

ADAPTING REDUCED TILLAGE WITHIN MEDITERRANEAN IRRIGATED CONSERVATION AGRICULTURE ENHANCES SOIL HEALTH AND WATER PRODUCTIVITY

L'ADAPTATION DU TRAVAIL DU SOL REDUIT DANS LE CADRE DE L'AGRICULTURE DE CONSERVATION IRRIGUÉE EN MILIEU MÉDITERRANÉEN AMÉLIORE LA SANTÉ DES SOLS ET LA PRODUCTIVITÉ HYDRIQUE

Juan David Dominguez Bohorquez¹, Claire Wittling¹, Nicolas Urruty²

ABSTRACT

Conservation agriculture (CA) is widely promoted as a strategy to enhance soil health and resilience, yet its performance under Mediterranean irrigated conditions remains insufficiently documented, particularly when structural constraints emerge during the transition from conventional tillage. This study evaluated the five-year trajectory (2021–2025) of an experiment in southern France comparing CA and conventional tillage (CT) under three water supply modes: non-irrigated (NI), sprinkler (S) irrigation, and subsurface drip (SSD) irrigation.

During the first three years, CA was managed under strict no-tillage while maintaining the other CA pillars (winter cover crops and diversified rotations). Although this practice enhanced several indicators of soil functioning, it also led to increased soil compaction and reduced infiltration. To alleviate these limitations while maintaining CA principles, a one-off decompaction (<25 cm depth) was implemented in 2024, followed by reduced shallow tillage (10–15 cm depth) in 2025.

This study compared conditions during the 2022 and 2025 experimental years, representing the early strict no-till phase and the adaptive reduced-tillage phase, respectively. We analyzed soil physical, chemical, and biological indicators as well as sorghum grain yield and water productivity. In 2022, CA improved aggregate stability, organic matter fractions and microbial activity, but also showed greater penetration resistance and lower infiltration than CT, resulting in significantly lower yields and water productivity. By 2025, soil structural conditions improved while gains in soil organic carbon, particulate and mineral-associated organic matter, microbial biomass, aggregate stability, and basal respiration were maintained or strengthened. Sorghum yield increased markedly, reaching from 8 to 9.2 t ha⁻¹ under irrigation, and irrigation water productivity under CA exceeded CT by 24% under S and 53% under SSD. The results indicate that CA in Mediterranean systems should be viewed as an adaptive management trajectory rather than a strict no-tillage doctrine. While maintaining the other CA pillars, strategic reduced tillage alleviated structural limitations while preserving soil health benefits and substantially improving crop and water productivity.

Keywords: Conservation agriculture; conventional tillage; organic matter; soil health; water productivity.

RESUME

L'agriculture de conservation (CA) est fortement conseillée comme une stratégie visant à améliorer la santé et la résistance des sols; cependant, ses performances en vertu des conditions méditerranéennes irriguées restent insuffisamment documentées, en particulier lorsque des contraintes structurelles apparaissent lors de la transition depuis le travail du sol conventionnel. Cette étude a évalué l'évolution

¹ G-EAU, INRAE, AgroParisTech, BRGM, CIRAD, Institute Agro, IRD, University of Montpellier, 34000 Montpellier, France, Email: juan-david.dominguez-bohorquez@inrae.fr, Email: claire-wittling@inrae.fr

² Société du Canal de Provence (SCP), Le Tholonet, 13182 Aix-en-Provence, France, Email: nicolas.urruty@canal-de-provence.com

d'une expérience menée sur cinq ans (2021-2025) au sud de la France, tout en comparant l'agriculture de conservation (CA) et le travail du sol conventionnel (CT) dans le cadre de trois modes d'approvisionnement en eau : sans irrigation (NI), irrigation par aspersion (S) et irrigation goutte-à-goutte souterraine (SSD).

Au cours des trois premières années, l'agriculture de conservation (CA) a été pratiquée dans le cadre de méthode sans le travail du sol strict, tout en maintenant d'autres éléments fondamentaux de cette approche (cultures de couverture hivernales et rotations diversifiées). Bien que cette pratique ait amélioré plusieurs indicateurs du fonctionnement du sol, elle a également donné lieu à une augmentation du compactage du sol et une réduction de l'infiltration. Afin de pallier à ces limites tout en respectant les principes de l'agriculture de conservation, un décompactage unique (à une profondeur de < 25 cm) a été réalisé en 2024, suivi d'un travail du sol réduit superficiel (à une profondeur de 10 à 15 cm) en 2025.

