction among management, date, and location was highly significant ($X^2 = 1817.75$, $p < 0.001$), highlighting the combined influence of these factors on NH_4 levels. Over the three years of the study, a increase NH_4^+ availability was maintained for five months each year in the compost + cover crops plots.

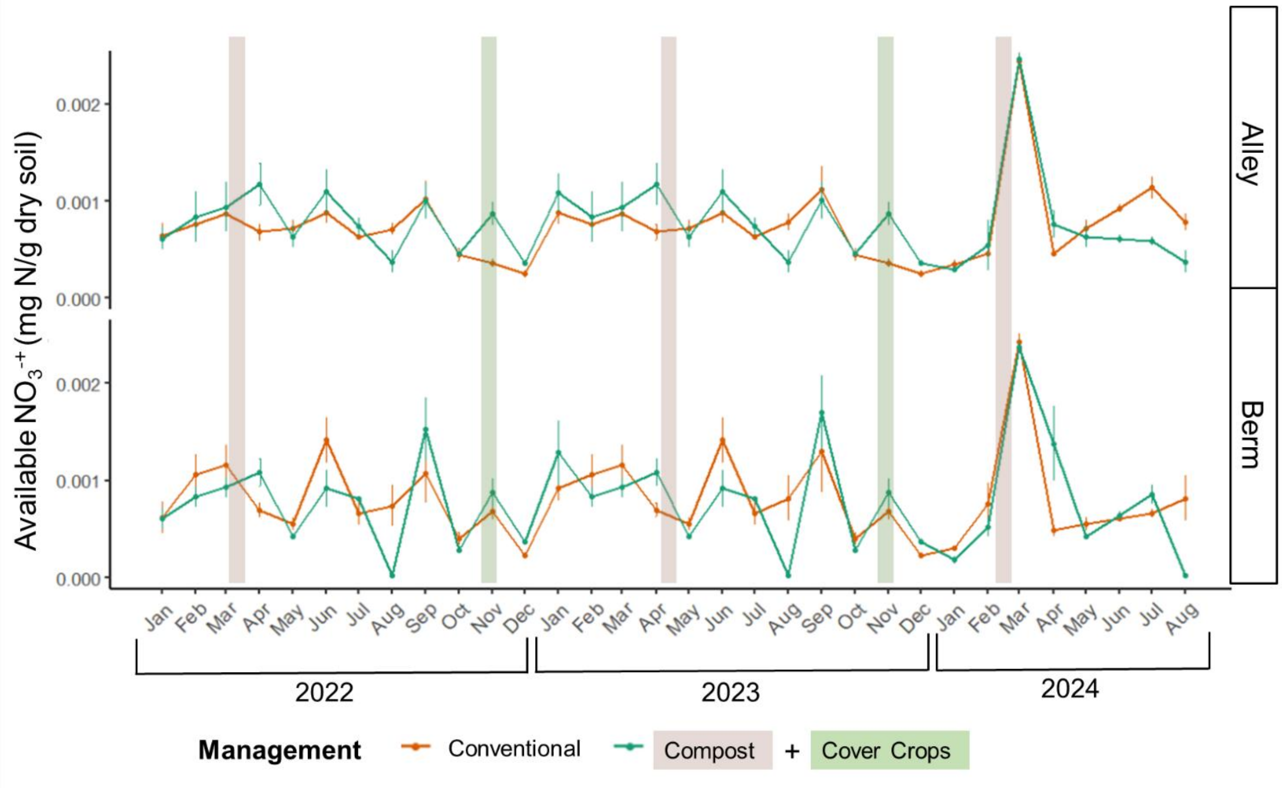


Figure 9. Average available nitrate (NO_3^-) content of the soils across sites for the three years after application of compost + cover crops. Brown and green highlights represent the application of compost or the planting of compost throughout the study.

Nitrate (NO_3^-) levels exhibit are highly variable with slight seasonal patterns, with peaks generally occurring in the spring and in the fall around September. The analysis of nitrate availability (*NO3*) revealed significant effects of date (χ^2= 976.2, *p* < 0.001), management by date (χ^2= 315.9, *p* < 0.001), management by location (χ^2= 23.3, *p* < 0.001), date by location (χ^2= 138.29, *p* < 0.001), and the three-way interaction of management, date, and location (χ^2= 173.58, *p* < 0.001). The main effects of management (χ^2= 1.95, *p* = 0.2) and location (χ^2= 2.66, *p* = 0.1) were not significant. Over the course of the study, compost + cover crops resulted in significantly higher nitrate levels compared to conventional management in six instances. These occurred primarily in the alley location, with one significant contrast in the berm location. The observed patterns are often results of fertigation events, where both plots increased in nitrate.

Biological Soil Health Indicators

Table 5. Biological soil indicators of microbial biomass nitrogen (MBN) in mg N per dry soil, microbial biomass carbon (MBN) in mg C per dry soil, permanganate oxidizable carbon (POXC), and short-term C mineralization cumulative fluxes (CO2)in µg C/g dry

soil for the management plots of conventional (C) and compost + cover crops (T) across the locations of alley and berm for the four years of the study.

