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Early-stage impacts of conservation agriculture on soil health in a French Mediterranean irrigated system

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ABSTRACT

In Mediterranean regions, climate change has intensified droughts and extreme weather events, accelerating soil degradation through organic matter loss, erosion, and nutrient depletion. Conservation agriculture (CA), involving practices like zero or reduced tillage, crop diversification, and soil cover maintenance, offers a resilient strategy for mitigating these challenges. This study examines the short-term effects of irrigated CA on soil health in Mediterranean conditions over 3 years (2021–2023). Using the Biofunctool® field kit (assessing carbon transformation, nutrient cycling, and structure maintenance) alongside functional indicators from the laboratory, the study compares CA with conventional tillage (CT) under different water supply methods: sprinkler, subsurface drip, and rainfed conditions. Results reveal that CA enhances soil health indicators from the first year, improving soil aggregation and carbon transformation compared to CT. By 18 months, Soil Health Index (SHI) scores were 38% higher in CA than in CT. Minimal soil disturbance in CA addressed compaction and maintained SHI 23% higher than CT. Neither the water supply mode nor temporality post-CA adoption significantly affected soil functions in the short term. The complementary use of field-based and laboratory indicators provided a holistic view of soil functionality, confirming the potential of CA to improve soil health under irrigated Mediterranean conditions.

HIGHLIGHTS

- Under Mediterranean conditions, CA significantly improves soil health indicators in the short-term compared to CT
- Incorporating additional soil functional indicators enriches soil health assessments under CA
- Minimal tillage can mitigate soil compaction while maintaining soil health in sensitive Mediterranean soils

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Introduction

In Mediterranean regions, climate change has significantly impacted precipitation and temperature patterns, leading to more frequent, intense, and prolonged droughts (Fader et al. 2016), as well as heightened soil degradation risks (Ferreira et al. 2022). These changes threaten both soil health (Mehra et al. 2018) and agrosystem productivity (Topp et al. 2024). Extreme weather events, including flooding and heatwaves, intensify soil degradation by eroding soil structure, depleting nutrients, and harming soil biota (Furtak and Wolińska 2023). Higher temperatures can accelerate soil organic matter decomposition, reducing soil fertility and structure, while increasing evaporation rates and soil drought. Additionally, altered rainfall patterns cause both prolonged droughts, increasing wind erosion risks, and intense storms that enhance surface runoff and nutrient loss.

Agroecological practices improve agricultural resilience against these challenges under these extreme conditions (Hong et al. 2018). These practices positively impact on the soil's physical, chemical, and biological properties while maintaining acceptable yield levels (Kelly et al. 2021). Specifically, conservation agriculture (CA), which includes soil cover crops, crop rotation and diversification, and reduced to zero soil tillage (FAO 2020), offers numerous advantages in the Mediterranean context, especially under rainfed conditions (Kassam et al. 2012). Reduced soil disturbance enhances soil structure, water infiltration, and aeration (Fuentes et al. 2009), creating suitable conditions for biological activity (Cozim Melges et al. 2024). Surface residues improve soil moisture retention and carbon storage, fostering greater biological activity, while moderating soil temperature and supporting soil organisms (Lee et al. 2019). These improvements in soil properties enhance key soil functions that ultimately boost sustaining productivity while minimizing environmental degradation (Verhulst et al. 2010).

Healthy soils are characterized by good soil functionality translated into high biological diversity and activity, effective nutrient cycling, and resilience to disturbances (Van Bruggen and Semenov 2000). Assessing soil health is then relevant for detecting potential degradation linked to agricultural practices. Different methods are available for evaluating soil functional indicators that can contribute to soil health assessment. For example, microbial respiration, which reflects biological activity, is typically assessed through field samples analyzed under controlled and standardized laboratory conditions. While these laboratory analyses provide detailed and valuable insights into specific soil properties, they primarily measure potential and do not account for the structural state of the soil at the time of sampling. Additionally, these analyses can be expensive, limiting their ability to be conducted frequently or over large areas. In contrast, tools like the Biofunctool® field kit (Thoumazeau et al. 2019a, 2019b) provide an integrative and cost-effective solution for assessing multiple soil functionalities. This tool evaluates key indicators of soil functionalities such as carbon transformation, nutrient cycling, and structural maintenance, directly in the field, offering a quick and practical method proven effective across diverse agricultural contexts (Kulagowski et al. 2021; Perron et al. 2022; Thoumazeau et al. 2024). Its applicability has also been demonstrated in conservation agriculture systems (Pheap et al. 2019). When combined with laboratory analyses, Biofunctool® enables a comprehensive understanding of soil health, balancing the precision of laboratory data with the practicality of on-site evaluations.

Soil health is also influenced by temporality, as soil functions interact over varying time scales (Kibblewhite et al. 2008). While some properties may respond rapidly to agricultural practices, others may take longer to manifest their effects (Al-Kaisi and Lal 2017). For example, mulching can influence soil infiltration in the short term, whereas long-term impacts on soil health, such as changes in soil organic matter content, can take more time to manifest. Therefore, dynamic assessments are essential to gauge the impact of management practices over time, particularly when compared to long-established practices (Lehman et al. 2015). Evaluating these effects allows for a better understanding of the trajectory of practice adoption and facilitates necessary adjustments.

While the benefits of CA on soil health are well documented in the long-term under rainfed conditions, its short-term impacts under irrigated systems remain insufficiently explored. This study aims to assess the early effects of conservation agriculture, water supply methods, and the time elapsed since CA adoption on soil health under irrigated Mediterranean conditions. Soil functional indicators were assessed using both laboratory and Biofunctool® field kit approaches. The study, conducted over 3 years (2021–2023), compares the outcomes of conservation agriculture (CA) and conventional tillage (CT) under three different water supply methods: sprinkler (S), subsurface drip (SSD), and no irrigation (NI). Additionally, in 2024, a minimal tillage intervention, which did not involve turning the soil, was conducted to address soil compaction identified on the site through penetrometer measurements, while maintaining the main principles of conservation agriculture (CA). To evaluate whether this intervention affected soil health, an additional Biofunctool® assessment was performed.

Materials and methods

Site description and experimental design

The study was conducted in southern France (Mediterranean climate), Montpellier, at the INRAE experimental platform (43.647°N, 3.871°E) (PRESTI 2025) over 3 years (2021–2023). Specific plots previously managed under conventional tillage for 20 years were transitioned to conservation agriculture practices starting in autumn 2020. This transition involved implementing (i) no-tillage (direct-seeded), (ii) winter cover crops, and (iii) diversified crop rotations. The soil at the study site is classified as a loam, comprising 21% clay, 43% silt, and 36% sand according to the USDA classification. The soil is alkaline, with a pH of approximately 8.5. A detailed description of the experimental design and additional variables assessed at the site is provided in Dominguez-Bohorquez et al. (2025).

Local climatic conditions were monitored using a Cimel data acquisition system, model 516i, which transmitted data via a GPRS link. This system measured daily averages of air temperature, cumulative global radiation, reference evapotranspiration (ETo), and rainfall (R) (Figure 1). Total annual rainfall amounts were 710 mm in 2021, 758 mm in 2022, and 437 mm in 2023, while total reference evapotranspiration values were 960 mm in 2021, 1026 mm in 2022, and 1023 mm in 2023.