Cette étude a comparé les conditions observées au cours des années expérimentales 2022 et 2025, représentant la phase initiale de sans travail du sol strict et la phase adaptative de travail du sol réduit respectivement. Nous avons analysé les indicateurs physiques, chimiques et biologiques du sol, ainsi que le rendement en grains de sorgho et la productivité hydrique.

En 2022, l'agriculture de conservation (CA) a amélioré la stabilité des agrégats, les fractions de matière organique et l'activité microbienne, mais a également présenté une plus grande résistance à la pénétration et une infiltration plus faible que le travail du sol conventionnel (CT), donnant lieu à la réduction significative des rendements et une productivité hydrique. En 2025, les conditions structurelles du sol s'étaient améliorées, tandis que les gains en carbone organique du sol, en matière organique particulaire et associée aux minéraux, en biomasse microbienne, en stabilité des agrégats et en respiration basale avaient été maintenus ou renforcés. Le rendement du sorgho a augmenté de manière sensible, atteignant entre 8 et 9,2 t ha⁻¹ sous la méthode d'irrigation, et la productivité hydrique d'irrigation sous le régime CA a dépassé celle du régime CT de 24% pour l'aspersion (S) et de 53% pour l'irrigation goutte-à-goutte souterraine (SSD).

Ces résultats indiquent que l'agriculture de conservation dans les systèmes méditerranéens doit être analysée comme une trajectoire de gestion adaptative plutôt qu'une doctrine stricte de sans travail du sol. Tout en préservant d'autres éléments fondamentaux de l'agriculture de conservation, le travail du sol réduit stratégique a permis d'atténuer les contraintes structurelles tout en maintenant les bénéfices de la santé du sol et en améliorant considérablement la productivité des cultures et la productivité hydrique.

Mots-clés : Agriculture de conservation; Travail conventionnel du sol; Matière organique; Santé des sols; Productivité hydrique.

1. INTRODUCTION

Mediterranean irrigated systems are increasingly exposed to the combined effects of climate change, including more frequent droughts, extreme events, and accelerated soil degradation through organic matter loss, erosion, and nutrient depletion. In this context, conservation agriculture (CA) is widely considered a promising approach to enhance soil resilience by promoting soil cover, crop diversification, and reduced soil disturbance (Kassam et al., 2014).

Most knowledge on CA, however, derives from rainfed systems, and its performance under irrigated Mediterranean conditions remains insufficiently documented. Additionally, little is known about the early stages of CA adoption, when soil processes are still adjusting and benefits and constraints may emerge simultaneously.

Understanding this transition period is essential because the first years of implementation often determine both the agronomic viability of the system and subsequent management decisions. At the INRAE experimental platform in Montpellier, southern France (PRESTI, 2025), previous work has

provided key insights into the early phase of CA adoption, characterized by strict no-tillage combined with systematic cover cropping and crop rotation. Over the first three years, CA improved several soil functions compared to conventional tillage (CT), notably those related to soil aggregation, soil basal respiration, organic matter content, and microbial activity (Dominguez-Bohorquez et al., 2025b). However, complementary analyses revealed the emergence of soil constraints, particularly compaction and reduced water infiltration, leading to a reduction of crop yields and water productivity (Dominguez-Bohorquez et al., 2025a).

To address soil constraints, a one-off decompaction to 25 cm depth was carried out in 2024. A subsequent assessment demonstrated that this intervention reduced compaction, increased water infiltration, and kept improvements in aggregate stability, organic matter fractions, and microbial activity (Dominguez-Bohorquez et al., 2025b). It also marked a transition from strict no-tillage to a more adaptive CA strategy based on limited and controlled mechanical disturbance (reduced shallow tillage) prior to each main crop sowing, typically restricted to the upper 10–15 cm of soil. In Mediterranean environments, this view is supported by evidence that strategic tillage can resolve agronomic constraints without systematically reducing soil moisture or crop productivity, although responses remain site-specific (Cicek et al., 2025).

Building on this experimental trajectory, the present study compares CA and CT within the same long-term field experiment during the 2022 and 2025 sorghum cropping seasons. Both systems were managed under identical water supply modes, including sprinkler (S) irrigation, subsurface drip (SSD) irrigation, and non-irrigated (NI) conditions. The 2022 season represents the CA strict no-tillage phase. The 2025 season represents the adaptive phase following the 2024 structural intervention and the shift toward reduced tillage. Crop rotation and cover cropping pillars were maintained without modification.