Site	Plot	Indice	2021		2022		2023		2024	
			Alley	*Berm*	*Alley*	*Berm*	*Alley*	*Berm*	*Alley*	*Berm*
Almond 1	C	MBN	0.04 ± 0.01	0.01 ± 0.00	0.04 ± 0.01	0.01 ± 0.00	0.13 ± 0.03	0.01 ± 0.00	0.04 ± 0.00	0.01 ± 0.00
	T		0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.04 ± 0.00	0.01 ± 0.00	0.05 ± 0.00	0.02 ± 0.00
	C	MBC	0.04 ± 0.01	0.02 ± 0.00	0.04 ± 0.01	0.03 ± 0.00	0.13 ± 0.03	0.03 ± 0.00	0.04 ± 0.00	0.01 ± 0.01
	T		0.03 ± 0.01	0.03 ± 0.00	0.08 ± 0.01	0.04 ± 0.01	0.17 ± 0.02	0.04 ± 0.01	0.33 ± 0.02	0.10 ± 0.03
	C	POXC	179 ± 3	197 ± 12	199 ± 48	222 ± 2	309 ± 27	392 ± 22	367 ± 70	232 ± 7
	T		185 ± 48	209 ± 2	263 ± 5	344 ± 3	551 ± 14	551 ± 14	602 ± 57	593 ± 106
	C	CO_2	5.1 ± 0.8	3 ± 0.43	3.8 ± 0.91	2.8 ± 0.62	2.4 ± 0.3	1.8 ± 0.3	1.8 ± 0.08	2.4 ± 0.13
	T		6.7 ± 1.25	1.4 ± 0.14	14.3 ± 3.88	5.2 ± 0.81	7.4 ± 1.5	13.9 ± 6.71	6.7 ± 0.58	3.8 ± 0.08
Almond 2	C	MBN	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.00 ± 0.00	0.02 ± 0.01	0.01 ± 0.00
	T		0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.04 ± 0.00	0.01 ± 0.00	0.06 ± 0.00	0.02 ± 0.00
	C	MBC	0.06 ± 0.01	0.05 ± 0.02	0.06 ± 0.01	0.05 ± 0.02	0.13 ± 0.03	0.03 ± 0.00	0.03 ± 0.00	0.02 ± 0.01
	T		0.05 ± 0.01	0.05 ± 0.02	0.09 ± 0.00	0.04 ± 0.00	0.18 ± 0.03	0.05 ± 0.01	0.31 ± 0.03	0.07 ± 0.03
	C	POXC	155 ± 26	259 ± 43	199 ± 48	222 ± 2	303 ± 25	356 ± 30	309 ± 27	219 ± 7
	T		176 ± 8	225 ± 22	263 ± 5	344 ± 3	575 ± 16	271 ± 29	555 ± 4	437 ± 26
	C	CO_2	5.1 ± 0.78	4.6 ± 1.56	3.8 ± 0.91	2.8 ± 0.62	2.5 ± 0.27	1.8 ± 0.3	3.5 ± 0	3 ± 0.06
	T		8.1 ± 2.34	1.4 ± 0.16	14.3 ± 3.88	5.2 ± 0.81	7.4 ± 1.5	13.9 ± 6.71	10.6 ± 0.14	9.9 ± 0
Almond 3	C	MBN	0.01 ± 0.00	0.02 ± 0.01	0.01 ± 0.00	0.04 ± 0.02	0.02 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00
	T		0.01 ± 0.00	0.03 ± 0.00	0.05 ± 0.02	0.05 ± 0.00	0.04 ± 0.00	0.03 ± 0.00	0.03 ± 0.01	0.02 ± 0.00
	C	MBC	0.03 ± 0.00	0.01 ± 0.00	0.03 ± 0.00	0.01 ± 0.00	0.09 ± 0.03	0.04 ± 0.01	0.12 ± 0.00	0.05 ± 0.00
	T		0.03 ± 0.00	0.01 ± 0.00	0.07 ± 0.02	0.03 ± 0.00	0.20 ± 0.03	0.21 ± 0.02	0.29 ± 0.02	0.18 ± 0.00
	C	POXC	269 ± 9	242 ± 5	413 ± 6	435 ± 21	495 ± 17	456 ± 2	394 ± 7	304 ± 5
	T		266 ± 6	236 ± 3	455 ± 34	434 ± 25	591 ± 15	436 ± 10	462 ± 90	398 ± 3
	C	CO_2	3.8 ± 0.82	3.4 ± 0.93	2.6 ± 1.03	1.9 ± 0.52	3.6 ± 1.25	3.5 ± 1.61	4.6 ± 1.03	8.6 ± 0.35
	T		3.6 ± 0.23	2 ± 0.28	2.6 ± 0.43	9.5 ± 8.33	6.1 ± 1.95	5.4 ± 3.02	4.5 ± 0.15	16.4 ± 0.59
Almond 4	C	MBN								
	T									
	C	MBC								
	T									
	C	POXC	147 ± 6	214 ± 30	265 ± 17	129 ± 32	423 ± 7	266 ± 5	350 ± 35	362 ± 19
	T		156 ± 5	258 ± 9	307 ± 22	218 ± 23	528 ± 25	488 ± 4	451 ± 33	473 ± 19
	C	CO_2	6 ± 0.51	4.5 ± 0.65	3.2 ± 0.57	10.4 ± 5.71	3.2 ± 0.81	15.7 ± 12.18	7.1 ± 0	5.8 ± 0
	T		2.7 ± 0.19	3.4 ± 0.53	4.8 ± 0.16	4 ± 0.85	7.5 ± 1.55	5.4 ± 1.13	11.1 ± 1.1	7.5 ± 0
Walnut	C	MBN	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.03 ± 0.01	0.04 ± 0.03	0.02 ± 0.01
	T		0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.02 ± 0.01	0.08 ± 0.00	0.02 ± 0.00	0.11 ± 0.01	0.02 ± 0.00
	C	MBC	0.04 ± 0.00	0.01 ± 0.00	0.05 ± 0.00	0.02 ± 0.00	0.08 ± 0.01	0.10 ± 0.01	0.08 ± 0.04	0.07 ± 0.01
	T		0.04 ± 0.00	0.02 ± 0.00	0.06 ± 0.01	0.02 ± 0.00	0.30 ± 0.01	0.12 ± 0.00	0.09 ± 0.00	0.04 ± 0.00
	C	POXC	388 ± 2	153 ± 4	403 ± 0	167 ± 7	365 ± 19	306 ± 3	372 ± 29	280 ± 75
	T		403 ± 0	159 ± 12	531 ± 26	400 ± 6	695 ± 4	340 ± 27	564 ± 12	409 ± 3
	C	CO_2	2.4 ± 0.31	2.7 ± 1.69	1.2 ± 0.27	0.9 ± 0.49	2.8 ± 0.26	2.4 ± 0.83	6.4 ± 1.04	17.4 ± 4.76
	T		5.3 ± 4.2	1.2 ± 0.47	4.2 ± 1.67	9 ± 6.33	5.9 ± 4.54	2.5 ± 1.3	9.3 ± 1.4	6.7 ± 1.06

