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Experimental evaluation of a modified bentleg plough: improving soil structure and water infiltration under South Mediterranean pedo-climatic conditions

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Abstract. This study evaluates a mechanically modified Bent leg plough (experimental tool, ET) for deep soil decompaction under low tractor power conditions typical of South Mediterranean cereal systems. The tool integrates a curved blade with a negative rake angle to enhance subsoil loosening while preserving soil horizon integrity and minimizing draft resistance.
A field experiment using a randomized complete block design compared four tillage systems: conventional (CT), minimum (MT), no tillage (NT), and ET. Soil physical properties (penetration resistance and water infiltration) and durum wheat yield were assessed. A second trial related forward speed to specific fuel consumption to derive a Relative Traction Index (RTI), enabling comparison of traction demand and energy efficiency with a mouldboard plough.
Results showed that ET significantly improved infiltration and reduced soil compaction compared to CT, MT, and NT. Mean infiltration rates under ET were 63% higher than CT, 115% higher than MT, and 165% higher than NT ($p < 0.05$). Additionally, penetration resistance was reduced by up to 72% relative to NT, indicating enhanced porosity and structural stability across all soil profiles. Although CT achieved the highest yield (22.5 Qt ha^{-1}), ET produced comparable productivity (18.7 Qt ha^{-1}) with greater soil conservation and lower energy demand. Regression and ANOVA analyses confirmed that ET maintained stable soil conditions over time, unlike CT and MT, which showed rapid reconsolidation.
In term of energy performance, The ET maintained lower fuel consumption (12.6–17.4 L ha^{-1}) at significantly higher speeds than the conventional plough, which required up to 26.7 L ha^{-1}. A Relative Traction Index (RTI) analysis revealed th.
Overall, the modified Bent leg plough enables effective deep loosening with reduced compaction and traction requirements, while maintaining competitive yield under rainfed South Mediterranean conditions.

Key words: bentleg plough, conservation tillage, durum wheat, South Mediterranean region, infiltration, soil compaction, subsoiling.

INTRODUCTION

Modern agriculture faces an existential challenge: feeding a growing global population while managing the accelerating impacts of the climate crisis. In vulnerable regions like the Mediterranean basin, characterized by high rainfall variability and vulnerability to soil erosion (Zdruli et al., 2010; García-Ruiz et al., 2013; Sardans & Peñuelas, 2013). The focus is shifting from land quantity to the soil's ability to manage water and resist structural degradation. Maintaining the physical health of arable land is the primary line of defense against desertification and crop failure. Therefore, innovation in cultural practices and sustainable agricultural mechanization is imperative to ensure the resilience of local cereal systems against the combined threats of drought and compaction.

In response to these challenges, conservation tillage practices (NT, MT) have been widely adopted. However, scientific literature shows that these practices often lead to persistent subsurface compaction (tillage pan), evidenced by increased Penetrometer Resistance (PR) and Bulk Density (BD) in deeper horizons. For instance, long-term no-tillage systems have been found to increase BD in the 5–20 cm layer, leading to a narrower Least Limiting Water Range (LLWR) (Stošić et al., 2020). Furthermore, studies indicate that natural recovery processes struggle to restore the structural integrity of deep soil layers (10–60 cm), even over extended periods, justifying the need for targeted mechanical intervention (Naskar et al., 2025). The hydrological impact of this deep compaction is critical, especially given the intensifying threat of droughts (Shao et al., 2018), as compaction severely alters the pore structure. In this context, the creation of macropores is essential for regulating water retention and mitigating the effects of crucial drying-wetting cycles prevalent in arid climates (Xiao et al., 2022).

To understand these dynamics, a parallel body of research investigates soil-water behaviour at the micro- and pore scales. Pore-scale simulations and imaging studies have demonstrated that pore size distribution and connectivity directly control the hysteresis of water retention curves (Liu et al., 2024; Liu et al., 2025; Zhou et al., 2025). These findings establish that improved water retention is intrinsically linked to enhanced mechanical resistance to compression, highlighting the need to consider soil moisture conditions during tillage (Guedioura et al., 2023; Tan et al., 2025). On the other hand, considerable efforts are directed towards developing materials to enhance unsaturated hydraulic conductivity and water retention. Such findings emphasize that sustainable tillage should aim not only to loosen compacted horizons but also to preserve pore continuity, balance aeration and water storage, and limit structural collapse.

This study experimentally evaluates a newly developed mechanically modified Bentleg plough designed for sustainable tillage under South Mediterranean conditions. The tool features an inclined-share geometry with a negative rake angle, enabling deep soil decompaction while operating efficiently with low-power tractors. Unlike conventional subsoilers, it aims to achieve significant loosening without soil inversion, preserving horizon integrity and reducing draft resistance. The research specifically investigates whether this modified design can improve soil penetration resistance, water infiltration, and crop yield compared to conventional, minimum, and no-tillage systems in South Mediterranean calcareous soils.

MATERIALS AND METHODS

Description of the innovated tool

The developed prototype is a tillage tool inspired by the bentleg plough and specifically adapted to South Mediterranean pedo-climatic conditions. It is designed to achieve effective soil decompaction down to 40 cm without inverting the soil layers, thereby preserving the vertical organization and pedological stratification of the soil profile. To meet these objectives, several design modifications were introduced.

The blade geometry was optimized to minimize draft resistance. The rake angle (α), which is negative compared to that of a conventional bentleg plough (Fig. 1), significantly reduces power requirements while maintaining effective soil fragmentation. This configuration enables the blade to initiate cutting at the surface, where compaction is lowest, and to progressively lift and fracture the soil along the curved cutting line of the blade (Fig. 1). This gradual action reduces draft force and allows higher operating speeds.

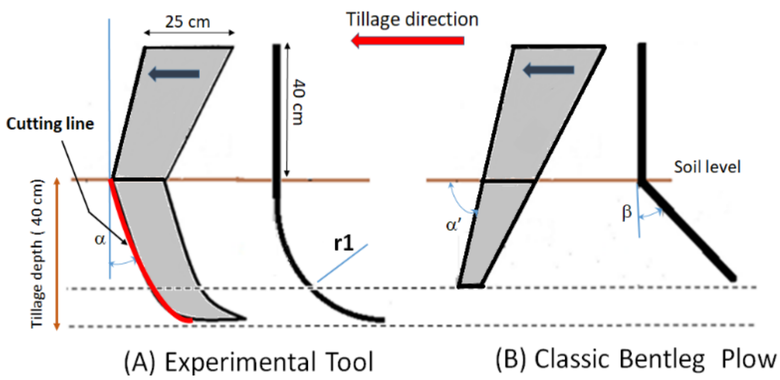

Figure 1. Comparison of blade geometry between (A) the experimental bentleg plough (ET) and (B) the conventional bentleg plough. α and α′ represent the rake angles of the experimental and conventional tools, respectively, while r_1 denotes the curvature radius of the bentleg. The negative rake angle of the ET is designed to reduce draft force while enhancing deep soil loosening without inversion.

