Journal of Agricultural Science and Technology (JAST), 29(4)
In Press, Pre-Proof Version

Three-Year Effects of Conventional Tillage versus Direct Seeding on Root System Development and Soil Hydro-Physical Properties of Durum Wheat under Semi-Arid Conditions of Algeria

Rima Labad[1]*, Zekari Mohammedi[1], Mokrane Kadir[2], Nasredine Louahdi[1], and Mohamed Amine Feddal[1]

Abstract

In semi-arid regions, where water scarcity limits cereal production, tillage practices significantly influence soil properties and root development in durum wheat (*Triticum durum*). This study evaluated the effects of conventional tillage (CT) and direct seeding (DS) on the root system under rainfed conditions over three growing seasons (2017-2021) in the northeastern part of Algeria. The experimental site was characterized by clay loam soil, low organic matter content, and a semi-arid climate, with an average annual rainfall ranging from 200 to 400 mm. The objectives aimed to understand how root density (RD) and root surface area (RSA) are influenced by, and related to soil properties: soil moisture content (SMC), soil penetration resistance (SPR), soil porosity (SP), and infiltration rate (IR) under conventional tillage (CT) and direct seeding (DS) systems. Soil parameters were measured at key growth stages (emergence, tillering and heading). Statistical analyses were performed using Python and statsmodels, including Pearson correlations and multivariate linear regression. The DS generally maintained higher SMC during dry periods, reducing water stress compared to CT. SPR was higher under DS, indicating compaction, but SP and IR improved progressively under CT, enhancing aeration and water absorption. By the way, RD was stable under CT but increased under DS at tillering. By the way, RSA expanded more under DS over time, particularly at the heading stage, correlating positively with SMC ($r = 0.74$) and negatively with SPR ($r = -0.55$). Regression confirmed SMC as a key driver for both RD and RSA under DS ($p < 0.01$).

Keywords: Conventional tillage, Direct seeding, Root density, Root surface area, Soil parameters.

INTRODUCTION

Cereal yields are influenced not only by agronomic practices but also by environmental factors such as temperature and water availability (Awika, 2011). In semi-arid regions, water availability is often the most limiting factor for rainfed agriculture (Rockström et *al.*, 2010).

[1] Agricultural Water Management Laboratory (LMEA), Department of Agricultural Engineering, National Higher School of Agronomy (ENSA), El Harrach, Algeria.
[2] Department of Hydraulics, Faculty of Construction Engineering, Mouloud Mammeri University, Algeria.
*Corresponding author; e-mail: rima.labad@edu.ensa.dz

This is particularly in the Mediterranean-type climate of North Africa, where irregular and insufficient rainfall can drastically reduce durum wheat production (El Melki et *al.*, 2024). By the way, tillage practices have a significant impact on soil water dynamics and root development. According to Lampurlanés et *al.* (2001), selecting appropriate tillage systems can improve water availability for crops by enhancing infiltration, reducing evaporation, suppressing weeds, and promoting deeper root growth. Conservation tillage systems, particularly those that incorporate crop rotation, enhance soil moisture retention and can result in higher yields than conventional tillage, depending on soil and climate conditions.

Generally, no-tillage systems perform best in arid and semi-arid climates with well-drained soils, whereas conventional tillage may be more effective in humid regions with poorly drained soils (Idowu et *al.*, 2017). The long-term benefits of no-tillage practices include improved soil nitrogen and carbon levels, enhanced microbial activity, and increased crop yields, especially when combined with cereal-legume rotations (Cookson et *al.*, 2008). These systems also allow root systems to penetrate deeper soil layers owing to better soil moisture conservation (Lampurlanés et *al.*, 2001). Notably, the influence of tillage on root development is considered one of the most critical effects of tillage practices on crop performance (Yin et *al.*, 2024).

Root development is a key component of crop adaptation to water-limited environments, as differences in root architecture influence soil exploration, water uptake, and the ability of plants to maintain growth under stress conditions. Recent studies have shown that wheat genotypes exhibit considerable variation in root architecture and growth responses under drought and salinity stresses, highlighting the importance of root traits as indicators of stress adaptation and tolerance. These findings emphasize that root development is controlled by both genetic factors and environmental conditions. Agronomic practices, particularly tillage, may also affect root growth by modifying soil physical properties, soil water availability, and conditions in which roots develop (Rahnama et *al.*, 2019; Rahnama et *al.*, 2024; Kaur et *al.*, 2026).

In Algeria, several studies have investigated cereal root development under water-deficit conditions, both in controlled and field conditions, highlighting the importance of root traits in crop adaptation to drought stress (Adda et *al.*, 2005; Boudiar et *al.*, 2020). In parallel, research on tillage systems has demonstrated the beneficial effects of no-tillage on soil quality, water conservation, and cereal productivity under water-limited conditions (Labad et *al.*, 2023). However, quantitative information on cereal root system development under field conditions remains limited, particularly regarding the effects of contrasting tillage systems, crop rotations, and water availability in semi-arid environments. Moreover, the relationships among soil physical properties, root development, and grain yield under different tillage practices have received relatively little attention in Algeria. This knowledge gap highlights the need for field-based studies that consider root development together with changes in soil conditions and crop performance.