We hypothesized that (1) structural improvements previously achieved through decompaction under adaptive CA are maintained one year later under reduced tillage, (2) soil biological and organic matter gains are maintained or enhanced, and (3) crop performance and water productivity improve in 2025 relative to 2022 (strict no-tillage phase). To test these hypotheses, we conducted an integrated before–after assessment of system functioning based on measurements collected in both years. We compared soil physical indicators (penetration resistance), multifunctional soil indicators with the Biofunctool approach, laboratory-derived soil organic matter and microbial activity indicators, and agronomic performance indicators, including sorghum grain yield and water productivity.

2. MATERIALS AND METHODS

2.1. Experimental site description

The experiment was conducted at the INRAE experimental platform in Montpellier (PRESTI, 2025) and is described in detail in Dominguez et al. (2025a, 2025b). Briefly, a 1.5 ha field trial was established in 2021 to compare two soil management systems: conventional tillage (CT) and conservation agriculture (CA), combined with three water supply modes: sprinkler (S) irrigation, subsurface drip (SSD) irrigation, and non-irrigated (NI), resulting in six treatments arranged in large strips.

Total annual rainfall amounts were 758 mm in 2022 and 905 mm in 2025 while evapotranspiration (E_{to}) values were 1026 mm in 2022 and 1012 mm in 2025. However, drought intensity characterized by the ratio of cumulative E_{to} and cumulative R for the period of April to September (period of sorghum development) was 5.14 for 2022 and 5.27, classifying both years as “dry” relative to the 1991–2025 record.

2.2. Cropping system management and conservation agriculture trajectory

Cropping system management from 2020 to 2025 is summarized in

Table 1. It followed a maize–sorghum–soybean–fallow–sorghum rotation as main crops. Under CA, winter cover crops were systematically established and maintained as surface residues after termination,

whereas CT plots were managed with annual ploughing, seedbed preparation, and no cover crops in winter.

The first three years (2021–2023) following CA adoption were characterized by strict no-tillage combined with systematic cover cropping. Due to emerging soil structural constraints associated with compaction, a one-off decompaction operation was implemented in 2024 at a depth of 25 cm (Dominguez et al., 2025b). This intervention marked a shift from strict no-tillage to a more adaptive conservation agriculture strategy in which the cover crop and crop rotation pillars were maintained, but limited soil disturbance was reintroduced to preserve favorable soil structural conditions. In practice, this strategy involved shallow soil operations prior to main crop establishment, including stubble cultivation at 10–15 cm depth in 2025. Consequently, the 2025 cropping season represents a conservation agriculture system managed under reduced tillage, in contrast to the strict no-tillage approach used during the initial years of adoption.

2.3. Field measurements and sampling strategy

Field measurements focused on the 2022 and 2025 cropping seasons, as both years involved sorghum cultivation within the crop rotation, enabling comparison under the same crop species. The variables assessed included: (i) soil penetration resistance; (ii) multifunctional soil indicators determined using the field Biofunctool approach, including aggregate stability, visual evaluation of soil structure, infiltration rate, nitrate captured on anion exchange membranes, soil available nitrogen, permanganate-oxidizable carbon, basal soil respiration, and macro- and mesofauna feeding activity; (iii) laboratory-assessed indicators of soil organic matter and microbial activity, comprising soil organic carbon, mineral-associated organic matter, particulate organic matter, microbial biomass, and the microbial activity index; and (iv) agronomic performance indicators, including sorghum grain yield, total water productivity, and irrigation water productivity. Measurements dates are detailed in

Table 1. In both years, multifunctional Biofunctool indicators and laboratory-assessed soil indicators were measured before sorghum seeding. In 2025, soil penetration resistance was also collected at this same pre-sowing stage. In contrast, in 2022, soil penetration resistance was not initially planned and was measured only after sorghum harvest following field observations that suggested the development of compaction under CA. Agronomic performance indicators were assessed at harvest each year. Measurement protocols for soil penetration resistance and agronomic performances are described in Dominguez et al. (2025a), whereas protocols for multifunctional Biofunctool indicators and laboratory assessed soil organic matter and microbial activity indicators are detailed in Dominguez et al. (2025b).

Table 1. Cropping system management under conservation agriculture (CA) and conventional tillage (CT) systems from 2020 to 2025, and timing of field measurements (in italic) for sorghum (2022 and 2025). In the CA trajectory, light green indicates the strict no-till phase (2020–2023), whereas dark green corresponds to the period following decompaction and the implementation of reduced tillage.