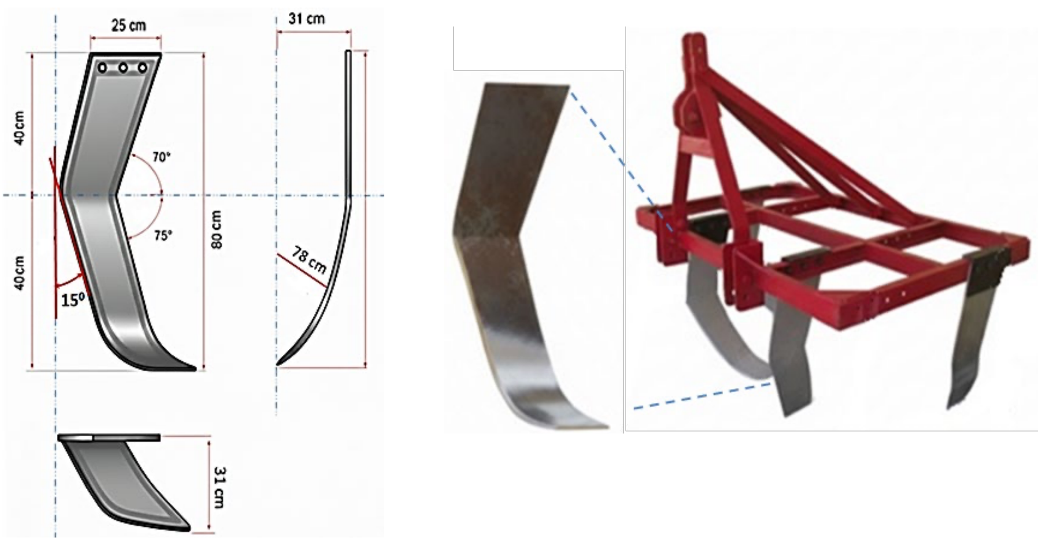

Figure 2. Prototype of the mechanically modified bentleg plough featuring four elements and an adjustable working width of up to 2.1 m.

The prototype features an adjustable working width of of 1.2 m using two elements - 2.1 m using four elements (Fig. 2), an optimal operating speed of 8–12 km h^{-1}, and compatibility with tractors rated between 50 and 80 horsepower.

Thus, the developed tool retains the agronomic advantages of the bentleg plough (alleviating compaction, maintaining natural soil organization, and enhancing both water infiltration and retention) while substantially reducing power demand.

The Fig. 2 shows the full-scale modified bentleg plough equipped with an inclined-share blade and a negative rake angle. The design allows deep soil decompaction while maintaining structural stability and compatibility with low-power tractors. The prototype was fabricated and tested under South Mediterranean field conditions.

Experimental site and design

Experimental site the experiment was conducted at the station of the Technical Institute of Field Crops (ITGC) in Oued Smar (36° 34’ N, 3° 48’ E, 24 m Alt) (Fig. 3). The site is located 24 meters above sea level, between the 600 mm and 700 mm isohyets.

The experiment was carried out from mid-November to July. The I.T.G.C. station is located in the sub-humid bioclimatic zone characterized by mild, rainy winters and hot, dry summers. During the study period (2020), the mean annual temperature was 21.6∘C, and the average annual precipitation was 30.8 mm (Fig. 4).

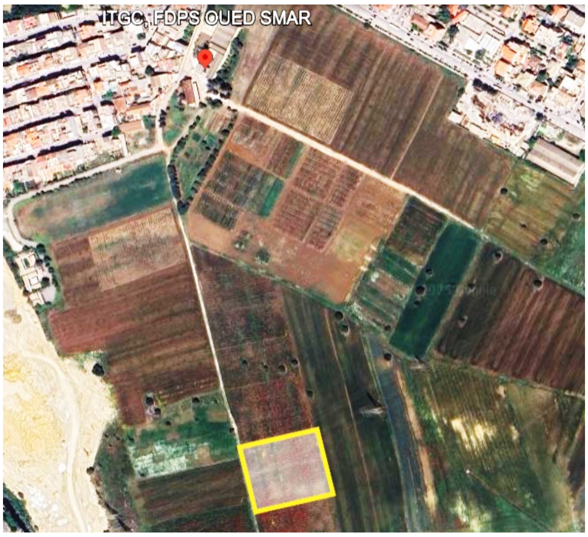

Figure 3. Geographic location of the experimental site at the Technical Institute of Field Crops (ITGC), Oued Smar, Algeria (Google Earth, 2024).

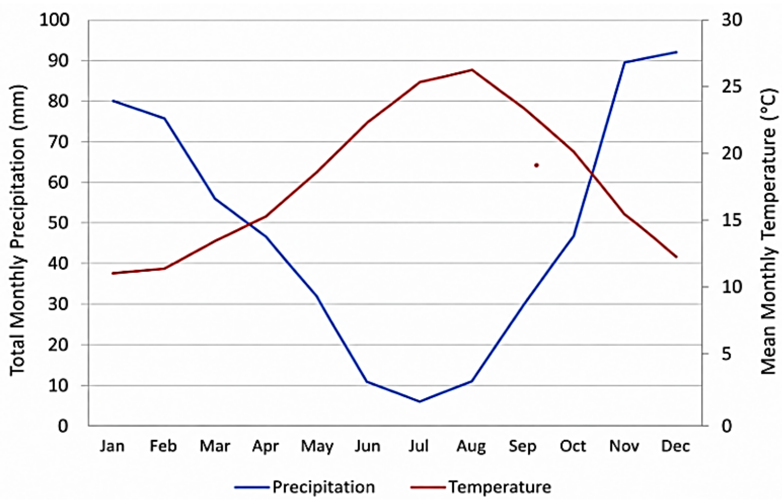

Figure 4. Annual umbrothermal diagram of 2020 at the experimental site, illustrating monthly precipitation and temperature patterns.

Experimental Design The experimental plot was divided into four blocks using a Randomized Complete Block (RCB) design, consisting of four repetitions of four distinct tillage practices (cultural treatments) (Fig. 5).

The experimental design covers a total area of 6,720 m² (96 m × 70 m) and is arranged as a randomized complete block design with four blocks. Each block, with an area of 1,680 m² (24 m × 70 m), is subdivided into four elementary plots corresponding to the treatments (CT, MT, NT, ET). Each plot measures 6 m × 70 m, giving a unit area of 420 m². This design allows comparison of soil management systems while controlling spatial heterogeneity of the experimental site (Fig. 5). The characteristics of the different tillage treatments, including implements used, working depth, and number of operations before sowing, are presented in Table 2 (Conventional tillage CT, Minimum tillage MT, No till NT and experimental tool ET). The used tractor develops a power of 80 hp. ‘

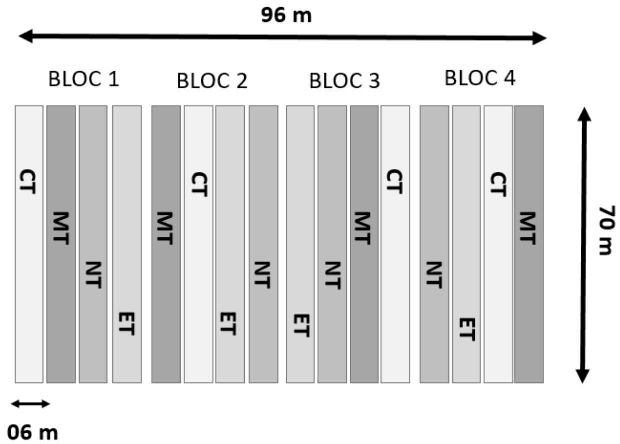

Figure 5. Layout of the experimental field arranged in a randomised complete block design (RCBD). CT: conventional tillage; MT: minimum tillage; NT: no-tillage; ET: experimental tool tillage.