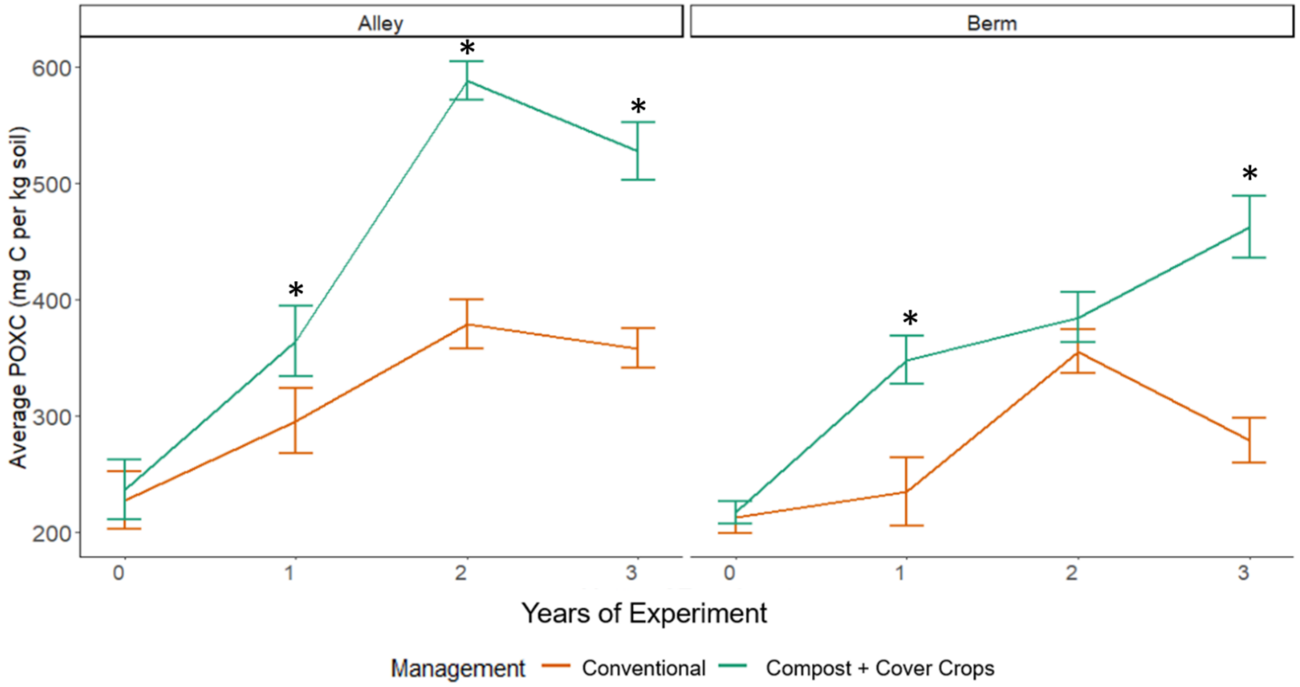


Figure 10. Average POXC across sites, with standard error bars of the mean. The orange line represents conventional, while the green represents the treatment plots of compost+ cover crops. Asterisks indicate p< 0.05.

As an indicator for reactive C, the POXC levels for most sites were similar at the beginning of the study with a mean of 223.8 ± 9.7 mg /kg soil (Figure 10). Management had a significant effect across sites ($p < 0.05$) on the amount of POXC, with the compost + cover crops plots increasing on average by 81% by year three. Throughout the study, both management plots demonstrated an increase in POXC until year three. By year three there was a significant increase for both alleys and berms across sites between the management of compost + cover crops compared to conventional ($p < 0.05$). There was a significant difference between the conventional alley and compost + cover crops alleys for year 1, 2 and 3 ($p < 0.001$) with treatment plots having 164 ± 29 mg C per kg soil more than conventional plots in year 3 (Table 5). There was a significant difference between the conventional berms and compost + cover crops berms for year 1 and year 3 ($p < 0.001$) with treatment plots having 182 ± 32 mg C per kg soil more than conventional plots in year 3 (Table 5).

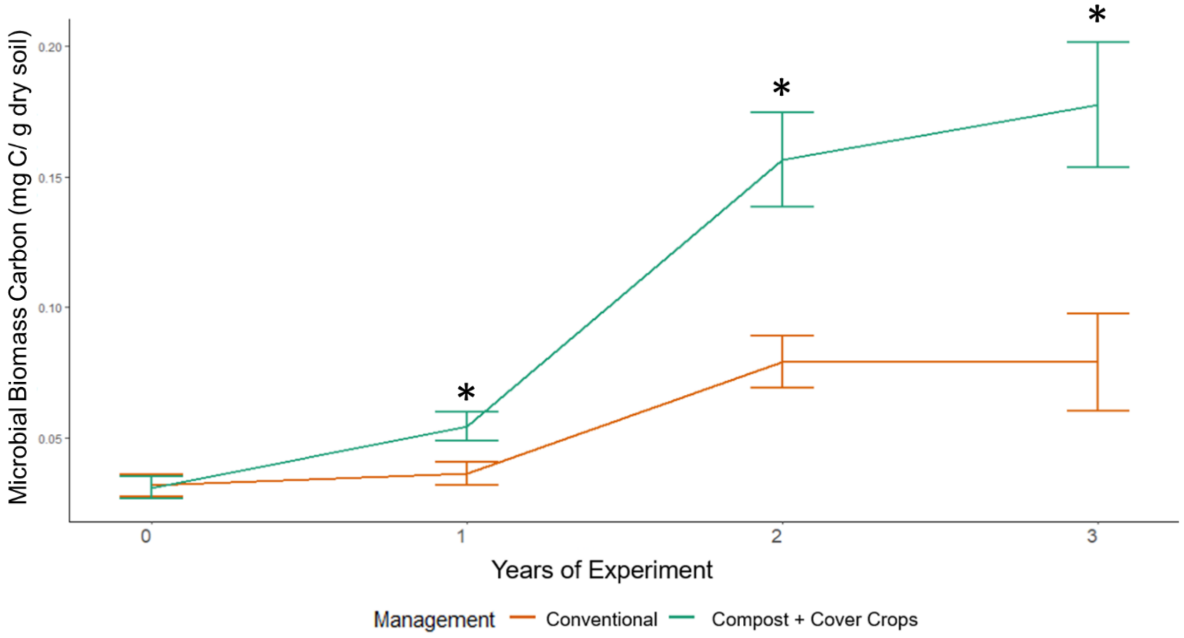


Figure 11. Microbial biomass carbon averaged across sites over the four years of the study, combining data from both alley and berm locations. Year 0 corresponds to 2021, and Year 3 corresponds to 2024. Asterisks indicate significance at p < 0.05.

The shift in MBC across all sites exhibited a consistent trend of increase in plots managed with compost + cover crops compared to conventional management (Figure 11). Management practices had a significant influence on MBC levels ($X^2 = 32.1$, $p < 0.0001$), as did location ($X^2 = 81.4$, $p < 0.0001$) and year ($X^2 = 169.5$, $p < 0.0001$). The interaction between management and year was also significant ($X^2 = 16.8$, $p < 0.05$), indicating that the effects of management practices on MBC varied over time. In Year 1, MBC was significantly higher in compost + cover crops plots compared to conventional plots, with an estimated difference of 0.36 ± 0.17 (p=0.03). This difference increased in Year 2, with an estimated difference of 0.69 ± 0.17 (p<0.0001), and Year 3, with an estimated difference of 0.88 ± 0.17 (p<0.0001). Across all management practices, alleys consistently contained approximately twice the amount of MBC compared to berms, with significant differences between these locations ($p < 0.05$). By year three, MBC increased by 0.22 (± 0.03) mg C/g in alleys and 0.07 (± 0.03) mg C/g in berms under compost + cover crops management, resulting in percentage increases of 573 ± 98% for alleys and 307 ± 100% for berms.