Date	Conservation Agriculture (CA)	Crops in CA	Crops in CT	Conventional Tillage (CT)
03/04/2020: Cover crop seeding 04/04/2020: Cover crop termination 05/04/2020: Cover crop termination		Winter beans	No cover crop / bare soil period	Tillage No cover crop / bare soil period
03/04/2021: Main crop seeding 04/04/2021: Main crop seeding 05/04/2021: Main crop seeding 06/04/2021: Main crop seeding		Maize	Maize	Main crop seeding Main crop seeding Main crop seeding Main crop seeding
07/10/2022: Cover crop seeding 08/10/2022: Multifunctional Biofunctool indicators 09/10/2022: Cover crop termination 10/10/2022: Cover crop termination		Winter wheat (first and second year) phosphorus and nitrate	No cover crop / bare soil period	Tillage Multifunctional Biofunctool indicators Main crop seeding Main crop seeding
03/04/2023: Main crop seeding 04/04/2023: Laboratory-assessed indicators of soil OM and MB 05/04/2023: Grain yield and water productivity 06/04/2023: Main crop termination		Sorghum	Sorghum	Main crop seeding Laboratory-assessed indicators of soil OM and MB Grain yield and water productivity Main crop termination
08/04/2023: Cover crop seeding 09/04/2023: Soil penetration resistance 10/04/2023: Cover crop termination 11/04/2023: Cover crop termination		Maize (first and second year) bare soil period	No cover crop / bare soil period	Soil penetration resistance Tillage Main crop seeding Main crop seeding
03/04/2024: Main crop seeding 04/04/2024: Multifunctional Biofunctool indicators 05/04/2024: Cover crop termination 06/04/2024: Cover crop termination		Sorghum	Sorghum	Main crop seeding Multifunctional Biofunctool indicators Main crop termination Main crop termination
03/04/2025: Main crop seeding 04/04/2025: Multifunctional Biofunctool indicators 05/04/2025: Laboratory-assessed indicators of soil OM and MB 06/04/2025: Grain yield and water productivity 07/04/2025: Main crop termination		Winter wheat (first and second year) phosphorus and nitrate	No cover crop / bare soil period	Tillage Main crop seeding Main crop seeding Main crop seeding Main crop seeding
03/04/2026: Main crop seeding 04/04/2026: Multifunctional Biofunctool indicators 05/04/2026: Laboratory-assessed indicators of soil OM and MB 06/04/2026: Grain yield and water productivity 07/04/2026: Main crop termination		Sorghum	Sorghum	Main crop seeding Multifunctional Biofunctool indicators Laboratory-assessed indicators of soil OM and MB Grain yield and water productivity Main crop termination

2.4. Integrated Soil Functioning Indicators and Analytical Framework

To compare soil functioning across years, we developed an integrated analytical framework combining multifunctional Biofunctool indicators with laboratory-assessed indicators of soil organic matter and microbial activity (**Table 2**).

Table 2. Summary of field-assessed multifunctional Biofunctool soil indicators and laboratory-assessed indicators of soil organic matter and microbial activity.

Soil Indicator	Indicator	Unit
Multifunctional Biofunctool Soil Indicators		
Aggregate stability (0–2 cm)	AggSurf	Score
Aggregate stability (2–10 cm)	AggSoil	Score
Visual evaluation of soil structure	VESS	Score
Infiltration rate	Beerkan	mL min ⁻¹
NO ₃ -fixed on anion exchange membrane	AMNO ₃	μg cm ⁻² d ⁻¹
Soil available nitrogen	Nmin	mg kg ⁻¹
Permanganate oxidizable carbon (labile organic carbon)	POXC	mg kg ⁻¹
Basal soil respiration	SituResp	Absorbance difference
Little macro- and mesofauna feeding activity (decomposition of organic matter)	Lamina	% d ⁻¹
Laboratory-assessed Indicators of soil organic matter and microbial activity		
Mineral-Associated Organic Matter	MAOM	g kg ⁻¹
Particulate Organic Matter	POM	g kg ⁻¹
Microbial Activity Index	MAI	–
Microbial biomass	MB	mg C kg ⁻¹
Soil Organic Carbon	SOC	g kg ⁻¹

This integrated dataset combines indicators representing complementary physical, chemical, and biological dimensions of soil functioning. Data were structured in long format and filtered to the two target years (2022 and 2025). As water supply modes (S, SSD and NI) did not significantly affect the variables analyzed, observations were pooled by soil management system (results not shown here). For each indicator, values were then averaged by year and soil management practice (CA and CT) to reduce within-group variability and highlight central tendencies.