The main characteristics of the experimental site, climatic conditions, soil properties, and experimental design are summarized in Table 1.

Table 1. Main characteristics of the experimental site and field design

Parameter	Description / Value
Location	Technical Institute of Field Crops (ITGC), Oued Smar, Algeria
Geographic coordinates	36°34′ N, 3°48′ E
Altitude	24 m a.s.l.
Bioclimatic zone	Sub-humid, mild rainy winters and hot dry summers
Mean annual temperature (2020)	21.6 °C
Mean annual precipitation (2020)	30.8 mm
Experimental design	Randomized Complete Block Design (RCBD)
Replications	4
Tillage treatments	Conventional (CT), Minimum (MT), No-tillage (NT), Experimental tool (ET)
Experimental period	Mid-November to July
Physical soil characteristics	The soil texture is clay-loam with 46.51% clay; 25.30% silt and 26.79% sand.

Table 2. Description of tillage treatments, implements used, working depth, and number of operations prior to sowing

	Technique	Tools used	Working depth (cm)	Number of operations before sowing
CT	Conventional tillage	- Ploughshare -Spring cultivator -Harrow - Seeder	25	03
MT	Minimum tillage	-Spring cultivator - Seeder	15	01
NT	No Till	- Seeder	00	00
ET	Experimental tool tillage	-Experimental tool - Seeder	40	01

Agricultural management and measurements

The wheat variety used for the experiment belongs to the durum wheat species and is widely cultivated in the region and throughout Algeria. The selected variety was Simeto (pedigree: Capeiti/Valvona), originally developed in Italy. No fertilization programme was applied in order to clearly distinguish the effect of the tillage method and the experimental tool on crop development. The experiment was conducted under rainfed conditions, without supplemental irrigation, for two main reasons: (1) to align with common agricultural practices in the region, where wheat is primarily grown under rainfall, and (2) to better isolate and evaluate the expected effects of the experimental treatment. The parameters analyzed in this experiment were primarily related to the soil condition after the application of the different tillage techniques, with four replications for each measurement.

Measurements included soil penetration resistance, soil infiltration capacity, and crop yield. Soil penetration resistance was measured using a static penetrometer. The penetrometer is a geotechnical instrument used to determine cone resistance and the maximum allowable stress. Measurements were taken after the passage of the tillage tool to quantify the degree of soil crumbling (tillage quality) and evaluate the tool's effectiveness. Soil infiltration capacity was evaluated using a double-ring infiltrometer to characterize the soil's ability to transmit water under ponded, near-saturated conditions. Infiltration capacity was defined as the depth of water infiltrated per unit time, expressed as mm s^{-1}.

Measurements were performed in accordance with the NF EN ISO 22282-5 standard. The infiltrometer consisted of an inner ring with a diameter of 50 cm and an outer ring with a diameter of 70 cm, both inserted vertically into the soil to the same depth. Water was simultaneously applied to both rings in order to establish ponded conditions, while the outer ring was used to limit lateral flow and promote predominantly vertical infiltration beneath the inner ring.

The double-ring infiltrometer measurements were conducted using standard procedures with clearly defined conditions. In each plot, five measurement points were randomly selected to account for spatial variability. The inner and outer rings were inserted into the soil to a depth of 10 cm to minimize lateral water flow. Prior to the test, a pre-saturation phase was applied to stabilize infiltration, and the initial infiltration depth was standardized at 5 cm. Soil moisture content before measurements was recorded and averaged for each mesurment to ensure comparable initial conditions across plots.

Infiltration was determined by recording the time required for a known depth of ponded water in the inner ring to completely infiltrate into the soil. The infiltration rate was calculated as the ratio between the infiltrated water depth and the corresponding infiltration time. This procedure provides an estimate of field infiltration capacity under ponded conditions, which is strongly influenced by soil structure and macroporosity and is therefore particularly suitable for assessing the impact of different tillage techniques on soil hydraulic behavior.

Harvesting was carried out at the end of June using an experimental combine harvester. Yields were calculated by dividing the total production by the cultivated area for each mini-plot, according to the following equation:

$$Yield\ (Qt/\mathrm{h}) = \frac{Total\ Production\ (Qt)}{Cultivated\ Area\ (\mathrm{h})} \quad (1)$$

Assessment of traction power and energetic efficiency

To evaluate the traction power requirements and energetic efficiency of the experimental tool implement, a second series of experimental trials was conducted by correlating forward speed with specific fuel consumption. The trials were carried out using an 80 hp tractor, successively coupled with the experimental tool (two modified bentleg plough elements) and a two-corp mouldboard ploughs. Measurements were taken using a stopwatch, a graduated container, and a measuring ruler.

The experiment was conducted on homogeneous soil, with moisture close to the friable state. Tractor settings were kept constant (≈ 1,800 rpm). Working depths were set at 40 cm (experimental tool) and 25 cm (mouldboard plough).

The trials were performed on 50 m strips, with three replications. Target speeds were 8, 10, and 12 km h^{-1} for the experimental tool, and 3, 4, and 5 km h^{-1} for the plough. The measured variables included travel time, working depth, fuel consumption, and qualitative observations.

The specific fuel consumption Cs (L ha^{-1}) was estimated as:

$$\mathrm{Cs} = \frac{f}{a} \times 10{,}000 \quad (2)$$

where *f* is the volume of fuel consumed (L), a is the the worked area (m^2).

The speed and consumption parameters were calculated to provide a synthetic indicator of field performance. A relative empirical traction index (RTI) was defined as:

$$\mathrm{RTI} = \frac{s}{\mathrm{Cs}} \quad (3)$$

where s is the forward speed and Cs is the specific fuel consumption.

This index is based on the assumption that fuel consumption serves as a proxy for the energy mobilized by the tractor–implement system, in the absence of direct measurement of draft force (Grisso et al., 2004). Furthermore, the relationship:

$$\mathrm{P} = \mathrm{Ft} \times \mathrm{V} \quad (4)$$

implies that, for a given power, an increase in speed associated with a decrease in fuel consumption indicates a reduction in the required draft force.

Thus, the ratio s/Cs links kinematic performance and energy demand, providing an indirect estimate of traction efficiency. Although empirical, this index allows for consistent relative comparison between implements under controlled experimental conditions.

Statistical analyses

For the agro-pedological effects, a comprehensive multiple regression analysis was carried out using dummy variables to explore the relationships between the dependent variables (infiltration and penetration resistance) within the framework of the Experimental Tool (ET) which was designated as the reference method in this analysis. The objective of this analysis was to quantify and compare the effects of the reference ET method with those of the alternative tillage systems: conventional tillage (CT), no-tillage (NT), and minimum tillage (MT). By applying dummy coding, the model effectively captured variations in performance indicators among the different tillage methods, providing a clearer understanding of their respective impacts on soil physical properties and overall agricultural performance.