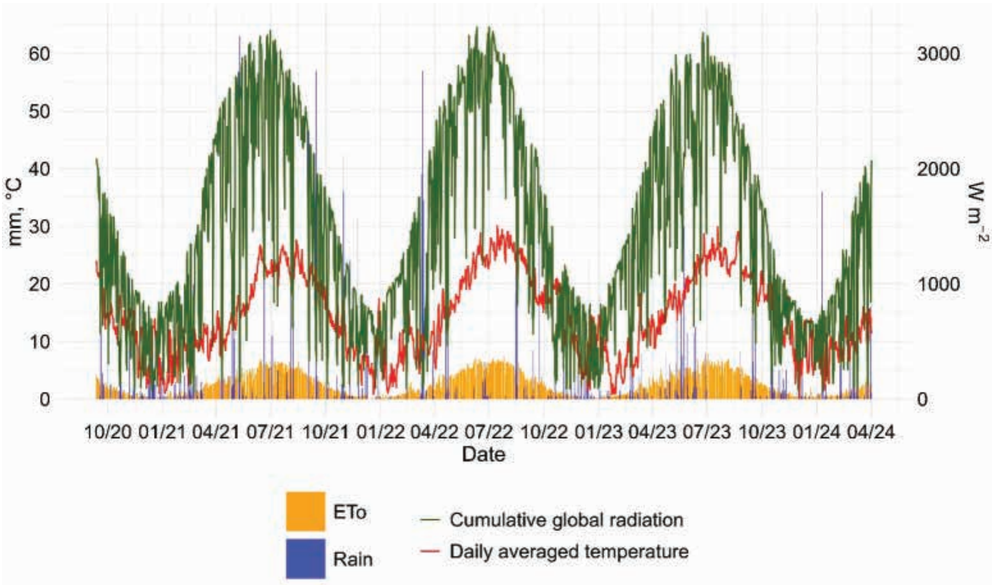

Figure 1. Daily meteorological variables observed during the study period. Averaged air temperature (°C), reference evapotranspiration ETo (mm) and rain (mm) on the left axis and cumulative daily global radiation (W m^{-2}) on the right axis.

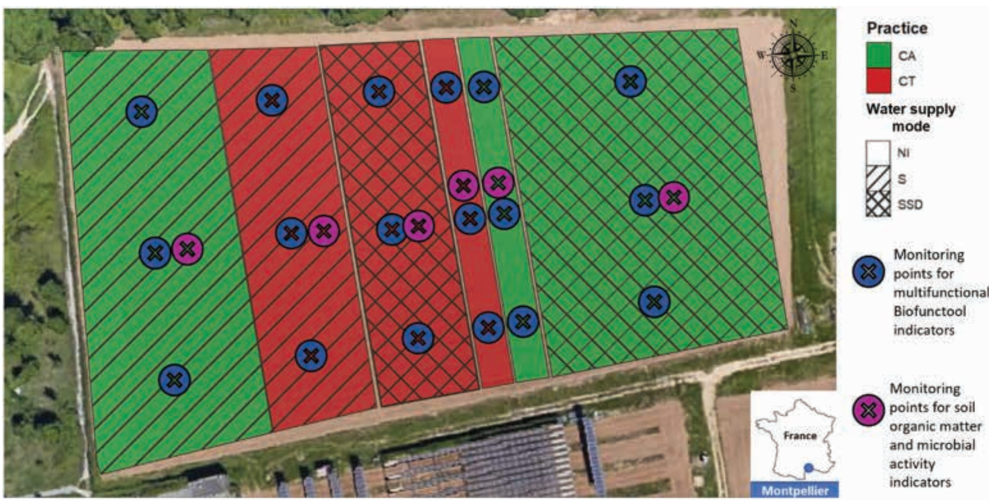

Figure 2. Treatments on the experimental site (INRAE experimental platform, Montpellier, France). From left to right: conservation agriculture irrigated by sprinkler irrigation (CA-S), conventional tillage irrigated by sprinkler irrigation (CT-S), conventional tillage irrigated by subsurface drip irrigation (CT-SSD), conventional tillage not irrigated (CT-NI), conservation agriculture not irrigated (CA-NI) and conservation agriculture irrigated by subsurface drip irrigation (CA-SSD).

From 2021 to 2023, crops were cultivated under conventional tillage (CT), or conservation agriculture (CA) practices. For both soil management practices (CT and CA), water supply was performed for crops in summer with sprinkler (S) irrigation, subsurface drip (SSD) irrigation, or no irrigation (NI), leading to six treatments in total covering an area of 1.5 ha (Figure 2).

Cropping system management and farming practices

Figure 3 illustrates the chronological sequence of cropping systems and farming practices over time. The annual planting of three main cereal crops: maize (*Zea mays L.* (RAGT IXABEL)), sorghum (*Sorghum bicolor L.* (HUGGO)), and soybean *(Glycine max L.* (RGT SPEEDA)) were realized under both CT and CA. Additionally, in the CA treatments, direct seeding was used for both the main crops and the cover crops (winter crops) planted between the main crop cycles: Faba bean (*Vicia faba* (DIANA)) in 2021, a mixture of mustard (*Sinapis alba L.* (ABRAHAM)), phacelia (*Phacelia tanacetifolia* (STALA)), and vetch (*Vicia sativa L.* (NACRE)) in 2022 and a mixture of faba bean (*Vicia faba* (DIANA)) and oat (*Avena sativa L.* (ALTESSE)) in 2023. All harvested winter crops were left at the soil surface. Conversely, in the CT treatments, the soil remained bare between the main crops, with tillage operations (ploughing) at a depth of 30 cm conducted in autumn, followed by seedbed preparation (rotary harrow) before planting the main crops and weed control through hoeing once or twice during the main crop season. Fertilizer doses were applied to the soil for each cropping season as follows: 180 kg N, 120 kg P, and 0 kg K per hectare for maize; 90 kg N, 70 kg P, and 150 kg K per hectare for sorghum; and no fertilizers (0 kg N, P, and K) for soybean. At the beginning of 2024, a one-off minimum tillage operation (reduced non-inversion tillage) was conducted using a Demeter cracker (Actisol 2023) to a depth of 25 cm in all CA plots to alleviate soil compaction issues identified during the first 3 years of CA adoption. These compaction issues were evidenced by elevated soil

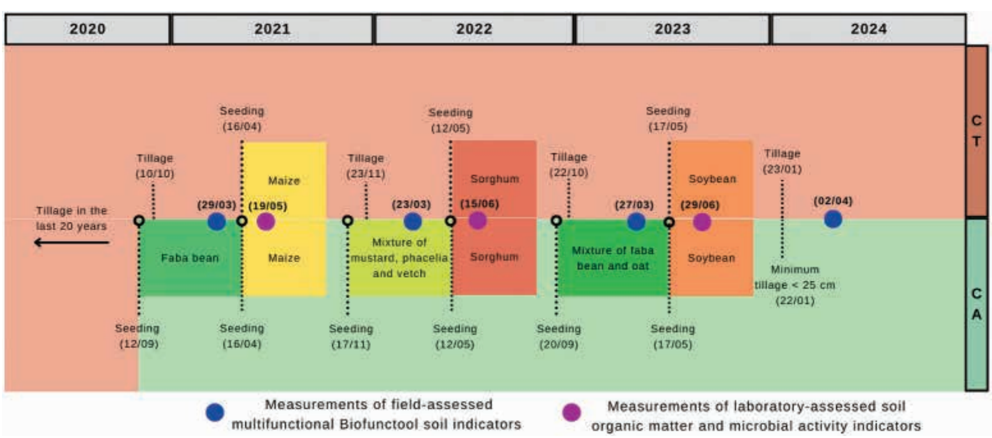

Figure 3. Crop rotation, farming practices and timing of soil indicators measurements for conservation agriculture (CA) and conventional tillage (CT) treatments.

penetration resistance and observations from visual soil evaluations (Dominguez-Bohorquez et al. 2025).