In contrast, conventional management practices resulted in increases of 0.08 (± 0.03) mg C/g in alleys and 0.01 (± 0.01) mg C/g in berms, with percentage increases of 200 ± 59% and 59 ± 21%, respectively.

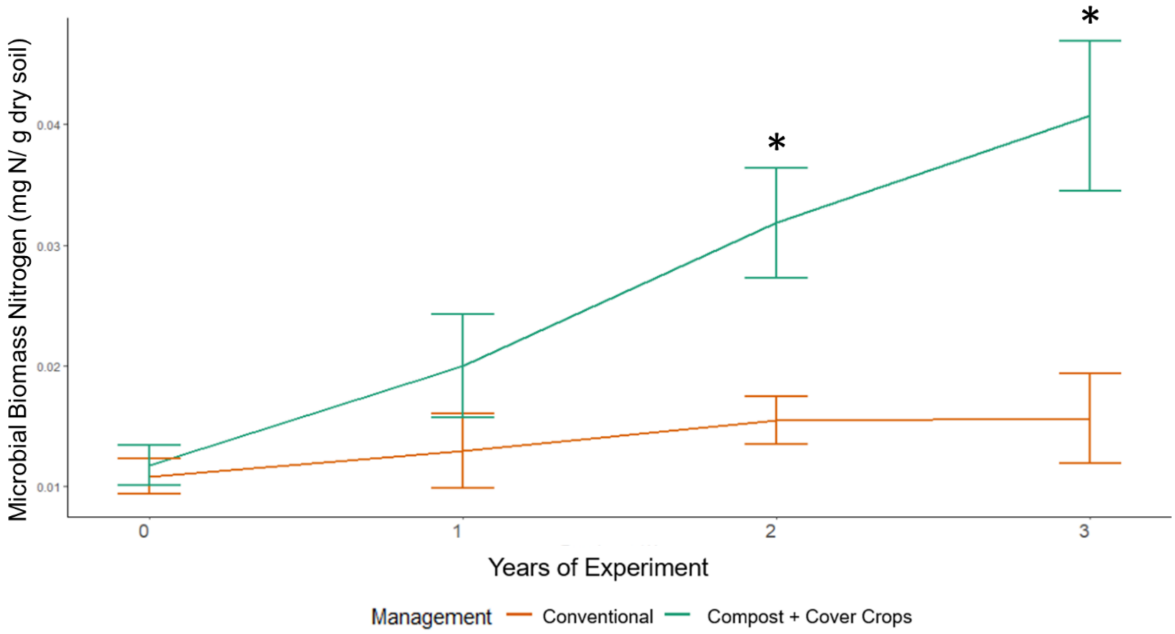
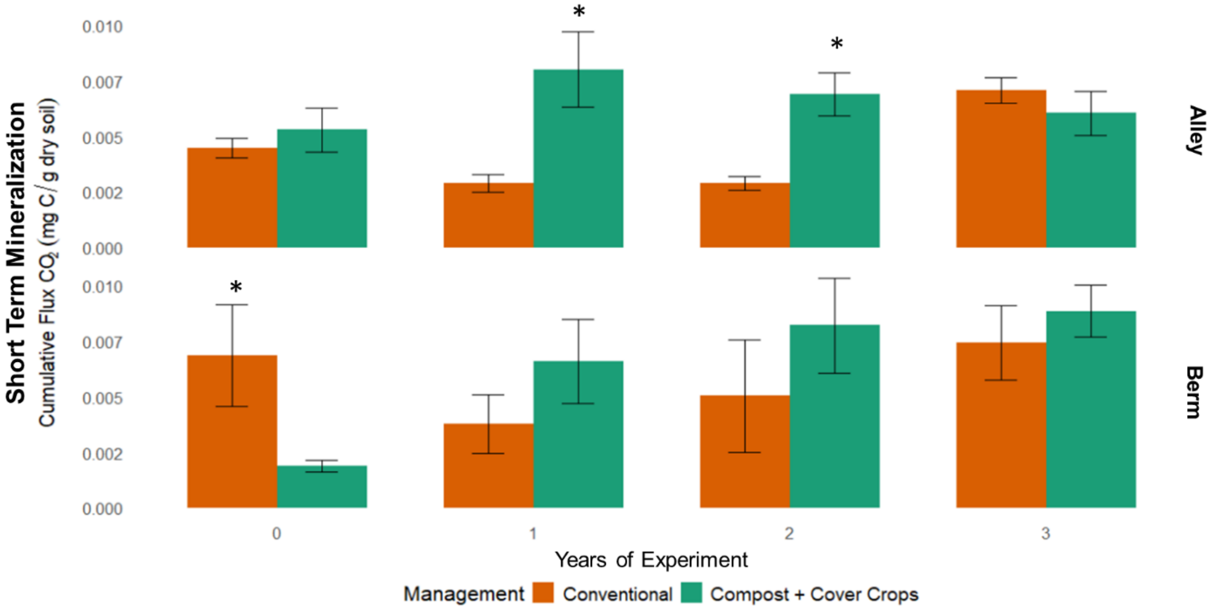


Figure 12. Microbial biomass nitrogen averaged across sites over the four years of the study, combining data from both alley and berm locations. Year 0 corresponds to 2021, and Year 3 corresponds to 2024. Asterisks indicate significance at p < 0.05.