A one-way analysis of variance (ANOVA) was conducted to evaluate the differences in average production quantities among various tillage methods. This statistical approach allows us to determine whether there are significant differences between the means of the different groups. Following the ANOVA, post-hoc tests were performed to further analyse the data and identify which specific tillage methods produced significantly different average yields. This rigorous comparison provides clear insight into the effectiveness of each tillage method in enhancing agricultural productivity. In regression and ANOVA analysis, validity tests like model residual normal distribution, residual homogeneity of variances, and linear multiple correlation between independent variables are used to ensure the model's efficiency.

The linear relationships describing soil physical behavior are specified as follows.

For Infiltration Rate (mm s^{-1}):

$$Y_{\text{inf}} = \beta_0 + \beta_{\text{time}}X + \sum(\beta_i D_i) + \sum(\beta_{\text{int},i} D_i X) + \varepsilon_1(02) \quad (5)$$

For Penetration Resistance (N):

$$Y_{\text{pen}} = \alpha_0 + \alpha_{\text{time}}X + \sum(\alpha_i D_i) + \sum(\alpha_{\text{int},i} D_i X) + \varepsilon_2(03) \quad (6)$$

Definition of Terms

- $\beta_0$and α_0 (Intercepts / Baseline levels) These parameters represent the estimated infiltration rate and penetration resistance, respectively, at month zero for the reference evapotranspiration (ET) method.
- $\beta_i$and α_i (Intercept differences) These coefficients quantify the initial deviation of the alternative management methods conventional tillage (CT), minimum tillage (MT), and no-tillage (NT) from the ET baseline.
    - For infiltration, a negative $\beta_i$indicates a lower initial infiltration rate relative to ET.
    - For penetration resistance, a positive $\alpha_i$indicates greater soil strength (i.e., increased compaction) relative to ET.
- $\beta_{\text{time}}$and α_{time} (Baseline temporal trends) These parameters describe the monthly rate of change in infiltration rate and penetration resistance, respectively, for the ET treatment.
- $\beta_{\text{int},i}$and $\alpha_{\text{int},i}$ (Interaction / slope differences) These interaction terms capture differences in temporal trends between the alternative methods and the ET baseline,

indicating whether each method exhibits a faster or slower rate of change over time relative to ET.

- X Time, measured in months.
- D_i Dummy variables identifying the alternative management methods (CT, MT, NT), with ET serving as the reference category.
- $\varepsilon_1$and ε_2 Random error terms associated with the infiltration and penetration resistance models, respectively.

RESULTS AND DISCUSSION

Soil physical responses to the mechanically modified bentleg plough (experimental tool, ET) were evaluated in comparison with conventional tillage (CT), minimum tillage (MT), and no-tillage (NT) using water infiltration rate and soil penetration resistance as key indicators. These variables are widely recognized as integrative measures of soil structural modification and physical quality, as they reflect the combined effects of soil loosening, pore continuity, aggregate stability, and reconsolidation processes over time.

Soil water infiltration

Infiltration performance was strongly influenced by the tillage method. Fig. 6 shows that mean infiltration rates were 0.252 mm s^{-1} for ET, 0.155 mm s^{-1} for CT, 0.117 mm s^{-1} for MT, and 0.095 mm s^{-1} for NT.

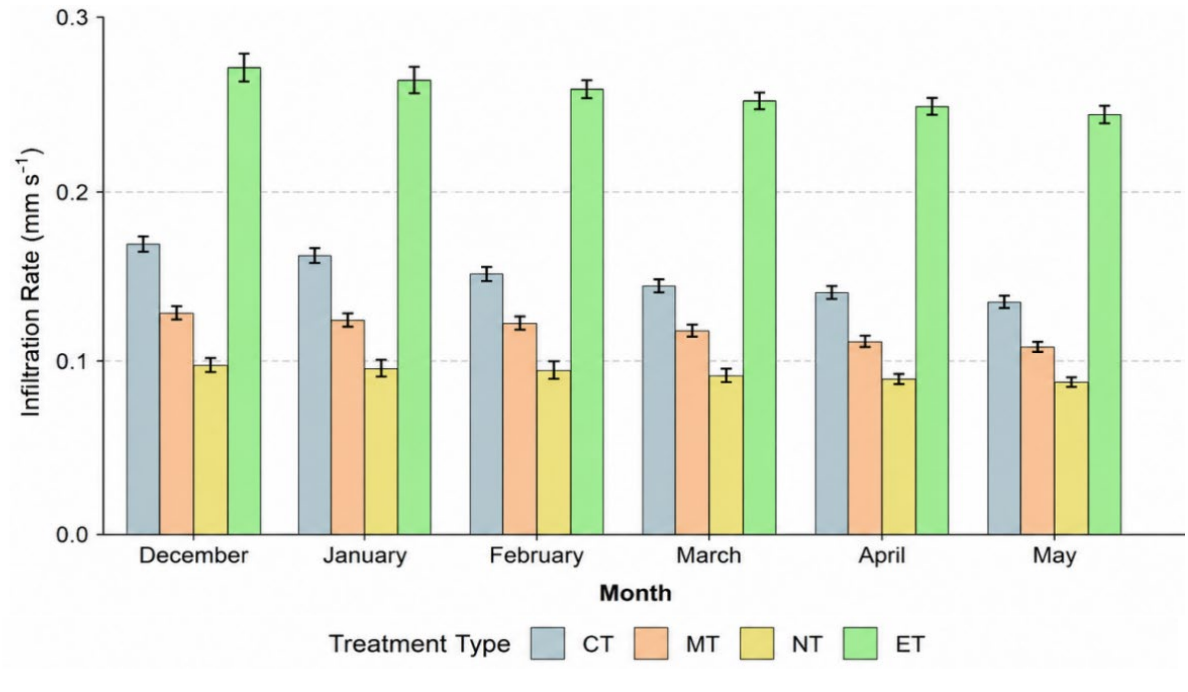

Figure 6. Temporal evolution of soil water infiltration rates over six months under different tillage treatments. Values represent mean infiltration rates measured using a double-ring infiltrometer.

These results confirm that the ET enhanced water infiltration by 63%, 115%, and 165% relative to CT, MT, and NT, respectively. Similar improvements in infiltration following deep, non-inverting tillage have been reported by several studies, which emphasise the restoration of macropore continuity and enhanced percolation through compacted layers (Peña-Sancho et al., 2017; Boincean & Dent, 2019; Wilkes, et al., 2021). The improved behaviour observed under ET can be attributed to its specific mechanical design: the negative attack angle directs shearing forces downward, fragmenting the subsoil and forming continuous vertical fissures while maintaining the natural stratification of the horizons. Such geometry differs from CT, where soil inversion destroys aggregates, disrupts pore continuity, and accelerates reconsolidation (Arriaga et al., 2017; Totsche et al., 2018).