Irrigations were applied to summer crops each year. The irrigation system used for sprinkler (S) irrigation consisted of a solid set in 2021 and a hose reel with a spray gun in 2022 and 2023. The subsurface drip (SSD) irrigation system comprised of drip lines NAAN HYDRO PC (diameter 16 mm) spaced at intervals of 80 cm and buried at a depth of 35 cm, with pressure compensating drippers, for a nominal flow rate of 1.6 L h^{-1}, positioned every 50 cm along the drip tapes. Specifically, this system has been positioned at 35 cm soil depth to avoid damage due to tillage before CA adoption. The irrigation schedule was standardized across all treatments, with weekly applications programmed to deliver the same water volume. However, variability in actual irrigation volumes was noted in sprinkler systems due to wind-induced drift during application (around 15%). The volume loss due to wind was determined using the irrigation uniformity method, with pluviometers distributed across the field to measure spatial water distribution during irrigation events. Over the three-year study, recorded irrigation applications varied between crops. In 2021 (maize), irrigation volumes were 210 mm for CA-S, 250 mm for CA-SSD, 240 mm for CT-S and 250 mm to both CA-SSD and CT-SSD treatments. In 2022 (sorghum), CA-S was irrigated with 240 mm, CA-SSD with 260 mm, and both CT-S and CT-SSD with 260 mm. In 2023 (soybean), CA-S received 300 mm, while CA-SSD, CT-S, and CT-SSD all recorded 270 mm.

Soil sampling and analyses

Laboratory-assessed soil organic matter and microbial activity indicators

From 2021 to 2023, soil functional indicators were assessed in the laboratory to provide insight into the living components of the soil and the dynamics of soil organic matter (Celestalab 2020). Soil samples were collected from the top 20 cm of the soil profile, with composite samples consisting of 16 subsamples taken from the central point of each treatment after the sowing of each summer main crop (Figure 3). The laboratory-based analyses included the Microbial Activity Index (MAI), which describes the soil's ability to degrade organic substrates via enzymes produced by microorganisms; Microbial Biomass (MB), representing the mass of active microorganisms such as bacteria, fungi, and protozoa; Soil organic matter separated in Mineral-Associated Organic Matter (MAOM) for

Table 1. Soil organic matter and microbial activity indicators analyzed in the laboratory.

Soil Indicator	Indicator	Unit	Norm/Method
Mineral-Associated Organic Matter	MAOM	g kg^{-1}	NF X 31–516–09/2007
Particulate Organic Matter	POM	g kg^{-1}	NF X 31–516–09/2007
Microbial Activity Index	MAI	–	FDA adapted from (Schnürer and Rosswall 1982)
Microbial biomass	MB	mg C kg^{-1}	NF ISO 14,240–2 modified as (Chaussod et al. 1988)
Soil Organic Carbon	SOC	g kg^{-1}	NF ISO 13,878
Carbon Mineralization Index	Min Index C	Mineralized C/SOC (%)	FD U 44–163
Soil Total Nitrogen	STN	g kg^{-1}	NF ISO 13,878
Nitrogen Mineralization Index	Min Index N	Mineralized N/STN (%)	FD U 44–163

Table 2. Summary of multifunctional Biofunctool® soil indicators and normalization criteria for SHI calculation.

Soil function	Soil indicator	Indicator	Unit	Normalization criteria
Structure maintenance	Aggregate stability (0–2 cm)	AggSurf	Score	More is better
	Aggregate stability (2–10 cm)	AggSoil	Score	More is better
	Visual evaluation of soil structure	VESS	Score	More is better
	Infiltration rate	Beerkan	mL min^{-1}	More is better
Nutrient cycling	NO_3-fixed on anion exchange membrane	AMNO3	µg cm^{-2} d^{-1}	More is better
	Soil available nitrogen	Nmin	mg kg^{-1}	More is better
Carbon transformation	Permanganate oxidizable carbon (labile organic carbon)	POXC	mg kg^{-1}	More is better
	Basal soil respiration	SituResp	Absorbance difference	More is better
	Little macro- and mesofauna feeding activity (decomposition of organic matter)	Lamina	% d^{-1}	More is better

particles smaller than 50 µm and Particulate Organic Matter (POM) for particles larger than 50 µm. Additional indicators included the total Soil Organic Carbon (SOC); the Carbon Mineralization Index (Min Index C), calculated as the ratio of total mineralized carbon to SOC; the Soil Total Nitrogen content (STN) and the Nitrogen Mineralization Index (Min Index N), calculated as the ratio of the total mineralized organic N to STN. Units for each functional indicator are summarized in Table 1.

Field-assessed multifunctional soil indicators: the Biofunctool® approach

Every spring, from 2021 to 2024, the Biofunctool® set of nine functional indicators (Thoumazeau et al. 2019a, 2019b) was used to delineate the impacts of contrasting practices and irrigation systems on soil health. This set of indicators focuses on three primary soil functions: (i) soil carbon transformation, (ii) nutrient cycling, and (iii) soil structure maintenance. To assess soil carbon transformation, the indicators included permanganate oxidizable carbon (POXC), basal soil respiration (SituResp), little macro- and mesofauna feeding activity (Bait Lamina). Nutrient cycling was assessed by measuring NO_3- fixed on anion exchange membrane (AMNO3) and soil available nitrogen in the form of ammonium and nitrate (Nmin). Soil structure maintenance was evaluated through aggregate stability in the 0–2 cm (AggSurf) and 2–10 cm (AggSoil) horizons, visual evaluation of soil structure (VESS), and water infiltration rate measured with the Beerkan method (Beerkan). The units for these indicators are presented in Table 2.

Soil samples were collected from the 0–10 cm layer, except for the VESS samples which were taken from the 0–25 cm soil layer. Measurements were carried out at the beginning of each spring to capture the initial soil conditions for the main crop. To ensure robustness, Biofunctool® indicators were assessed at three different points within each plot, providing replication (Figure 2). Additionally, soil moisture and bulk density were measured using undisturbed cylindrical core samples. Wet and dry weights were recorded after drying the samples at 105 °C to account for potential influences of soil moisture and bulk density on the health indicators.