Since indicators are expressed in different units and ranges, we applied a standardization step using z-score normalization to enable meaningful cross-indicator comparison. For each indicator i , normalization was computed as:

$$Z_{i,j} = \frac{X_{i,j} - \mu_i}{\sigma_i} \quad (1)$$

where $X_{i,j}$ is the mean value of indicator i for a given year–practice combination j , μ_i is the overall mean of indicator i across all observations, and σ_i is the corresponding standard deviation. This transformation centers each indicator around zero and scales it by its variability, ensuring that all indicators contribute equally to the multivariate profile regardless of their original magnitude or units.

The normalized values were then visualized using radar (polar) plots to represent multidimensional soil functioning profiles for each practice within each year. To explicitly quantify the relative difference between practices, we computed a differential index for each indicator and year:

$$\Delta_i = Z_{i,CA} - Z_{i,CT} \quad (2)$$

where Δ_i represents the standardized effect size of management practice. Positive values indicate higher performance under CA relative to CT, whereas negative values indicate the opposite.

3. RESULTS

3.1 Soil penetration resistance

Figure 1 shows the vertical distribution of soil penetration resistance (kPa) from 0 to 30 cm depth in 2022 and 2025 under CA and CT, for the three water supply modes NI, S, and SSD irrigation. In 2022, CA tended to exhibit higher penetration resistance than CT, particularly under NI and SSD. Under NI and SSD, CA showed a marked increase from 500 kPa at the surface to approximately 3000 kPa 2,500 kPa below 10 cm and approached 3,000 kPa at 25–30 cm, while CT remained substantially lower, reaching about 2,500–3,000 kPa only in the deepest layers. Under S, differences between practices were smaller and both systems displayed relatively moderate resistance values, generally ranging between 200 and 1,800 kPa. These results exhibited that during the early phase of CA, the absence of tillage led to soil compaction, particularly under NI and SSD.

By 2025, one year after the decompaction intervention (< 25 cm), penetration resistance profiles indicated a sustained reduction in compaction compared with 2022, particularly in the upper 20 cm of soil under CA. Nevertheless, CA still maintained slightly higher resistance than CT below 20 cm, reaching approximately 3,000 kPa at 25–30 cm compared with 2,000 kPa under CT. Under S irrigation, penetration resistance remained moderate and the profiles of CA and CT became much more similar, with values mostly below 1,800 kPa throughout the profile. Under SSD, CA continued to show higher resistance than CT, particularly between 20 and 30 cm where values reached 3,000–3,200 kPa, while CT generally remained below 2,000 kPa, indicating that compaction constraints persisted in deeper layers beyond the depth of mechanical intervention.

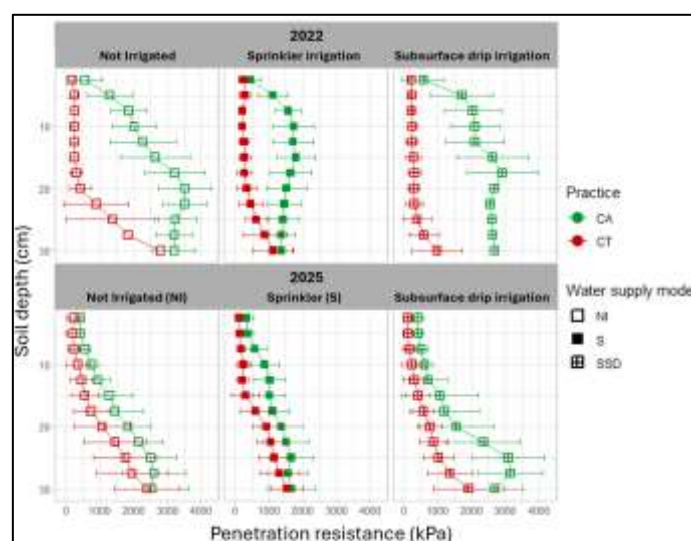


Figure 1. Soil penetration resistance profile in 2022 and 2025 under different agricultural practices (conservation agriculture (CA) and conventional tillage (CT)) combined with different water supply modes (not irrigated (NI), sprinkler (S) and subsurface drip (SSD)). Error bars indicate standard deviations.

3.2. Soil functioning

The standardized CA–CT effect index (Δ , z-score range -2 to $+2$) revealed substantial differences in the response of soil functions indicators between 2022 and 2025 (

Figure 2). Positive values indicate higher performance under CA, while negative values indicate higher values under CT.

In 2022, CA showed generally positive effects for most biological and organic matter indicators, but structural and hydraulic functions were less favorable. In particular, visual evaluation of soil structure (VESS) and water infiltration rate (Beerkan) were strongly negative, indicating less favorable structural conditions and reduced water entry under CA compared with CT. By contrast, indicators related to soil organic matter (SOC, POM, MAOM, POXC) and microbial activity (MB, MAI, SituResp) were already positive but of moderate magnitude.