Temporal monitoring over six months revealed that infiltration rates under ET remained relatively stable (0.231–0.283 mm s^{-1}), suggesting the persistence of functional porosity and stable structure even after natural settling. In contrast, CT and MT exhibited progressive decreases in infiltration rates after the third month, indicating pore closure and surface sealing due to mechanical reconsolidation and rainfall impact. NT maintained low but consistent infiltration rates, reflecting the low permeability of undisturbed and compacted soil layers. Similar temporal declines in infiltration under repeated CT operations have been documented in long-term studies of clay loam and sandy soils, where compaction beneath the plough layer reduced infiltration and water storage capacity (Yang et al., 2017; Amami et al., 2021).

The regression analysis confirmed these patterns (Table 3). The infiltration model explained 98% of the variance ($R^2 = 0.98$). ET displayed the highest intercept (0.262 mm·s^{-1}, $p < 0.001$), while NT (−0.163), CT (−0.093), and MT (−0.134) were significantly lower. The small negative time coefficient under ET (B = −0.0028, $p < 0.001$) indicates a slight but significant reduction in infiltration rate over time. However, the significantly steeper decline observed in treatments such as CT and MT (Table 3) reflects the gradual degradation of soil structure and pore closure under conventional management. Conversely, the more stable slope observed under NT ($p = 0.001$ for slope difference) suggests that while undisturbed soil exhibits lower overall permeability, its structure remains more consistent over time.

Table 3. Multiple regression analysis of soil infiltration rate as affected by tillage treatment and time

Predictor	B (Coefficient)	SE	t	*p*
Baseline Rate (ET Intercept)	0.26253	0.0017	157.76	< 0.001
Monthly Rate Change (ET Slope)	−0.00284	0.0004	−6.65	< 0.001
Rate Difference (NT)	−0.16311	0.0024	−69.31	< 0.001
Slope Difference (NT)	0.00209	0.0006	3.47	0.001
Rate Difference (CT)	−0.09304	0.0024	−39.54	< 0.001
Slope Difference (CT)	−0.00059	0.0006	−0.97	0.33
Rate Difference (MT)	−0.13393	0.0024	−56.91	< 0.001
Slope Difference (MT)	0.00059	0.0006	0.97	0.331
R^2	98.25%			

These outcomes are consistent with findings showing that subsoiling or modified bentleg tools, such as the ET used here, maintain soil porosity and hydraulic conductivity more effectively than disc or moldboard ploughing (Solhjou & Alavimanesh, 2023; Reddy et al., 2016).

Soil penetration resistance

Penetrometric resistance data shown in Fig. 7 further supported the infiltration results. The lowest mean resistance was observed under ET (240 N), followed by CT (410 N), MT (690 N), and NT (870 N). ET thus reduced resistance by 41%, 65%, and 72% relative to CT, MT, and NT, respectively. Such reductions indicate a sustained loosening effect in deeper layers, a result frequently reported for conservation-oriented deep tillage techniques that maintain pore continuity and relieve compaction (Vakali et al., 2011; Guedioura et al., 2023). The observed trend suggests that ET effectively minimized mechanical impedance to root growth, a critical determinant of crop establishment and nutrient uptake.

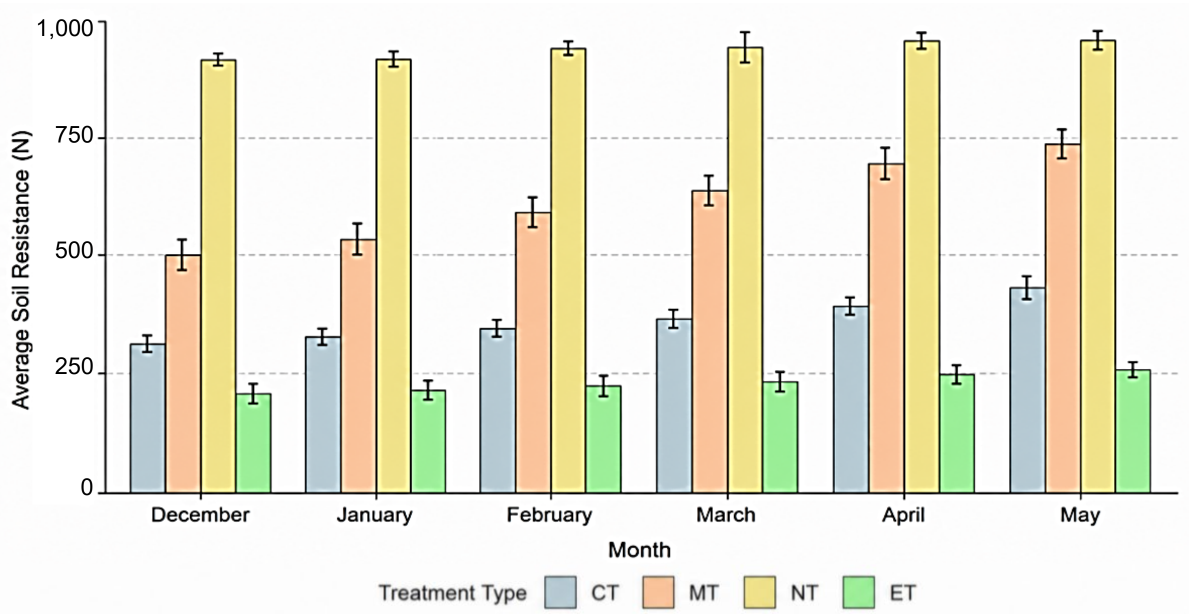

Figure 7. Changes in soil penetration resistance over six months following different tillage treatments, measured using a static penetrometer.

Over time, resistance increased in all treatments due to natural reconsolidation, but the rate of change was smallest under ET (140–390 N). In CT and MT, values increased steadily beyond 500 N and 900 N by the sixth month, consistent with the re-compaction reported in repeated tillage systems (Bogunovic et al., 2018, Özpinar, 2024). NT maintained a stable but high resistance, typical of undisturbed profiles where mechanical penetration remains limited.

Regression analysis demonstrated in Table 4 explained 44.2% of the variance ($R^2 = 0.442$). The baseline ET intercept (582.87) did not differ significantly from other treatments, yet the time coefficient for ET (B = 10.16, $p = 0.047$) confirmed a mild increase in resistance with time. MT displayed a much higher coefficient (B = 40.71, $p < 0.001$), indicating rapid densification, while CT and NT showed no significant trends. Comparable studies have found that minimum tillage often accelerates reconsolidation because the lower disturbance fails to alleviate pre-existing compaction, whereas specialized tools maintain looser conditions deeper in the profile (Bauer et al., 2015).

Table 4. Multiple regression analysis of soil penetration resistance as affected by tillage treatment and time

Predictors	B	SE	t	p
Intercept (ET)	582.87	20.36	28.63	0
Time (ET)	10.16	5.08	2	0.047
Intercept Difference (NT)	21.17	28.8	0.74	0.4625
Time Difference (NT)	-5.13	7.21	-0.7	0.477
Intercept Difference (CT)	-25.18	28.8	-0.87	0.3823
Time Difference (CT)	7.03	7.21	0.98	0.33
Intercept Difference (MT)	-47.8	28.8	-1.66	0.0976
Time Difference (MT)	40.71	7.2	5.64	0
R^2	44.20%			

When both hydraulic and mechanical indicators are considered together, ET provided the most balanced soil condition. CT produced moderate short-term improvements but suffered from fast reconsolidation and decreased infiltration. MT and NT maintained compact profiles characterized by limited pore connectivity and restricted water flow. The dual improvement achieved by ET enhanced infiltration and lower resistance indicates a well-structured soil with stable porosity and efficient internal drainage. This effect aligns with prior observations that moderate, non-inverting deep tillage increases both infiltration and aggregate stability while reducing mechanical resistance (Giannitsopoulos et al., 2019).