MBN consistently increased in plots managed with compost + cover crops compared to conventionally managed plots across all sites (Figure 12). Management showed a significant effect (X^2 = 24.9, *p*<0.0001), with compost + cover crops consistently improving MBN compared to conventional management. Location (Alley vs. Berm) also had a significant impact (X^2 = 34.5, *p*<0.0001), MBN in the alleys was approximately seven times higher than in the berms. In addition, year was a significant effect (X^2 = 39.8, *p*<0.0001), reflecting temporal variations in MBN levels. Interactions between management and year (X^2 = 11.8, *p*=0.008) and location and year (X^2 = 19.7, *p*<0.001) were also significant, indicating that the effects of management practices and spatial differences (alley vs. berm) varied over time. Across locations, MBN was significantly higher in compost + cover crops plots compared to conventional plots, with an estimated difference of 0.6 ± 0.2 (*p*=0.003). This trend persisted and became more pronounced in Year 3, where compost + cover crops plots exhibited an estimated MBN difference of 0.9 ± 0.2 compared to conventional plots (p<0.0001). These findings highlight the sustained and increasing benefits of compost + cover crops for enhancing MBN over time. By year three, compost + cover crops management led to increases of 487 ± 95% for alleys and 55 ± 14% for berms. In contrast, under conventional practices, only led to an increase of only 113 ± 37% in alleys and a decrease of -21 ± 7% in berms.



* = *p* < 0.05

Figure 13. Cumulative CO2 (mg C/dry soil) fluxes averaged across sites that were included in the microbial respiration incubation study conducted over four days. The data spans four years, with 2021 designated as Year 0 (baseline) and 2024 as Year 3 of the study. Cumulative fluxes were calculated based on the respiration measurements taken during the 4-day incubation period. An asterisk (*) indicates a significant difference between the management plots of conventional and compost + cover crops.

Short-term C mineralization rates varied across locations of alley and berms through the years, with a compost + cover crops plots demonstrating significantly ($p = 0.04$) higher cumulative soil fluxes for most of the years (Figure 13). Across sites, after the baseline year (2021), the average increase in CO_2 emissions from the compost + cover crops plots were 118 ± 0.002% for 2022, 90 ± 0.001% for 2023, 3 ± 0.001 % for 2024. There was a significant interaction effect between management and date ($p < 0.05$.

Soils under conventional management exhibited lower microbial respiration rates compared to compost + cover crops management, for all years except 2024 (Table 5). After application, across sites there was a significant increase in cumulative CO_2 emissions in both the alleys and berms, see figure 13. There was not a significant difference between locations and emissions. By year three, there was not a significant difference between CO_2 emissions due to the change in management.

There was not an obvious trend of increased or decrease nitrous oxide (N_2O)and methane (CH_4) with the addition of compost + cover crops across the sites and throughout the study. Management plots did not demonstrate a significant increase in these gases with the addition of compost + cover crops. There was also no significant difference between the alley and berm, as the measurements were highly variable.

Discussion

Physical Indicators

The physical properties of the baseline soils across sites were extremely compacted with higher than ideal bulk density for roots, especially in the alley, and exhibited low aggregation leading to potential erosion via water and wind. These characteristics, often resulting from management practices in conjunction with inherent soil type effects, contributed to the degraded soil quality observed at the start of the study. However, throughout the study period, physical indicators of soil health demonstrated consistent improvement, highlighting the effectiveness of the compost and cover crop management practices in enhancing soil structure and functionality. Compost application to agricultural lands is widely recognized for its effectiveness in enhancing the physical properties of soils, particularly those with poor structure and low organic matter levels (S. Brown & Cotton, 2011; Kranz et al., 2020). Additionally, cover crops have proven effective in reducing soil compaction, increasing aggregation and pore space, particularly when they include a diverse mix of plant species (Adetunji et al., 2020). Our study utilized a "soil builder mix" that included daikon radishes, which are known for their ability to penetrate and alleviate compacted soil layers.

Compacted soils with high bulk density can adversely affect crop health by reducing nutrient infiltration and limiting root growth. Compost has long been recognized for its ability to alleviate soil compaction (Aggelides & Londra, 2000; Curtis & Claassen, 2009), and so has the planting of cover crops (Haruna et al., 2020). By the end of our study, the bulk density of the soils at the 10 cm at the study sites decreased by 0.15 g/cm^3. These results are consistent, but higher than, the findings from a study on citrus orchards, where the bulk density at the 0-10 cm depth decreased by 0.07 g/cm^3 after two years of annual mulch and cover crop applications(Dung et al., 2022). The response of soil physical properties to compost and cover crops can vary depending on the soil's intrinsic texture characteristics (Siedt et al., 2021). For instance, Chen et al. (2021) observed notable improvements in soil quality from applying straw compost in semi-arid sandy soils. Conversely, Tian et al. (2015) reported a decline in soil quality with the use of complete organic manure in loamy soils.

In agricultural systems, the formation of larger and more stable soil aggregates plays a crucial role in enhancing soil aeration, water infiltration, and root penetration, thereby improving the availability of water and nutrients to plants (Annabi et al., 2007). Enhanced aggregate stability also mitigates soil erosion and compaction risks, preserving soil structure and function over the long term. The reduction in microaggregates and the concurrent increase in larger aggregates suggest that the soil in these plots is becoming more resistant to erosion and compaction. These findings are consistent with research by Scavo et al. (2022), who reported that the application of compost and the use of cover crops significantly enhance soil aggregate stability. These changes occurred relatively quickly, suggesting that added organic matter from both cover crops and compost can rapidly enhance wet aggregate stability. Soil aggregate stability is influenced by intrinsic properties like texture and mineralogy, alongside management-sensitive factors such as soil organic matter (Bissonnais, 1995; Mamedov et al., 2017). Soil clay content is closely linked to aggregate stability, as clay particles serve as cementing agents that promote aggregate formation (Wagner et al., 2007). Notably, in our high-clay-content sites, we observed the most rapid and significant increases in aggregate size. Our results of improvements to aggregate stability align with other compost studies (Annabi et al., 2007; Whalen et al., 2003). However, some studies suggest that organic amendments may have limited effects on aggregate stability in highly compacted or degraded soils. McClelland et al. (2021) found that in certain soils, the benefits of compost on aggregate stability were not as pronounced unless mechanical interventions such as tillage were also applied. It suggests that while compost and cover crops can significantly improve soil structure, the degree of improvement may depend on the initial soil conditions. In some studies, it is suggested that the addition of organic amendments like compost can enhance the formation of larger aggregates, promoting the stabilization of particulate organic matter (POM) rather than mineral-associated organic matter (MAOM) (Ozlu & Arriaga, 2021; Shi et al., 2023; Six et al., 2002) This shift may indicate that the added carbon is contributing to the formation of stable aggregates through improved soil structure, rather than being primarily mineral-associated. Potentially, this stabilization pathway might lead to a labile or less persistent soil carbon pool that is more readily available for microbial decomposition and then release (Poeplau et al., 2021). We demonstrated that compost and cover crops can improve physical soil health indicators relatively quickly, which will have implications for improved soil functioning at the structural level, potentially improving water dynamics while decreasing erosion via wind and rain.