By 2025, CA effects became stronger and more consistently positive across almost all indicators. Improvements were particularly marked for soil structure, with VESS shifting from strongly negative in 2022 to positive values, and Beerkan also turning from negative to positive, indicating recovery of soil physical functioning. Aggregate stability (AggSoil and AggSurf) also increased. In parallel, organic matter indicators and microbial activity showed reinforced positive responses, often approaching the upper end of the standardized scale.

Overall, the Δ index highlights a clear transition from a mixed system response in 2022, characterized by biological gains but physical structural limitations, to a more balanced and consistently CA-favorable soil functioning in 2025, with simultaneous improvement in soil physical indicators, carbon dynamics, and microbial activity.

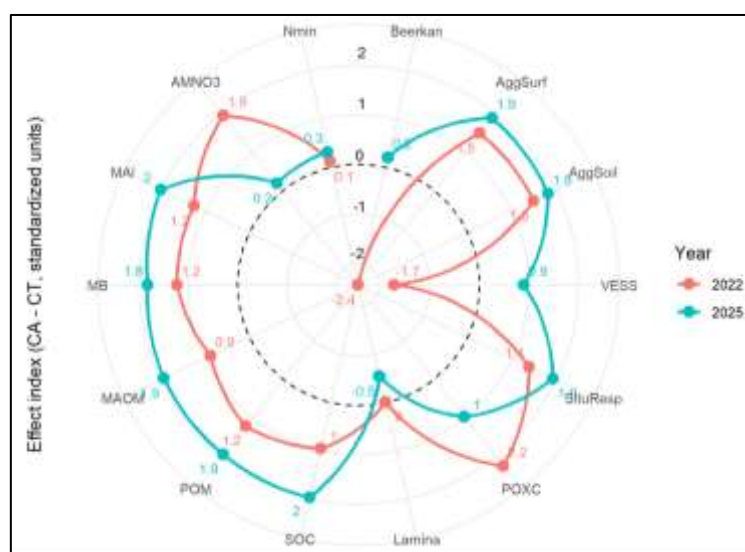


Figure 2. Integrated assessment of conservation agriculture versus conventional tillage (CA–CT, z-score standardized Δ) across multifunctional Biofunctool and laboratory-derived organic matter and microbial activity indicators in 2022 and 2025. Positive values indicate higher performance under CA, while negative values indicate higher values under CT.

3.3. Agronomic performances

3.3.1. Sorghum Grain Yield

Grain yield varied markedly between years and water supply modes under CA and CT (

Figure 3). In 2022, CA yields were significantly lower than CT. Under S irrigation, CT produced significantly higher yields than CA, with CT-S reaching the highest overall value and being significantly greater than CA-S. Under SSD irrigation, CT also yielded significantly more than CA. In contrast, under NI, yields were low, as expected, and did not differ significantly between CA and CT

In 2025, yields increased strongly across all treatments, ranging from approximately 4.6 to 9.2 t ha⁻¹. A clear irrigation gradient was observed in both CA and CT, with S > SSD > NI, indicating strong and consistent effects of water supply mode. However, within each water supply mode, no significant differences were detected between CA and CT, indicating convergence of system performance. S and

SSD irrigation mode therefore remained the main drivers of yield variation, with the highest value recorded under CA-S (9.24 t ha⁻¹).