Mechanically, the ET geometry plays a key role in this outcome. Its negative attack angle and bentleg configuration direct the shearing force downward, producing deep and uniform fractures without disturbing surface layers. The tool's operational speed allows a single-pass decompaction with reduced traction resistance, limiting fuel consumption and mechanical stress on the soil. These properties correspond with reported advantages of energy-efficient deep tillage systems that loosen subsoil layers while preserving topsoil integrity and minimizing erosion risk (Schneider et al., 2017; Hussein et al., 2019; Ning et al., 2022).

Crop yield response

Average wheat yields under the four tillage systems are presented in Fig. 8. Yield differed significantly among treatments ($F = 7.19$; $df = 3, 12$; $p = 0.005$). Average yields were 2.9 Qt ha^{-1} for NT, 12.83 Qt ha^{-1} for MT, 18.68 Qt ha^{-1} for ET, and 22.50 Qt ha^{-1} for CT. Although CT achieved the highest yield, ET produced a comparable yield while maintaining superior soil physical conditions and lower energy demand. These results are consistent with previous studies showing that deep, non-inverting tillage improves water availability and root penetration, supporting stable yields under moderate drought stress (Tian et al., 2016; Ning et al., 2022).

The relationship between infiltration, penetration resistance, and yield underscores the central role of soil physical quality in productivity under rainfed conditions. Maintaining macroporosity and low mechanical impedance favors deeper rooting and efficient water uptake, a factor considered more critical for yield stability than temporary surface loosening (Berisso et al., 2012; Yang et al., 2021).

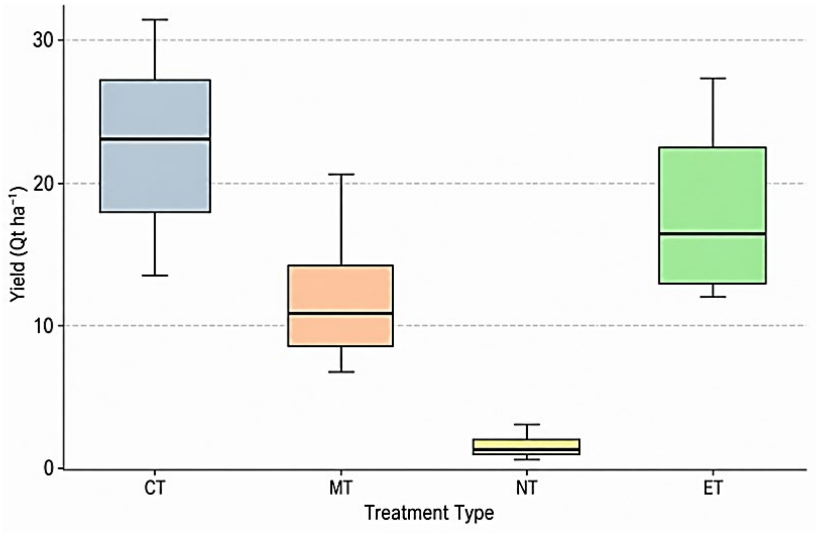

Figure 8. Mean durum wheat grain yield under different tillage treatments at harvest. Error bars indicate standard deviation (n = 4).

Integrated agro-pedological performance

As detailed in Table 5 (Comparative Performance Summary), the ET consistently provided the highest infiltration capacity throughout the experimental period, stabilizing around 0.255 mm s^{-1}. These deep structural improvements are crucial, especially since literature shows that deep soil layers struggle to recover their capacity without targeted mechanical intervention.

Table 5. Comparative summary of agro-pedological performance indicators across tillage treatments

Key indicator	ET (Experimental tool)	CT (Conventional tillage)	MT (Minimum tillage)	NT (No tillage)	Justification for ET
Stabilized infiltration (mm s^{-1})	0.255	0.155	0.125	0.098	Best permeability and macroporosity
Stabilized resistance (N)	390	> 500	> 900	Stable but high	Minimization of root impedance
Reconsolidation rate	Lowest rate (minimum b slope)	Rapid	Very rapid	Stable (highly compacted)	Porosity stability (non-inverting mechanism)
Yield (Qt ha^{-1})	18.68	22.50	12.83	2.9	Comparable yield with improved structure

The mechanical benefits of the ET further support its superiority. The penetrometric data confirmed that the experimental tool effectively reduced Penetration Resistance (PR) by 72% relative to NT. This reduction indicates a sustained loosening effect in deeper layers, minimizing mechanical impedance to root growth. A critical aspect of the ET design is its impact on long-term stability. The regression analyses revealed that while all treatments showed signs of natural reconsolidation, the rate of increase in resistance was smallest under ET, which stabilized between 140–390 N. In contrast, MT and CT plots suffered from rapid reconsolidation, with MT exceeding 900 N by the sixth month. This difference is directly attributed to the ET's negative rake angle and bentleg configuration, which induces deep, uniform fractures without inverting the surface horizons, preserving aggregate stability.

The yield results, though not prioritizing maximization, support the ET as an optimal compromise. Conventional Tillage (CT) achieved the highest overall yield at 22.50 Qt ha^{-1}, but the ET produced a comparable yield of 18.68 Qt ha^{-1}. The innovation lies in the fact that this performance is achieved with a low draft requirement. The ET provides a decompaction solution compatible with low-power tractors, rated between 50 and 80 horsepower, directly addressing a technical and socio-economic gap for small and medium farms in the South Mediterranean. This factor strongly favors the ET over CT, which incurs higher energy costs and leads to faster structural degradation and reconsolidation over time. The ET provides a mechanical and structural solution that optimizes the use of *in situ* rainwater and supports stable yields under moderate rainfall conditions, offering a sustainable alternative to complex material amendments like biochar or polymers.

The Modified bentleg plough achieves an optimal balance between the mechanical efficiency required to break the hardpan and ecological structural preservation. By providing superior structural stability, enhanced water infiltration, and a competitive yield with reduced energy input, the ET offers a viable technical path for sustainable soil management and durum wheat resilience in sensitive agricultural systems.

Traction power and energetic efficiency of experimental tool

The mouldboard plough exhibited significantly higher fuel consumption than the experimental tool (ET) at all tested speeds (Table 6). The highest value was recorded at 5 km h^{-1} for the mouldboard plough (26.7 L ha^{-1}), which differed significantly from all Experimental tool (ET) treatments. Analysis of variance revealed a significant effect of implement type and operating speed on fuel consumption per unit area ($p < 0.05$).