Statistical analysis

Soil functional indicators obtained from the laboratory and the soil health indicators (Biofunctool®) were analyzed through Principal Component Analysis (PCA) to explore the correlations between each indicator and its associated axes. Furthermore, mixed linear models were applied to evaluate the effects on soil health indicators of agricultural practice (variable Practice), water supply mode (variable Water Supply), and time since adoption (variable Months after adoption), including their interactions. These models included random effects, taking into account a possible spatial heterogeneity from landscape, with the Bloc variable as a random intercept: Indicator ~ Practice * Water supply * Months after adoption + (1|Bloc). The corrected Akaike Information Criterion (AICc) was used to select the most informative and parsimonious models. Assumptions of normality and homoscedasticity were confirmed (visually and/or statistically). All statistical analyses were conducted using the R software (version 4.4.1) and models were conducted with 'nlme' package and the correlation matrix with 'corrplot'. All significance levels were set at a p-value <0.05.

Soil health Index (SHI)

As explained by Obriot et al. (2016) and Brauman and Thoumazeau (2019a) the soil health index (SHI) is a multicriteria indicator designed to aggregate various soil health parameters into a score ranging from 0 to 1, based on their contributions in a multivariate PCA. To construct the SHI, individual soil health indicators (Biofunctool®) are normalized by dividing each observation's value by the reference value that corresponds to the criterion for optimal soil health. These criteria are categorized as 'the more is better', 'the less is better', or 'the optimum' (Table 2). A weighted PCA was conducted with equal weight for each soil function. The indices were calculated by multiplying the relative contributions of the soil indicators to the principal components whose eigenvalues are greater than 1 with the individual soil health indicators normalized. The final SHI was calculated by summing these indices.

Specifically, for VESS, the original score is transformed to better represent the soil structure by dividing the initial score by the 'optimum' value of 2. If the original score is less than 2, it is simply divided by 2. However, if the original score is greater than 2, the transformation consists in dividing 2 by the original score. This ensures that the transformed score ranges from 0 to 1, with 1 indicating the best soil structure (the value closest to the optimum score of 2). This transformation makes it easier to compare soil structure across different practices, with 1 representing the optimal outcome.

Results

Short-term impacts of CA on soil organic matter and microbial activity indicators

Figure 4 illustrates the PCA results for laboratory-derived soil functional indicators during the first 3 years following CA adoption. In Figure 4(a), the PCA shows that 73% of the total variance is explained by the first two dimensions. The first dimension (Dim1) accounts for 54% of the total variability and is associated with soil carbon storage metrics, including SOC, MAOM, POM, and Min Index C. The second dimension (Dim2), which explains 20% of the variance, reflects microbial activity, nitrogen content and mineralization, as represented by MAI,

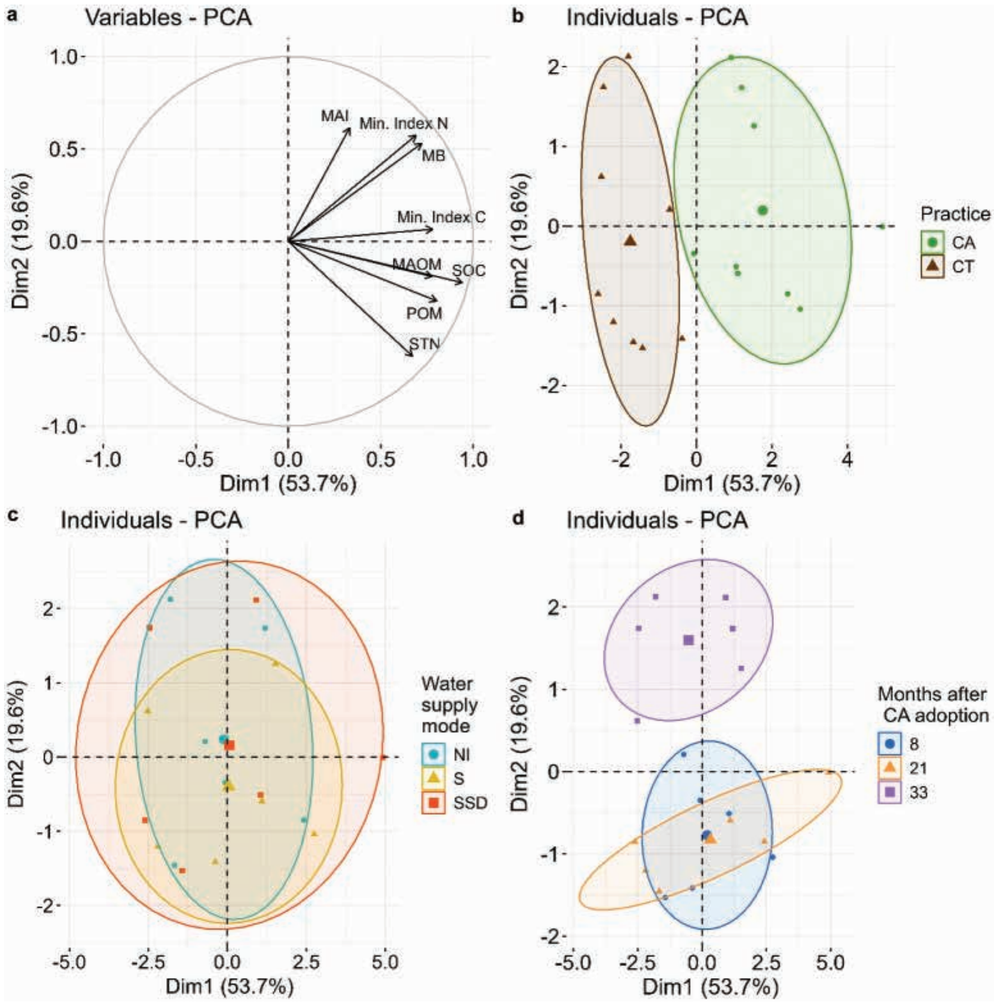

Figure 4. Principal component analysis (PCA) biplot of individuals and explanatory variables for soil organic matter and microbial activity indicators ($n = 18$): (microbial activity index: MAI; microbial biomass: MB; mineral-associated organic matter: MAOM; particulate organic matter: POM; soil organic carbon: SOC; carbon mineralization Index: min Index C; soil total nitrogen: STN; nitrogen mineralization Index: min Index N). (a) Correlation circle displaying vectors representing the scores of explanatory variables; (b) Graph of individuals illustrating the effect of practice (conservation agriculture (CA – green circles) and conventional tillage (CT – brown triangles)); (c) Graph of individuals illustrating the effect of water supply mode (sprinkler irrigation (S – yellow triangles), subsurface drip irrigation (SSD – red squares), and no irrigation (NI – blue circles)); (d) Graph of individuals illustrating the effect of time after CA adoption (8 months – blue circles, 21 months – yellow triangles, 33 months purple squares).

MB, STN, and Min Index N. Notably, some variables, such as MB, are more closely linked to Dim3 with 12.5% of the total variance, while MAOM is better represented by Dim4 (not shown here). Figure 4(b) highlights a clear separation between CA (green points) and CT (brown triangles) along Dim1, indicating that CA practices substantially enhance the potential biological activity and organic matter content in the soil surface compared to CT.