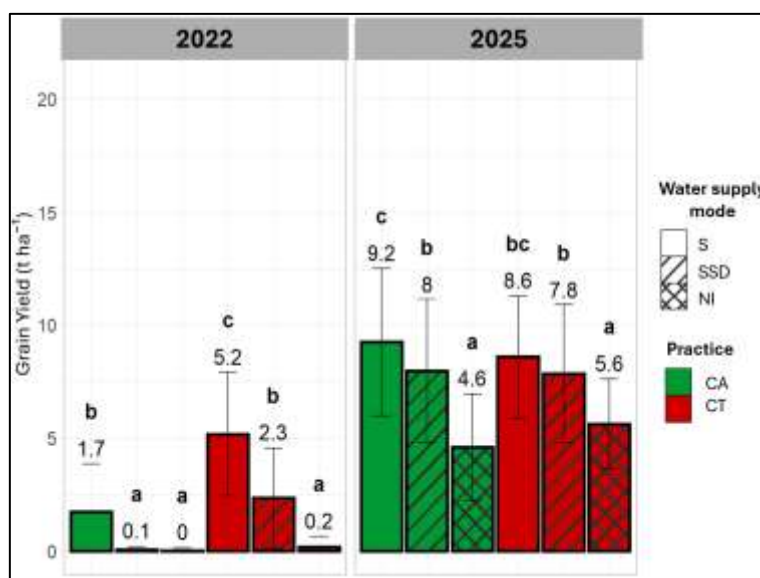


Figure 3. Grain yield values across sorghum seasons for 2022 and 2025 under different agricultural practices (conservation agriculture—CA and conventional tillage—CT) combined with different irrigation systems (not irrigated—NI, sprinkler—S and subsurface drip—SSD). Error bars indicate standard deviations. Different letters above the bars indicate statistically significant differences among treatments based on Tukey's post-hoc test ($p < 0.05$); treatments sharing the same letter are not significantly different, while those with different letters differ significantly.

3.3.2. Total Water Productivity (TWP) and Irrigation Water Productivity (IWP)

Table 3 reports total water productivity (TWP) and irrigation water productivity (IWP) for sorghum in 2022 and 2025. In 2022, productivity was low across treatments. Under S irrigation, TWP and IWP were higher in CT (1.4 and 1.9 kg m⁻³) than in CA (0.5 and 0.7 kg m⁻³). Under SSD, CT also outperformed CA (0.6 and 0.8 vs 0.0 kg m⁻³ for both TWP and IWP). Under NI, productivity was near zero in CA and very low in CT. Overall, CA showed lower water-use efficiency than CT in 2022.

In 2025, water productivity increased markedly across all treatments, driven by higher yields and reduced irrigation inputs (from -25 in CA-S to -45% in CT-S). A clear irrigation gradient was observed ($S > SSD > NI$), while differences between CA and CT were reduced. CT-S showed the highest TWP, but system differences were generally small. IWP was slightly higher under CA in some cases, particularly under SSD, indicating improved irrigation efficiency under the adaptive management.

Table 3. Summary of real irrigation volumes (I), total water input (rainfall R + irrigation I), total water productivity (TWP) and irrigation water productivity (IWP) across sorghum seasons in 2022 and 2025 under different agricultural practices (conservation agriculture—CA and conventional tillage—CT) combined with different irrigation systems (not irrigated—NI, sprinkler—S and subsurface drip—SSD).

Treatment	2022				2025			
	I (m ³ ha ⁻¹)	R+I (m ³ ha ⁻¹)	TWP (kg m ⁻³)	IWP (kg m ⁻³)	I (m ³ ha ⁻¹)	R+I (m ³ ha ⁻¹)	TWP (kg m ⁻³)	IWP (kg m ⁻³)
CA-S	2400	3550	0,5	0,7	1780	2430	3,8	2,6
CA-SSD	2600	3750	0,0	0,0	1450	2250	3,5	2,3
CA-NI	-	1150	0,0	-	-	1000	4,6	-
CT-S	2600	3750	1,4	1,9	1440	2090	4,1	2,1
CT-SSD	2600	3750	0,6	0,8	1450	2250	3,5	1,5
CT-NI	-	1150	0,2	-	-	1000	5,6	-

4. DISCUSSION

The results demonstrate that the transition from strict no-tillage to an adaptive reduced-tillage strategy successfully addressed the main limitations encountered during the early phase of CA while preserving, and in several cases strengthening, the soil functioning benefits already established. In 2022, CA exhibited clear advantages over CT for indicators related to aggregate stability, soil organic matter fractions, microbial biomass, and microbial activity, reflecting the rapid effects of cover crops, residue retention, and no disturbance. These improvements were particularly evident in the carbon transformation function, which integrates organic matter and microbial indicators and likely reflects the continuous supply of fresh carbon from winter cover crops and their maintenance as surface residues. At the same time, CA showed higher penetration resistance, poorer visual structural quality (VESS), and slightly lower infiltration (Beerkan), indicating that physical constraints had developed despite improvements in biological functioning. This imbalance was associated with significantly lower sorghum yields and water productivity under CA than under CT, especially under irrigated conditions, confirming that enhanced biological activity alone was insufficient to sustain crop performance when root growth and water movement were restricted. This can be partly explained by the inherent sensitivity of the studied silt loam soil to compaction, which can rapidly reduce pore continuity and limit both root penetration and hydraulic functioning.