Chemical indicators

The addition of compost and cover crops led to improvements in the chemical indicators of soil health we monitored throughout the study: pH, EC, CEC, plant available nitrogen, soil C content, and storage. This change is likely driven by the direct increase in soil organic matter from compost and the indirect contribution from the decomposition of root biomass from the cover crops.

By enhancing soil organic matter, compost and cover crops buffer soil pH and enhance CEC by providing additional negatively charged sites that facilitate cation retention and exchange (Oyetunji et al., 2022). Additionally, compost helps to moderate electrical conductivity (EC) by supplying balanced nutrients, thus reducing the risk of salinity-induced stress and fostering a more favorable soil chemical environment (Scotti et al., 2016). There was a significant increase in EC across the treatment plots, which relates to the addition of cations and anions to the soil from the compost (Gondek et al., 2020). A significant increase in CEC was observed in the treatment plots, particularly in the alley regions. The significant increase in CEC observed in our orchard sites across alleys and berms was 37 ± 6%, which is lower than a previous study on almonds in the Central Valley. Villa et al (2021) reported an average increase of 58 ± 22% in CEC across two soil types (loam and sand) following green waste compost amendments (Villa et al., 2021). This indicates an improved ability of the soil to retain and exchange nutrients, which is critical for maintaining soil fertility and plant health. The application of compost is known to enhance CEC by increasing the soil's ability to hold positively charged ions (cations) such as potassium, calcium, and magnesium. The positive impact of compost on CEC has been well-documented in the literature. The study by Murphy (2015), emphasized that the increase in organic matter from compost leads to higher CEC, which in turn improves nutrient availability and reduces the risk of nutrient leaching. Additionally, Repullo-Ruibérriz de Torres et al. (2021) found that cover crops contribute to increasing CEC by adding organic matter through root turnover and biomass decomposition, further enhancing the soil's nutrient-holding capacity. The findings align with these studies, confirming that the use of compost and cover crops can significantly improve soil fertility through enhanced CEC. Some studies suggest that the impact of compost on CEC may be limited with certain soil types. Rakhsh et al. (2017)reported that in coarser soils with low clay content, the increase in CEC from organic amendments may not be as pronounced. This could explain some of the variability observed in our study, where certain sites exhibited smaller increases in CEC, particularly in the berm areas. This finding suggests that the effectiveness of compost in improving CEC may depend on soil texture and composition. The chemical properties of soil, including pH, EC, and CEC, are interrelated and collectively impact soil fertility and plant nutrient availability.

Compost quickly provides ample amounts of available nitrogen in the form of NH_4^+, a finding that is well reported across agricultural systems (Goldan et al., 2023; Jain & Kalamdhad, 2020). The application of compost in our study led to rapid increases in NH_4^+ levels in the soil, indicating that compost quickly provides plant-available nitrogen. This is a critical finding for orchard systems where nitrogen is often a limiting nutrient for optimal levels of production. However, NO_3^- levels did not show consistent increases across all sites, suggesting that nitrate is more prone to leaching, particularly during periods of high NH_4^+ levels is consistent with findings from Sullivan et al., (1998) who reported that compost supplies nitrogen in a slow-release form as NH_4^+, reducing the risk of nitrogen loss and providing a more sustainable source of nutrients. In addition, the use of cover crops has been shown to reduce NO_3^- leaching by increasing water retention, minimizing soil erosion, and enhancing nitrogen cycling (Ordóñez-Fernández et al., 2018). Our study aligns with these results, demonstrating the effectiveness of compost and cover crops in managing nitrogen availability in orchard systems.

However, Wang et al. (2024) noted that compost application can sometimes result in increased NO_3^- levels, especially in wetter climates or under conditions of excessive irrigation. This was observed at one site, Almond 3, where compost was applied in late fall. We documented a significant increase in NO_3^-, likely due to the wetter soil environment along with decrease nutrient demand from trees preparing for dormancy. However, for most of our sites, this contrasts with our findings where NO_3^- levels remained relatively responsive to fertigation events. Some research suggests that compost may not always provide sufficient nitrogen for high-demand crops like almonds, which often require additional inputs of synthetic fertilizers. Bijay-Singh & Craswell (2021) argue that compost alone may not meet the nitrogen needs of certain crops, particularly during peak growth periods. This highlights the potential need for supplemental nitrogen inputs, especially in high-yield systems like almond and walnut orchards. The baseline levels of soil C content were very depleted, but the implementation of compost and cover crops resulted in a significant increase in C storage at three of five sites, highlighting the effectiveness of these stacked practices in enhancing soil C levels. At the onset of our study, the average cumulative (30 cm depth) across sites and plots soil C content was 32 ± 3 Mg C ha^{-1}, the annual compost application added an average of 5.13 Mg C ha^{-1}, which would have in total by year three a potential increase of ~15 Mg C ha^{-1}. If the increases in SOC storage were completely from the exogenous C, we would expected values near 55 Mg C ha^{-1}. However, we observed an average cumulative soil C content was 61 ± 3 Mg C ha^{-1} , resulting in a 91% increase in soil C content from the start to the end of the study. The difference of approximately 6 Mg C ha^{-1} could be attributed to carbon sequestration of trees photosynthetic processes, which truly support climate mitigation by the removal of atmospheric $CO_{2.}$ SOC can contribute to better soil structure, water retention, and nutrient availability, which are critical in orchard systems that experience soil degradation due to conventional management practices. The soil C concentration of the study had some interesting but expected trends, with the 10 cm depth demonstrating the most change in soil C concentration compared to the 30 cm depth. These findings are in line with the results of other studies that highlight the effectiveness of compost in boosting SOC. This is alignment with other orchards studies that found that the addition of organic amendments like compost significantly increases SOC stocks over time, promoting soil resilience and C sequestration (Lepsch et al., 2019; Nichols et al., 2024). Based on the observed changes in wet aggregate stability, it is likely that the added carbon is primarily contributing to the formation of POM, which is typically more labile and can be more easily decomposed, however persistence is a function of environmental and biological controls rather than just molecular structure. The persistence of the POM pool will largely depend on microbial activity inhibition, the degree of microbial limitations and carbon use efficiency, and microbial access constraints related to potential occlusion within fine aggregates within larger aggregates (Cotrufo et al., 2019; Cotrufo & Lavallee, 2022). It is also important to note that while our study indicates an increase in SOC, it is difficult to determine whether these changes were entirely the result of carbon inputs of compost. There is likely an increase in root exudation as well, which is a key process in forming or modifying MOAM by attaching organic compounds to the minerals (Keiluweit et al., 2015; Li et al., 2021; Poeplau et al., 2021). Similarly, other research reported that cover crops also contribute to SOC by adding organic matter through root exudates and biomass decomposition, further enhancing soil C storage (Castellano-Hinojosa et al., 2023; Ma et al., 2024). Moreover, the combination of compost and cover crops (a "stacked" practice) has been shown to have synergistic benefits for improving SOC storage. While the permanence and stability of these gains are still not fully understood, this study supports the hypothesis that using both practices together results in greater increases in SOC than using either practice alone.