Figure 4(c) shows no distinct clustering based on the water supply mode, suggesting that this factor does not influence the functional soil indicators when measured approximately 8 months after the last irrigation event, at least as revealed by the PCA. Finally, Figure 4(d) highlights a difference along Dim2, where data from 33 months post-CA adoption cluster higher on the Dim2 axis compared to those from 8 to 21 months. This pattern suggests a time-driven process in these soil functional indicators, particularly a marked increase in MAI and MB 3 years after CA adoption, observed in both CA and CT treatments (see Figure S1).

Short-term impacts of CA on Biofunctool® multifunctional soil indicators

Overview of the effects of practice, water supply mode, and temporality post-CA adoption

Figure 5 illustrates the PCA results for Biofunctool® soil indicators during the first 30 months following CA adoption. The first two dimensions (Dim1 and Dim2) explain 50% of the total variance (Figure 5(a)), increasing to 64% when including the third dimension (not shown). Dim1, accounting for 29.4% of the variance, is primarily associated with positive correlations with SituResp, AggSurf, and POXC, while negatively correlated with Nmin, VESS, Beerkan, and Lamina. Dim2, which explains 20.2% of the variance, reflects positive correlations with AMNO3 and Nmin and small negative correlations with Lamina and AggSoil. Some indicators are less strongly represented in these dimensions; for instance, Lamina is better aligned with Dim3, which accounts for an additional 14% of the variance. Similarly, Beerkan is more closely associated with the fourth dimension (not shown).

Supplementary variables, including soil moisture (SM) and bulk density (BD), were also integrated into the PCA analysis. BD positively correlates with Dim1 and variables such as POXC, SituResp, and AggSurf, while negatively correlating with VESS, Beerkan, and Lamina. SM is poorly represented on Dim1 and Dim2, as indicated by the short length of its arrow, confirming its limited correlation with the indicators on these axes. However, SM shows a slight positive correlation with AggSoil and Lamina on Dim3, while it negatively correlates with Beerkan.

When grouping individuals by practice, Figure 5(b) reveals a clear distinction between CA (green points) and CT (brown triangles). CA is strongly associated with higher values for SituResp, AggSurf, AggSoil, POXC, and BD, whereas CT aligns more closely with higher scores for VESS, Nmin, Lamina, and Beerkan. The clear separation along Dim1 underscores significant differences between practices, with CA promoting enhanced soil aggregation, carbon transformation, and higher BD during the first 30 months compared to CT.

In contrast, the effect of the water supply mode appears less pronounced (Figure 5(c)). The PCA does not reveal clear clustering based on the mode of water supply, indicating its minimal influence on the soil functional indicators under the conditions studied.

Finally, the temporal effects of CA adoption are illustrated in Figure 5(d). Limited changes in soil indicators are observed at 6 and 18 months post-adoption, indicating stability in soil properties during these periods. However, by 30 months post-adoption, notable changes emerge in CA, particularly marked by increases in AggSoil and a decrease of Nmin. These shifts suggest time-driven changes in soil functionality in 2023 overall for CA.

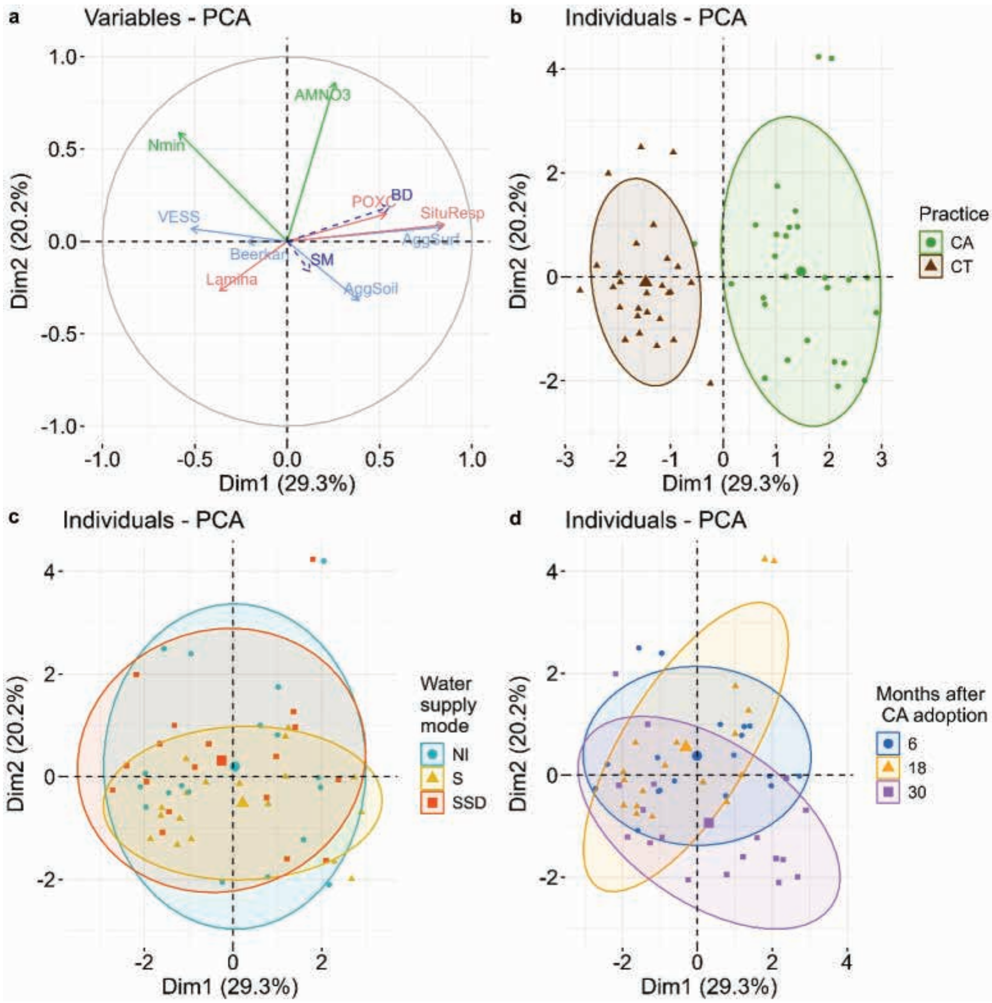

Figure 5. Principal component analysis (PCA) of individuals and explanatory variables for Biofunctool® indicators ($n = 54$). (a) Correlation circles for explanatory variables across the first two PCA dimensions. (b) Individual plots showing effects of practices: conservation agriculture (CA – green circles) vs. conventional tillage (CT – brown triangles). (c) Individual plots illustrating water supply modes effects: sprinkler (S – yellow triangles), subsurface drip (SSD – red squares), and no irrigation (NI – blue circles). (d) Individual plots depicting temporal effects at 6 months (blue circles), 18 months (yellow triangles), and 30 months (purple squares) post-CA adoption.