Table 6. Comparative analysis of field performance, energy consumption, and traction efficiency of experimental tool (ET) and mouldboard plough implements

Implement	Target speed (km h^{-1})	Actual speed (km·h^{-1})	Working depth (cm)	Time (50 m s^{-1})	Traction load	Fuel consumption (L ha^{-1})	Statistical group	RTI
Experimental tool (ET)	8	8.02 ± 0.15	40.2 ± 0.8	22.4 ± 0.5	Low	12.6 ± 0.7	d	1.56
	10	9.95 ± 0.20	40.1 ± 0.6	18.1 ± 0.6	Moderate	14.9 ± 0.9	cd	1.50
	12	11.48 ± 0.25	39.8 ± 1.0	15.7 ± 0.7	Moderate	17.4 ± 1.1	c	1.52
Mouldboard Plough	3	3.02 ± 0.10	25.3 ± 0.7	59.6 ± 1.2	Moderate	20.2 ± 1.0	b	6.67
	4	3.78 ± 0.15	25.1 ± 0.9	47.5 ± 1.5	High	23.5 ± 1.2	ab	6.13
	5	4.52 ± 0.20	24.8 ± 1.1	39.8 ± 1.8	Very high	26.7 ± 1.4	a	5.91

Values are expressed as mean ± standard deviation ($n = 3$). Means followed by the same letter are not significantly different at $p < 0.05$.

In contrast, the Experimental tool (ET) maintained lower fuel consumption even at higher speeds, with the lowest value observed at 8 km h^{-1} (12.6 L ha^{-1}). These results indicate a significantly lower apparent energy requirement for the Experimental tool (ET) compared to conventional ploughing under similar field conditions.

The performance of both implements was further evaluated using forward speed and fuel consumption measured under field conditions. A relative traction index (RTI), defined as the ratio of speed (km h^{-1}) to fuel consumption (L ha^{-1}), was used as an indirect indicator of draft force.

The results highlight a clear difference between the implements. The Experimental tool (ET) exhibited a stable RTI (1.50–1.56; mean 1.53), whereas the mouldboard plough showed higher values (5.91–6.67; mean 6.24), indicating an approximately fourfold higher traction demand.

This trend is consistent with field observations: the mouldboard plough caused a marked drop in engine speed and a high traction load, particularly at higher speeds, while the Experimental tool (ET) maintained more stable operation with moderate load.

These differences can be explained by soil-tool interaction. The mouldboard plough operates by full inversion, mobilizing a large volume of soil and increasing passive forces, whereas the Experimental tool (ET) primarily induces soil loosening, limiting soil displacement and reducing mechanical resistance.

These findings are consistent with previous studies (Godwin, 2007; Keller et al., 2019), which show that inversion tillage generates higher draft forces, while vertical tillage systems reduce mechanical constraints and energy consumption.

Finally, the relationship $P = Ft \cdot V$ supports this interpretation: higher speed combined with lower fuel consumption (Experimental tool ET) reflects reduced draft force, unlike the mouldboard plough.

Overall, the results highlight the superior energy and mechanical efficiency of the Experimental tool (ET).

CONCLUSIONS

The results of this study demonstrate that the modified Bentleg Plough (ET) offers a measurable improvement in soil physical and hydraulic properties compared to traditional tillage systems in South Mediterranean rainfed conditions.

- Mechanical Performance: The ET tool achieved the most consistent reduction in soil penetration resistance, maintaining values between 140–390 N, which is significantly lower than the critical thresholds found in No-Tillage (NT) and Conventional Tillage (CT) plots.
- Hydraulic Conductivity: Regarding water dynamics, the ET treatment resulted in a stabilized infiltration rate of 10.16×10^{-6} m s^{-1}. This represents a significant technical improvement over NT, facilitating better deep-drainage potential in hardsetting soils.
- Agronomic Viability: Although wheat yields for the ET treatment (1.87 t ha^{-1}) were slightly lower than CT (2.25 t ha^{-1}), the differences were not statistically significant within this single cropping season.
- Technical Implications: These findings suggest that the modified Bentleg geometry, characterized by a negative rake angle, provides a viable technical option for

subsoil decompaction. It offers a mechanical pathway to alleviate soil compaction while requiring lower draft force, making it suitable for the technical constraints of regional farming systems.

Future research should focus on multi-year monitoring to evaluate the long-term stability of these structural improvements and their cumulative effect on crop water-use efficiency.

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REFERENCES

Amami, R., Ibrahimi, K., Sher, F., Milham, P., Ghazouani, H., Chehaibi, S. & Iqbal, H.M. 2021. Impacts of different tillage practices on soil water infiltration for sustainable agriculture. *Sustainability* **13**(6), 3155. doi: 10.3390/su13063155

Arriaga, F.J., Guzman, J. & Lowery, B. 2017. Conventional agricultural production systems and soil functions. In: *Soil health and intensification of agroecosystems*, pp. 109–125. Academic Press. doi: 10.1016/B978-0-12-805317-1.00005-1

Bauer, T., Strauss, P., Grims, M., Kamptner, E., Mansberger, R. & Spiegel, H. 2015. Long-term agricultural management effects on surface roughness and consolidation of soils. *Soil and Tillage Research* **151**, 28–38. doi: 10.1016/j.still.2015.01.017

Berisso, F.E., Schjønning, P., Keller, T., Lamandé, M., Etana, A., de Jonge, L.W. & Forkman, J. 2012. Persistent effects of subsoil compaction on pore size distribution and gas transport in a loamy soil. *Soil and Tillage Research* **122**, 42–51. doi: 10.1016/j.still.2012.02.005

Bogunovic, I., Pereira, P., Kisic, I., Sajko, K. & Sraka, M. 2018. Tillage management impacts on soil compaction, erosion and crop yield in Stagnosols (Croatia). *Catena* **160**, 376–384. doi: 10.1016/j.catena.2017.10.009

Boincean, B. & Dent, D. 2019. Tillage and conservation agriculture. In: *Farming the black earth: Sustainable and climate-smart management of chernozem soils*, pp. 125–149. Springer, Cham. doi: 10.1007/978-3-030-22533-9_6

García-Ruiz, J.M., Nadal-Romero, E., Lana-Renault, N. & Beguería, S. 2013. Erosion in Mediterranean landscapes: Changes and future challenges. *Geomorphology* **198**, 20–36. doi: 10.1016/j.geomorph.2013.05.023

Giannitsopoulos, M.L., Burgess, P.J. & Rickson, R.J. 2019. Effects of conservation tillage systems on soil physical changes and crop yields in a wheat–oilseed rape rotation. *Journal of Soil and Water Conservation* **74**(3), 247–258. doi: 10.2489/jswc.74.3.247

Godwin, R.J. 2007. Advances in labour and machinery management for a profitable agriculture and forestry. Agricultural Engineering International: the CIGR Ejournal 9, Manuscript CIOSTA 07 007.

Google Earth. 2024. Satellite imagery. Google LLC. Available at https://earth.google.com/. Accessed March 2024.