The fifth year of the experiment revealed a markedly different situation. Following the one-off decompaction to 25 cm in 2024 and the subsequent adoption of shallow reduced tillage prior to each main crop, soil structural indicators improved substantially. Penetration resistance in the upper soil profile declined, VESS shifted from a strongly negative CA–CT differential in 2022 to a positive one in 2025, AggSurf and AggSoil increased, and Beerkan values became slightly more favorable under CA. Importantly, these structural improvements were accompanied by continued increases in soil organic carbon, particulate and mineral-associated organic matter, microbial biomass, and microbial activity, with several indicators reaching effect sizes close to +2 standard deviations relative to CT. Thus, the shift to reduced tillage while maintaining cover cropping and crop rotation not only helped alleviate compaction in the early years but also allowed the biological and functional advantages of CA to be more fully expressed, ultimately leading to improved agronomic performance.

These findings support the conceptual framework proposed by Ferchaud and Alletto (2026), who argue that tillage should be considered as a context-dependent management lever rather than a binary opposition between “no-till” and “tillage.” In our study, the shift away from strict no-tillage did not undermine CA performance; instead, limited and targeted disturbance restored soil physical functionality while maintaining, and even enhancing, the core ecological processes promoted by CA. The positive response observed in 2025 therefore suggests that the success of CA depends less on the complete elimination of tillage than on the capacity to balance reduced disturbance with corrective interventions when structural constraints emerge.

The results are also consistent with Liu et al. (2016), who showed that a one-off strategic tillage event in long-term no-till systems did not significantly alter soil physical, chemical, or biological properties. Similarly, the decompaction carried out in 2024 did not reverse the gains previously observed in aggregate stability, organic matter fractions, and microbial activity. Instead, these indicators continued to improve, demonstrating that the soil health legacy generated during the early CA phase was sufficiently resilient to withstand occasional shallow disturbance.

At the same time, the Mediterranean context plays a decisive role in modulating these responses. As highlighted by Cicek et al. (2025), the effects of strategic tillage are highly site-specific and depend on rainfall distribution, soil type, residue cover, and seasonal water stress. In Mediterranean environments, where compaction, residue management, and water scarcity interact strongly, occasional tillage may be beneficial when used to remove clearly identified structural constraints, but its effects cannot be generalized across all conditions. In this experiment, the intervention was effective because compaction had become a major limitation to rooting and water movement, and because the system retained the other foundational components of CA, including cover crops, residue retention, and crop diversifications.

Importantly, the results also support a key argument raised by Ferchaud and Alletto (2026) who explain that soil carbon dynamics are primarily driven by carbon inputs and system diversity rather than by tillage intensity alone. In this study, SOC, POM, MAOM, and microbial biomass increased under CA despite the introduction of shallow mechanical disturbance. This suggests that the biological trajectory of CA was driven by cover crops, residue retention, and rotation effects rather than strict absence of tillage. From an agronomic perspective, the most important outcome is the recovery of water-use efficiency. The strong increase in irrigation water productivity in 2025 indicates that the adaptive CA system improved the conversion efficiency of scarce water resources into grain yield. Although sprinkler irrigation maintained significantly higher yields than subsurface drip irrigation, both irrigation systems showed substantial improvements under adaptive CA. This is particularly relevant in Mediterranean irrigated systems, where water is one of the primary limiting factors. In this context, CA should not be evaluated only in terms of soil conservation, but also in terms of its ability to stabilize yield under constrained water availability.

Overall, the results support a re-interpretation of CA as a flexible management framework. The system functions optimally when minimal soil disturbance is combined with high organic inputs and when occasional corrective tillage is used strategically to resolve structural constraints. This hybrid behavior does not contradict CA principles but instead reflects a more realistic representation of agroecosystem dynamics in Mediterranean environments, where strict no-till is often difficult to maintain and may not always optimize system performance.

5. CONCLUSIONS

This study showed that the adaptive soil management strategy, allowing reduced shallow tillage, alleviated the structural constraints that had developed during the strict no-till phase. Second, the biological and organic matter gains accumulated during the early years of CA were maintained and generally amplified. Third, crop performance and both total and irrigation water productivity improved markedly, with sprinkler irrigation generally producing the highest yields, reaching levels comparable to or greater than those under CT. More broadly, the study suggests that CA in irrigated Mediterranean systems should be understood as an adaptive management trajectory rather than a rigid technical prescription. When combined with continuous organic inputs and limited, well-targeted disturbance, CA can reconcile soil health improvement, structural functionality, and efficient use of scarce water resources.

Future research should determine whether these improvements continue over longer time scales and under increasingly variable climatic conditions. Continued monitoring will help clarify the durability of the adaptive strategy and identify the thresholds at which strategic disturbance becomes necessary to sustain both soil multifunctionality and crop-water productivity.

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