Results from PCA were confirmed by different mixed model analyses (Table S1) which demonstrate that agricultural practices (CA vs. CT) significantly influence most indicators with strong effects ($p < 0.05$) except for AMNO3. Water supply shows significant effects on a narrower range of indicators, particularly AggSoil, POXC, and Nmin. Temporal variability is evident, with time significantly affecting almost all indicators except AggSurf, SituResp and POXC. Consequently, the interaction between agricultural Practice and Time emerges as dominant factors driving changes in soil indicators, while water supply plays a more specific role. Across all models, the standard deviation of the intercept (random effects) is

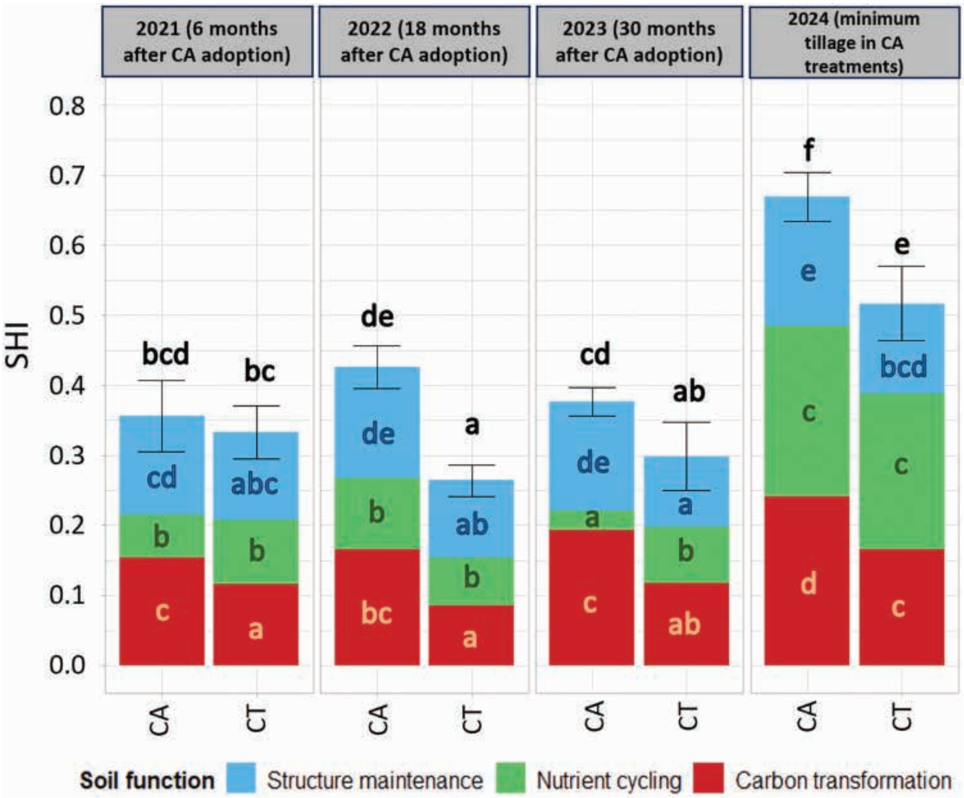

Figure 6. Temporal changes in the soil health index (SHI) under conservation agriculture (CA) and conventional tillage (CT), including the effects of minimal tillage under CA. Error bars indicate standard deviations of the total SHI. Colored letters represent statistical groupings by soil function, while black letters denote statistical groupings of total SHI based on post hoc tests. Treatments with the same letter within a color are not significantly different ($p > 0.05$), whereas different letters indicate significant differences.

much lower than the residuals, indicating that spatial variability is minimal compared to the variability explained by fixed effects.

Short-term effects of CA and minimal tillage on the soil health index (SHI)

The Soil Health Index (SHI) was calculated to monitor changes in soil functionality over time, including the effects of minimal tillage in CA treatments. The SHI values for each period following CA adoption are illustrated in Figure 6, with soil function contributions represented by different colors. While the effective water supply mode was detectable in the statistical analyses for certain indicators, it had minimal impact on SHI variation between treatments (data not shown). Consequently, only the SHI results by practice and time after CA adoption are presented.

When comparing CA and CT practices, the total SHI scores were higher under CA than under CT from 18 months post-adoption (Figure 6). Six months after CA adoption, structure maintenance was similar in CA compared to CT. Nutrient cycling contributions were 32% lower in CA than in CT but statistically similar. In contrast, the carbon transformation was 24% significantly higher under CA. Despite these differences, the mean total SHI scores for CA and CT differed by less than 7%. By 18 months, CA showed a total SHI score of 38% higher than CT, driven by a 48% increase in carbon transformation and a 33% improvement in structure maintenance compared to CT. Nutrient cycling also improved by 33% under CA but remained statistically similar to CT. At 30 months, CA systems exhibited a 35% advantage in structure maintenance over CT. Carbon transformation increased further, with scores 39% higher under CA than CT. However, nutrient cycling was significantly lower in CA than in CT by 65%. Despite these variations, the overall SHI scores were 21% higher in CA systems than in CT.

In response to compaction issues, assessed by penetration resistance measurements (Dominguez-Bohorquez et al. 2025), minimal tillage was introduced in CA systems in 2024. Following this intervention, total SHI values increased significantly compared to previous months. The total SHI score for CA was 23% higher than for CT, with notable improvements in carbon transformation (32% higher in CA than CT), structure maintenance (29% higher in CA than CT), and similar nutrient cycling scores for both CA and CT. Under CA, the improvement in carbon transformation was particularly significantly compared to earlier months. Structure maintenance showed a trend of improvement in CA compared to previous months, but these differences were not statistically significant. Both CA and CT demonstrated statistically similar improvements in nutrient cycling. However, the increase in nutrient cycling scores compared to previous years contributed to the highest total SHI scores observed throughout the study. Overall, the introduction of minimal tillage in CA did not reduce soil health indicators. On the contrary, it appeared to slightly enhance overall soil health, as CA systems consistently maintained higher functional scores than CT.

Discussion

How does the adoption of CA impact soil health in an irrigated Mediterranean agrosystem in the short term?

General impacts of CA on soil health

The results of this study have shown that Conservation Agriculture (CA) has a significant short-term impact ($p < 0.05$) on soil health indicators throughout the 3 years following its adoption under irrigated Mediterranean conditions. As observed by soil organic matter and microbial activity indicators derived from laboratory (Figure 4b), CA improved almost all of the indicators from the first 6 months after its adoption. The most important improvements were the pools of soil organic carbon (SOC) with increases of mineral-associated organic matter (MAOM) and particulate organic matter (POM) which also showed an increase of microbial biomass (MB) and the microbial activity index (MAI) compared to CT (Figure S1). The presence of soil organic carbon in CA systems supplies energy for soil microorganisms, leading to greater microbial biomass compared to tilled systems (Page et al. 2020). In this study, MB in CA was approximately 30% higher than CT, aligning with findings by Berner et al. (2008) who reported a 7.4% increase in organic carbon and a 28% increase in MB in soils managed with minimal tillage compared to conventional tillage.