Grisso, R.D., Perumpral, J.V., Vaughan, D.H., Roberson, G.T. & Pitman, R. 2004. *Predicting tractor fuel consumption*. *Applied Engineering in Agriculture* **20**(5), 553–561. doi: 10.13031/2013.17455

Guedioura, I., Rahmoune, B., Khezzaren, A., Dahoumane, A. & Laouar, N. 2023. Combined effect of soil practices and chemical treatments on weed growth, soil features and yield performance in field wheat crop under Mediterranean climate. *Agronomy Research* **21**(1), 62–77. doi: 10.15159/ar.22.079

Hussein, M.A, Muche, H., Schmitter, P., Nakawuka, P., Tilahun, S.A., Langan, S. & Steenhuis, T.S. 2019. Deep tillage improves degraded soils in the (sub)humid Ethiopian Highlands. *Land* **8**(11), 159. doi: 10.3390/land8110159

Keller, T., Sandin, M., Colombi, T., Horn, R. & Or, D. 2019. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. *Soil and Tillage Research* **194**, 104293. doi: 10.1016/j.still.2019.06.014

Liu, J., Leung, A.K., Dong, H. & Jiang, Z. 2025. Pore-scale investigation of the hysteretic water retention behaviour of unsaturated soils by tracking preferential water transport. *Computers and Geotechnics* **179**, 107049. doi: 10.1016/j.compgeo.2024.107049

Liu, J., Leung, A.K., Dong, H. & Lai, N.T. 2024. A state-dependent bimodal soil water retention model considering evolutions of pore-scale soil–water interaction. *Computers and Geotechnics* **175**, 106704. doi: 10.1016/j.compgeo.2024.106704

Naskar, J., Kumar Jha, A., Singh, T.N. & Aeron, S. 2025. Climate change and soil resilience: A critical appraisal on innovative techniques for sustainable ground improvement and ecosystem protection. *Journal of Hazardous, Toxic, and Radioactive Waste* **29**(4), 03125002. doi: 10.1061/JHTRBP.HZENG-1465

Ning, T., Liu, Z., Hu, H., Li, G. & Kuzyakov, Y. 2022. Physical, chemical and biological subsoiling for sustainable agriculture. *Soil and Tillage Research* **223**, 105490. doi: 10.1016/j.still.2022.105490

NF EN ISO 22282-5. 2012. *Geotechnical investigation and testing – Geohydraulic testing – Part 5: Infiltrometer tests*. International Organization for Standardization (ISO), Geneva, Switzerland.

Özpinar, S. 2024. Soil compaction effects on soil properties and crop productivity: An overview. *Impact of Climate Change on Agriculture and Ecosystems* **191**.

Peña-Sancho, C., López, M.V., Gracia, R. & Moret-Fernández, D. 2017. Effects of tillage on the soil water retention curve during a fallow period of a semiarid dryland. *Soil Research* **55**(2), 114–123. doi: 10.1071/SR15305

Reddy, P.P. 2016. Agricultural soil compaction. In: *Sustainable intensification of crop production*, pp. 41–52. Springer, Singapore. doi: 10.1007/978-981-10-2702-4_3

Sardans, J. & Peñuelas, J. 2013. Plant–soil interactions in Mediterranean forest and shrublands: Impacts of climatic change. *Plant and Soil* **365**(1), 1–33. doi: 10.1007/s11104-013-1591-6

Schneider, F., Don, A., Hennings, I., Schmittmann, O. & Seidel, S.J. 2017. The effect of deep tillage on crop yield – What do we really know? *Soil and Tillage Research* **174**, 193–204. doi: 10.1016/j.still.2017.07.005

Shao, M.A., Wang, Y., Xia, Y. & Jia, X. 2018. Soil drought and water carrying capacity for vegetation in the critical zone of the Loess Plateau: A review. *Vadose Zone Journal* **17**(1), 1–8. doi: 10.2136/vzj2017.04.0077

Solhjou, A. & Alavimanesh, S.M. 2023. Field evaluation of a bent leg tillage implement in dry soil conditions. *Research in Agricultural Engineering* **69**(3). doi: 10.17221/41/2022-RAE

Stošić, M., Brozović, B., Vinković, T., Ravnjak, B., Kluz, M. & Zebec, V. 2020. Soil resistance and bulk density under different tillage system. *Poljoprivreda* **26**(1), 17–24. doi: 10.18047/poljo.26.1.3

Tan, J., Si, B., Zhao, Y., Lu, Y., Chen, Y., An, N. & Yi, Y. 2025. Short-term no-tillage improves soil water retention and maintains soil aeration at high moisture conditions despite reduced macroporosity. *Soil and Tillage Research* **253**, 106677. doi: 10.1016/j.still.2025.106677

Tian, S., Ning, T., Wang, Y., Liu, Z., Li, G., Li, Z. & Lal, R. 2016. Crop yield and soil carbon responses to tillage method changes in North China. *Soil and Tillage Research* **163**, 207–213. doi: 10.1016/j.still.2016.06.005

Totsche, K.U., Amelung, W., Gerzabek, M.H., Guggenberger, G., Klumpp, E., Knief, C. & Kögel-Knabner, I. 2018. Microaggregates in soils. *Journal of Plant Nutrition and Soil Science* **181**(1), 104–136. doi: 10.1002/jpln.201600451

Vakali, C., Zaller, J.G. & Köpke, U. 2011. Reduced tillage effects on soil properties and growth of cereals and associated weeds under organic farming. *Soil and Tillage Research* **111**(2), 133–141. doi: 10.1016/j.still.2010.09.003

Wilkes, T.I., Warner, D.J., Edmonds-Brown, V., Davies, K.G. & Denholm, I. 2021. Zero t illage systems conserve arbuscular mycorrhizal fungi, enhancing soil glomalin and water stable aggregates with implications for soil stability. *Soil Systems* **5**(1), 4. doi: 10.3390/soilsystems5010004

Xiao, T., Li, P., Pan, Z. & Wang, J. 2022. Effect of compaction condition on the water retention capacity, microstructure and its evolution during drying of compacted loess. *Geoenvironmental Disasters* **9**(1), 27. doi: 10.1186/s40677-022-00229-y

Yang, Y., Wu, J., Zhang, J., Pan, X., Wang, Y. & He, F. 2017. Effect of tillage method on soil water infiltration, organic carbon content and structure. *Chinese Journal of Eco-Agriculture* **25**(2), 258–266. doi: 10.13930/j.cnki.cjea.160720 (in Chinese).

Yang, Y., Wu, J., Zhao, S., Mao, Y., Zhang, J., Pan, X. & van der Ploeg, M. 2021. Impact of long-term sub-soiling tillage on soil porosity and soil physical properties in the soil profile. *Land Degradation & Development* **32**(10), 2892–2905. doi: 10.1002/ldr.3874

Zdruli, P., Kapur, S. & Çelik, I. 2010. Soils of the Mediterranean region, their characteristics, management and sustainable use. In: *Sustainable land management: Learning from the past for the future*, pp. 125–142. Springer, Berlin, Heidelberg. doi: 10.1007/978-3-642-14782-1_4

Zhou, Z., Karimzadeh, A.A., Leung, A.K. & Fok, S.Y. 2025. Hysteretic water-retention behaviour of unsaturated hydrophobised soils. *Géotechnique* **75**(3), 337–347. doi: 10.1680/jgeot.23.00195