While our results demonstrate a clear increase in SOC, some studies suggest that chemical fertilizers can also contribute to SOC improvements, particularly in the short term. Khalsa et al. (2020) showed that intensive nitrogen fertilization can increase SOC by promoting faster plant growth and biomass production. We noted in our conventionally managed plots we do see an increase in SOC, just not to the magnitude of increase we saw with our compost + cover crops plots. This highlights the need for a balanced approach that incorporates organic amendments to conventional fertilization methods to sustain SOC levels over time. More research is needed to understand if this approach increased soil C storage via increased sequestration or via the direct exogenous inputs of C via the compost and cover crops, and whether the increase in soil C will be retained and protected from microbial decomposition.

Biological Indicators

We assessed biological soil health through measures of microbial biomass carbon and nitrogen, active carbon (POXC), and short-term C mineralization all followed a similar trend that by year 3, there was a significant difference between the plots that received compost and cover crops compared to conventionally managed.

Compost and cover crops improve microbial activity by providing a steady supply of organic matter, which serves as an energy source for soil microorganisms (Gougoulias et al., 2014). One such food source POXC, also known as active soil carbon, which is the portion of soil organic matter that is easily oxidized and biologically active (Duval et al., 2018). POXC is considered a key indicator of soil health because it responds quickly to changes in soil and crop management. As demonstrated in our study, although these changes unfold more slowly, they do materialize, typically showing significant improvements after about two years. This delay is influenced by several factors: the time required for microbes to decompose and utilize new organic matter, the need for soil conditions like moisture and pH to stabilize, and the gradual release of nutrients that microbes need to boost their activity (Wang et al., 2022).

However, it is important to note that some research challenges the reliability of certain microbial activity indicators, such as POXC. According to Margenot et al. (2024), POXC may not accurately measure labile carbon as previously thought but rather oxidizes polyphenols, which can skew results. Despite this, higher rates of available C can lead to increases in microbial growth and activity(Yang et al., 2024). The overall trends in microbial biomass and activity measured in our study are consistent with findings from other research in orchard systems (Baldi et al., 2018; Bechara et al., 2018; Yao et al., 2005).

We found a significant increase in microbial biomass carbon and microbial biomass nitrogen in treatment plots receiving compost and cover crops by the second and third years. These increases reflect enhanced microbial activity and nutrient cycling in the soil, which are crucial for improving overall soil health (Haruna et al., 2020; Nicolardot et al., 1994). Significant differences were also observed between the alley and berm areas, with alley regions consistently exhibiting higher microbial biomass. As both areas received compost, but only the alleys were planted with cover crops, it could be indicative that microbial biomass carbon and nitrogen were more readily responding to the multi-species cover crops inputs of root exudates and root biomass once terminated. A finding supported by Repullo-Ruiberriz de Torres et al., who found that microbial biomass was higher in alley with cover crops compared to soils beneath trees in pecan ochards. (2021). The increases in microbial biomass carbon and nitrogen in treatment plots align with other studies that have demonstrated the beneficial effects of organic amendments, such as compost, on microbial biomass (Bertrand, 2019; Tian et al., 2015). While our results show a clear increase in microbial biomass in treatment plots, some studies suggest that microbial biomass may not always respond as significantly to compost and cover crop treatments under all conditions. For example, Vukicevich et al. (2019) found that microbial biomass can be influenced by soil texture and cover crop species. In cases where soils are compacted or have low organic matter content, microbial biomass may not increase as expected, highlighting the importance of site-specific factors in determining the effectiveness of soil amendments.

The higher rates of short-term C mineralization observed indicate an increase in microbial respiration of CO_2, is a key indicator of soil microbial activity (Koritschoner et al., 2022). The compost and cover crops provide additional organic matter that microbes decompose, releasing CO_2 in the process. This metric combined with POXC are related are measures of active organic matter that may provide early indication of soil C stabilization and mineralization processes. With POXC better reflecting SOM stabilization while short term C mineralization reflects SOM mineralization. In our study, we observed that after the first year, SOC storage across sites decreased, which was initially reflected in an increase in mineralizable C and POXC, indicating an increase in microbial-accessible carbon. This suggests that early on, the addition of compost and cover crops likely enhanced the availability of more labile carbon forms, which stimulated microbial growth and activity(Gentsch et al., 2024; Rath et al., 2022). However, by year four, we noticed a decrease in the trend, with no significant increase in respiration, despite a continued increase in POXC. This transition may indicate that the added compost and cover crops are promoting the formation of organic matter that is less readily available to microbes, potentially contributing to long-term carbon sequestration. The biological component of soil health is a crucial component to measure when assessing changes in management influence on soil health, as these indicators are the underpinning processes to understanding nutrient availability, carbon storage, and the functioning of the soils as a true living system full of microbial activity.