CA also demonstrated positive effect on some multifunctional Biofunctool® indicators (Figure 5b), particularly, for soil structure maintenance (Aggsoil, AggSurf) and carbon transformation (SituResp and POXC), which are related to microbial activity (De Bona et al. 2006). Similar trends were reported by Pheap et al. (2019) who observed greater soil stability (reflected in higher Aggsoil and Aggsurf values) under CA, along with a threefold increase in POXC and SituResp values compared to CT. These improvements are attributed to the absence of tillage, the retention of crop residues on the soil surface (Bongiorno et al. 2019) and the implementation of crop rotation, which can influence soil microbial communities directly impacting soil health dynamics (Du Preez et al. 2024). By preserving soil aggregates and minimizing disruption, CA enhances soil physical quality (Alletto et al. 2022). Additionally, the input of carbon (higher values of POXC) by the crop residues also enhances the stability of soil aggregates with a greater proportion of macro aggregates (FAO and ITPS 2021). Moreover, the combination of crop residue retention and crop rotation may enhance soil respiration, one of the more representative indicators of soil biological activity (Al-Kaisi and Lal 2017), which promotes in the same time nucleation centers for aggregation (Koudahe et al. 2022).

However, some structure maintenance indicators, such as Beerkan (soil infiltration) and VESS (visual evaluation of soil structure) displayed lower values under CA compared to CT (Figure 5). These differences can be attributed to tillage in CT, which while disrupting soil aggregates temporarily improves soil porosity and enhances water and air movement (Mikha and Rice 2004). In contrast, CA promotes long-term soil structure maintenance through natural processes, such as biological aggregation and organic matter accumulation. However, the lower VESS scores observed in CA suggest that, in the short-term, soil structure may remain suboptimal for infiltration, particularly when compaction is present (Salem et al. 2015). This observation contrasts with long-term studies where CA plots typically showed higher values for these indicators (Lipiec et al. 2006; Thierfelder and Wall 2009; Pheap et al. 2019; Cueff et al. 2020; Heepngoen et al. 2021; Kulagowski et al. 2021; Roua et al. 2021). However, different studies have demonstrated that results about VESS might vary in the short and mid-term (Mloza-Banda et al. 2016; Khorami et al. 2018) and may stem from differences in infiltration assessment methods and soil factors such as compaction, which were observed in our study as well (Dominguez-Bohorquez et al. 2025). The benefits of CA on soil structures, such as improved porosity and better soil structure, may take several years to become apparent.

Regarding nitrogen dynamics, mineral nitrogen (Nmin) values under CA were reduced showing limited availability of nitrogen over time compared to CT. This aligns with findings by Verhulst et al. (2010), who reported that zero-tillage practices often lead to lower nitrogen availability due to increased immobilization by surface residues. In contrast, tillage disrupts soil aggregates, making organic matter more accessible to microorganisms and increasing the release of mineral nitrogen from both active and physically protected pools (Mikha and Rice 2004). However, nitrogen dynamics are highly variable and influenced by crop conditions, management practices, and the uneven release of nitrogen from organic matter under CA. In this study, nitrogen values fluctuated across periods, which could reflect both the greater variability in how organic matter becomes accessible for decomposition in CA systems and the timing of measurements. For instance, the presence of a winter cover crop during sampling likely influenced nitrogen availability due to active crop uptake at that time. In 2023, higher cover crop biomass compared to previous years (data not shown) may explain the lower Nmin values observed during this year (Figure 5). This suggests that reduced nitrogen availability under CA may reflect active crop uptake rather than a deficit in soil functionality.

Trends in the Soil Health Index (SHI) (Figure 6) confirm that CA generally leads to better soil functionality, with carbon transformation and structure maintenance contributing most to the SHI. Despite initial negative impacts of certain indicators, such as infiltration rate and VESS, the overall SHI remained higher under CA during the study period. These findings confirm that, in the short-term under Mediterranean conditions, CA promotes a more stable soil environment, particularly in the upper soil layers, with better soil aggregation and continuous organic carbon inputs enhancing both stable and labile organic matter and microbial activity. Panettieri et al. (2013) support this, highlighting that CA is a good option to increase soil biological and biochemical quality in irrigated Mediterranean farms. These effects are indicative of increased soil health and stable soil functionality, which are particularly important in Mediterranean regions, where temperature and drought stress can reduce microbial activity and organic decomposition (Laudicina et al. 2011).

Nevertheless, it is important to note that the observed improvements in key soil indicators under CA were confined to the topsoil and may not reflect soil health in deeper layers. This aligns with findings by Verhulst et al. (2010) affirming that the effects of tillage practices on soil indicators such as soil organic matter and microbial biomass are primarily limited to the surface layers. Luo et al. (2010) also observed increased soil carbon in the topsoil (0–10 cm) under no-till (NT) systems but reported no significant differences across the full soil profile (up to 40 cm).

Temporal effects of CA adoption on soil health

The results demonstrate that the effects of temporality on soil health changes under CA were not evident in this 3-years study. Although some soil indicators showed notable changes over time after CA adoption, there was no clear or consistent temporal trend specific to CA. For example, improvements in soil organic matter and microbial activity indicators over time were not unique to CA, as both practices, CA and CT, showed improvements for the same period (Figure 4d and Table S1). These improvements appear to have been influenced more by contextual factors, such as seasonal or environmental conditions, than by the duration of CA implementation.

Multifunctional Biofunctool® indicators, including Beerkan, VESS, Lamina, and Nmin, exhibited significant changes over time (Table S1). However, these changes were mainly driven by the high variability observed under CT, reflecting the disruptive effects of tillage practices. In both CA and CT, the observed trends were further influenced by seasonal environmental conditions and soil compaction issues in CA.

Regarding SHI, after 30 months of CA adoption, some soil functions exhibited more substantial improvements compared to previous years. Notably, the carbon transformation contributed more significantly to the overall SHI (Figure 6) than in earlier years. Interestingly, at 6 months, there were no significant differences in SHI between CA and CT, but by 18 months, significant differences emerged, with CA showing higher SHI values. These trends align with observations by Stagnari et al. (2014) who noted that the benefits of CA are mainly due to the accumulation of residues on the soil surface and can be expressed between 3 and 7 years in a Mediterranean context. These results highlight the progressive enhancement of soil health under CA, even when initial improvements are limited during the early transition years. This underscores the importance of evaluating soil health during the initial phases of CA to capture its initial post-adoption effects and understand their impact within specific contexts.

Multiple short-term studies have identified similar trends, generally showing an increase in soil carbon pools across different pedoclimatic contexts (Hok et al. 2015; Khorami et al. 2018; Mondal et al. 2020; Gura et al. 2022; Lazcano et al. 2022). These findings highlight the potential of CA to enhance soil organic carbon content and improve soil structure over time. Although the present study evaluates only short-term effects, it is worth noting that long-term studies have demonstrated significant benefits associated with sustained CA practices. For example, Pheap et al. (2019) and Kulagowski et al. (2021) documented improved topsoil structure and carbon transformation by CA under cropping systems in the long-term. In Mediterranean regions, Kassam et al. (2012) reviewed various studies and found that, generally in the mid- to long-term, total carbon soil was higher in CA systems compared to conventional tillage. These observations suggest that the trends identified in this study may align with the trajectory of CA systems when maintained over longer timescales.

Impacts of water supply mode

Analyses indicate that the mode of water supply did not have a significant impact on soil health. Measurements were conducted each spring, prior to the seeding of the main crop and before the onset of summer irrigation (8 months after the last irrigation). As a result, the residual effects of previous irrigation cycles were captured rather than their immediate impacts, which may explain the overlapping clusters of treatments (NI, S, SSD) observed in the PCA results (Figures 4(c) and 5(c)).

The limited differentiation between water supply modes in our study could be attributed to spring rainfall, which likely equalized soil moisture conditions across treatments, reducing the observable effects of irrigation. These findings highlight the importance of conducting assessments across multiple seasons and over extended periods to better capture the potential impacts of irrigation on soil health. For instance, De Bona et al. (2006) demonstrated that irrigation increased organic matter decomposition rates by 19% and 15% under CT and no-tillage systems, respectively, after 8 years of study, underscoring the potential for long-term effects of irrigation to become more pronounced in extended research studies.

Does one-off minimum tillage penalize soil health under CA?

CA ideally entails zero-tillage and direct seeding to minimize soil disturbance. However, as observed in the trends for indicators like Beerkan and VESS in Figure 5, which were lower in CA compared to CT, compaction issues can arise under CA, likely due to the absence of tillage and to the passage of heavy machinery during seeding and harvesting of both winter and main crops. Consequently, in various contexts, different minimal tillage techniques are accepted as they do not disrupt soil aggregates like conventional tillage and may be necessary to prevent compaction and control weeds (Cicek et al. 2023). In minimal tillage, soil is not turned over, which helps to preserve soil organisms. In this study, a Demeter cracker was used (Dominguez-Bohorquez et al. 2025), which works the soil vertically without disturbing or mixing the soil horizons (Actisol 2023), at a depth of less than 25 cm to avoid damaging the subsurface drip irrigation (SSD) system.

As shown in the results in Figure 6, minimal tillage had an impact on soil health in 2024. Overall, SHI components were more evenly balanced across soil functions in 2024 compared to previous years. Furthermore, SHI values under CA remained higher than those under CT, indicating that minimal tillage did not negatively affect soil health. This observation aligns with findings by Berner et al. (2008) which confirm that minimal tillage can positively impact soil health compared to conventional tillage systems. These results suggest that adopting minimal tillage practices within conservation agriculture, when needed, can lead to improved soil health trajectories, supporting sustainable agricultural practices while maintaining the integrity of soil ecosystems.

Carbon transformation increased more compared to conventional tillage (CT) and previous years, while structure maintenance showed slight improvement relative to earlier years, particularly in light of the declining values of transformed VESS and Beerkan observed over time. In this context, minimal tillage appeared to alleviate compaction issues and slightly enhance soil structure. However, this improvement remains subtle, as the results are based on a single datapoint collected only a few months after the decompaction intervention. Nutrient cycling also demonstrated increased contributions to the total soil health index (SHI) under both CA and CT, with a particularly notable increase in 2024 compared to prior years. This rise may be attributed to the relatively high soil moisture at the time of sampling (around 25% volumetric water content, notably higher than the range 10–16% for previous years), which likely influenced nutrient availability and cycling rather than being solely driven by soil minimum tillage through the Actisol intervention. Consequently, the observed differences for nutrient cycling could reflect annual variations rather than a consistent minimum tillage effect.

Improving soil health assessment: synergies and limitations of laboratory and field-based Biofunctool® methods

A comprehensive soil health assessment requires an integrated approach that captures the complexity of soil functions and their dynamics over time. Combining laboratory-based indicators (such as soil organic matter and microbial activity) with field-based Biofunctool® indicators may provide a more holistic understanding of soil properties, particularly how conservation agriculture practices influence soil dynamics. Laboratory analyses offer detailed insights into specific soil fractions and microbial dynamics, while Biofunctool® captures a broader range of soil functions in the field, such as soil structure and basal respiration. Notably, soil structure is considered in each measurement, and a dedicated function is assigned to it. The synergy between these methods strengthens the overall assessment of soil health, providing a clearer picture of how soil behaves across diverse agroecosystems. For example, moderate to strong correlations were observed between microbial biomass (MB), mineral-associated organic matter (MAOM), and Biofunctool® indicators such as basal respiration and soil aggregation (Figure S2), supporting the relevance of the complementary roles of both methods in assessing carbon transformation and soil health. Integrating these approaches leads to a more complete understanding of soil functionality, revealing the complex dynamics at play in different soil environments.

Despite its strengths, some limitations warrant consideration. A notable challenge was the temporal mismatch between laboratory-assessed indicators and Biofunctool® measurements, with a delay of 1.5 to 3 months between the two. This discrepancy may have influenced the interpretation of indicators sensitive to environmental factors like water or thermal stress (e.g. nutrient cycling). As a result, while observed correlations are informative, they should be interpreted with caution. Future assessments would benefit from synchronized sampling to strengthen temporal consistency.

Another important perspective involves broadening the range of indicators considered. While this study assessed different soil functions, it did not account for pest presence or soil biodiversity, factors which in turn affect soil functionality (e.g. Chiduza and Dube 2013; Perron et al. 2022). This highlights the importance of including a broader range of biological indicators in future soil health assessments.

Finally, while soil compaction was indirectly inferred from reduced soil indicator values (low values of Beerkan and VESS), it was not directly assessed in this analysis through measurements like soil resistance to penetration. Given the flexibility of the Biofunctool® kit, future assessments could incorporate such measurements to directly evaluate the impact of compaction on soil health. Understanding the relationship between compaction, root growth limitations, and crop production is critical, as compaction can significantly restrict root development and ultimately affect crop yield.

Conclusions

This study highlights the positive short-term effects of conservation agriculture (CA) on soil health in irrigated Mediterranean conditions, which are particularly susceptible to climate change impacts. By reducing soil disturbance and promoting organic matter retention through crop residues and crop rotations, CA improves soil aggregation, microbial activity, and carbon pools, suggesting its immediate potential to mitigate soil degradation risks from erosion and prolonged droughts. However, some indicators, such as soil infiltration and nitrogen mineralization, may take longer to respond, underscoring the need for continued application over several years to fully realize these benefits.

The influence of water supply methods and temporality remained inconclusive, highlighting the need for further observations across multiple seasons, especially during summer irrigation periods. Extending the study to the mid- and long-term would provide a clearer understanding of these dynamics.

The study underscores the adaptation of CA practices over time and shows that minimal tillage can reduce soil compaction without compromising soil structure, which is essential for compaction-sensitive soils in Mediterranean regions. These findings support the adoption of CA as a sustainable strategy to improve soil health while addressing the unique environmental challenges of Mediterranean agriculture.

Finally, the study emphasizes the importance of integrating a broader set of soil functional indicators to enhance soil health assessments, providing a more comprehensive evaluation of the impacts of CA.

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Disclosure statement

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Author contribution statement

The authors confirm their contribution to the paper as follows: study conception and design: J.D.D. B., J.F.F., and C.W.; data collection: J.D.D.B, J.F.F., and A.B.; analysis and interpretation of results: J.D.D. B, J.F.F., and C.W.; draft manuscript preparation: J.D.D.B.; writing – review and editing: J.D.D.B., J.F.F., C.W., A.B., and S.B.; validation: J.D.D.B., J.F.F., C.W., A.B., and S.B. All authors reviewed the results and approved the final version of the manuscript.

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