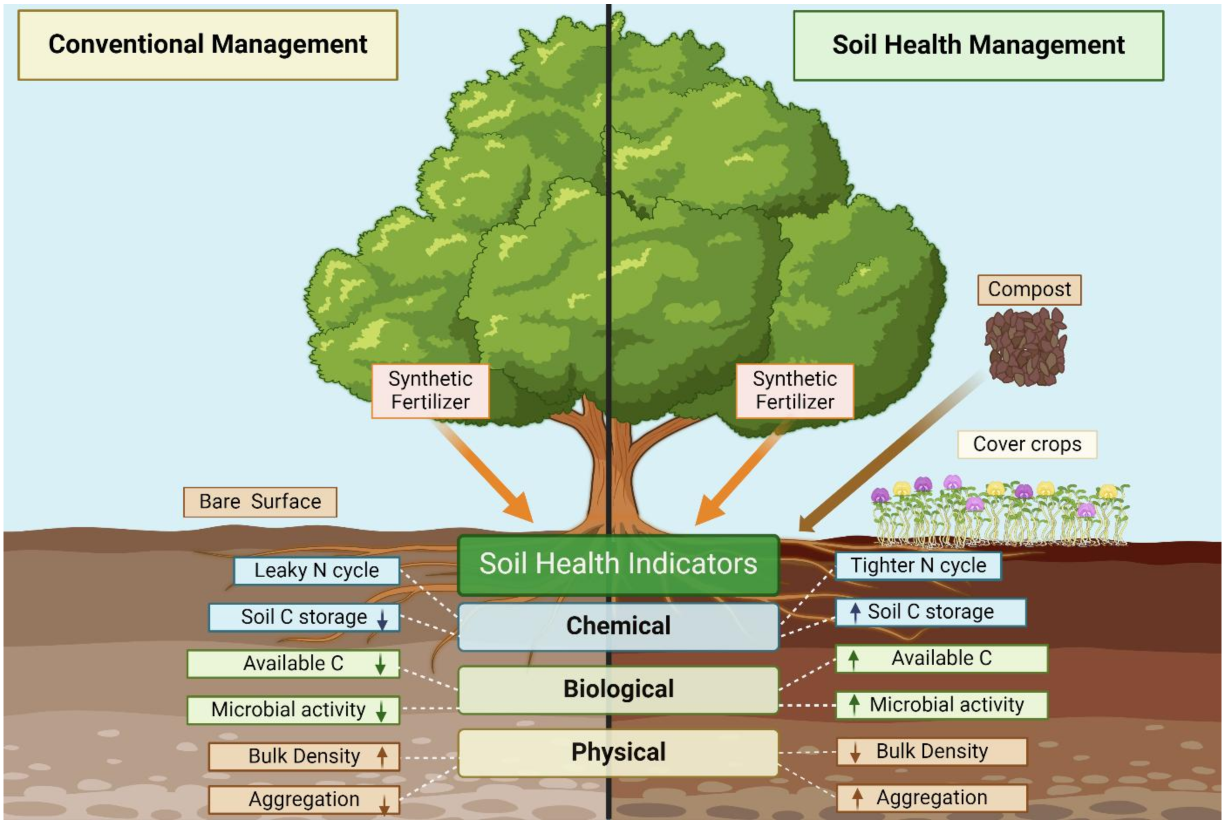


Figure 3.Comparison of conventional management and soil health management on the soil health indicators organized into chemical, biological, and physical indices that were measured within our study.

Management Implications

The stacked practices of compost and cover crops in our study demonstrated there were benefits to soil health's chemical, biological, and physical properties (Figure 14). Compost has demonstrated that it does quickly provide available nitrogen in the form of NH_4^+. The release of nitrogen from compost depends on factors influencing the rate of mineralization of organic nitrogen to plant-available forms of inorganic nitrogen. These factors include soil and management practices such as irrigation, microbial activity, and overall edaphic soil conditions. Whether the amount of inorganic nitrogen provided from compost is sufficient to support almond production without chemical fertilizer isn't quantified in this study. Some studies have already demonstrated that compost can provide the nutrients necessary for farmers to shift wholly over to organic amendments (Hernández et al., 2016). The aim of our study was not to provide data that these practices should be used instead of conventional management, but rather if they have synergistic beneficial effects to current management practices. The addition of compost and implementation of cover crops can help to improve the soil conditions that promote a tighter nitrogen cycle(Rath et al., 2022; Repullo-Ruibérriz de Torres et al., 2021). A more efficient nitrogen cycle relies on the improvement of the soil health indices that we monitored throughout our study, encompassing the biological, chemical, and physical components. Integration of cover cropping into the orchard's current operational system requires careful management to balance benefits with potential competition for water and nutrients, which relies heavily on timing of planting, and termination. In our system, winter cover crops were the best choice, as they do not require additional water and rely on winter rain events. The timing of termination can mitigate these risks of nutrient competition and ensure optimal performance of both cover crops and nut tree production, our management recommendation was to terminate in March after bees were removed, and before the spreading of compost. Termination methods varied across the study, with most terminating with mowing and some with light tillage. Another challenge to the implementation of both compost and cover crops in almond orchards is that harvesting practices currently use the ground to dry out hulls and to harvest. Most of the orchardists in our study did not report having any issues with the timing or shift of alley floor management to adjust to the use of compost and cover crops. While there are changes in management to integrate these practices, it was not prohibitive.

From an economic standpoint, cover crops along with compost are front-loaded costs, which might take time to see the benefits. Our study demonstrated that the effect was not immediate but became significantly improved by year 3. In states like California, there are programs which can help to cover the implementation costs of these practices, such the Soil Health Program and connecting with local Resource Conservation Districts to apply for grants. It is difficult to put a price on the functions of a healthy soil system that is more resilient to both abiotic stressors, such as drought, and biotic stressors, such as pests. This is especially crucial as the severity of these stressors is expected to rise with climate change. Healthier soils can act as a buffer, mitigating the impacts of these stressors while potentially increasing both the productivity and longevity of agricultural systems.

Conclusion

The combination of compost and cover crops in nut orchards is a powerful management strategy for enhancing soil health, fertility, and nitrogen cycling, which contributes to the transition towards more regenerative nut orchard production. While compost alone may not fully replace chemical fertilizers in nut production, our study demonstrates that integrating compost and cover crops into conventional orchard management offers benefits beyond nitrogen supplementation. These practices positively influence multiple biological, chemical, and physical soil health indicators, including microbial activity, aggregate stability, and carbon storage. All of which demonstrate the power of these practices to restart the ecological soil system services that support nutrient cycling and improved plant/soil interactions. These improvements were observed independently of site factors such as soil type, past management, and irrigation, highlighting the broader applicability of this integrated approach for promoting soil health in diverse orchard systems. This approach not only promotes agroecological resilience to climate change but also supports climate mitigation efforts through the potential of increased soil carbon sequestration.

Acknowledgments

This work was supported by the Conservation Innovation grant through the Natural Resource Conservation Services (NR203A750008G013), and by NSF-NRT CONDESA: Convergence of Nanoengineered Devices for Environmental and Sustainable Applications (NSF-DGE-2125510). A special thanks to the following people who have helped contribute to this research, soil processing, and manuscript editing: E. Perez-Agredano, V. Evans, A. Terriberry, J. Gonzales, J. Leon, P. Hundal, J. Hoff, E. Bischak, C. Cooper. We thank Dr. Robin B. Trayler and the staff of the Stable Isotope Ecosystems Laboratory of UC Merced for their assistance with stable isotope and elemental analysis. The authors declare no conflict of interest.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the final editing of this work the authors used ChatGPT by OpenAI to increase readability via syntax and fix grammatical errors. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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