Therefore, the main objective of this study was to improve our understanding of how contrasting tillage systems influence the root system development of durum wheat under semi-arid conditions and how these changes are related to crop productivity. Ultimately, this research aims to identify sustainable soil management practices that promote root growth, improve water use, and enhance durum wheat productivity in semi-arid regions.

The specific objectives were:

- To evaluate the development of the durum wheat root system under the two tillage systems;
- To analyse the interaction among tillage practice, water availability, and changes in soil physical properties within a semi-arid climate.

MATERIALS AND METHODS

SITE EXPERIMENT DESCRIPTION

The experiment was conducted in partnership with the Technical Institute of Field Crops (*Institut Technique des Grandes Cultures, ITGC*) at Sétif within the Conservation Agriculture in Crop-Livestock Systems (CLCA) project supported by the International Center for Agricultural Research in the Dry Areas (ICARDA).

The research was carried out over three crop seasons: Y_1: 2017-2018, Y_2: 2018-2019, and Y_3: 2020-2021, under rainfed conditions. The site is located in Setif province (36°08’N, 5°20’E), which is characterized by a semi-arid bioclimatic stage. During the three growing seasons, climatic conditions showed marked inter-annual variability. Cumulative rainfall ranged from approximately 242 to 442 mm. The 2017–2018 season was the wettest, with a total of 442.1 mm; the highest monthly rainfall occurred in March (90,4 mm). The 2018–2019 season received 346.3 mm, with the peak rainfall recorded in January (77,1 mm). The 2020–2021 season was the driest with 241.96 mm, and the highest precipitation was observed in May (84,63 mm) (Figure 1).

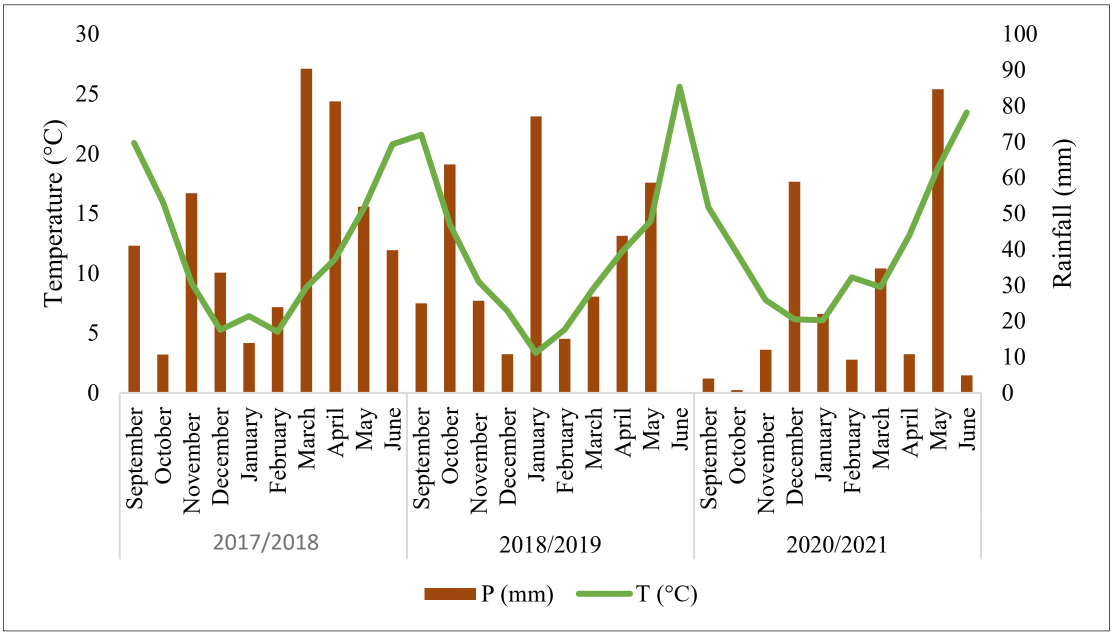


Figure 1. Variability in temperature and rainfall during the experimental period.

The experimental site was characterized by a clay loam soil texture, with 36.72% clay, 37.02% silt, and 24.60% sand. The soil had a low organic carbon content, averaging 1.04%. The soil was slightly alkaline (pH= 7.45) and was classified as non-saline, with an electrical conductivity (EC) of 1.04 dS m^{-1}.

The chemical properties of the soil were interpreted using SIDDRA (*Sistema Integrado de Diagnóstico y Recomendaciones de Abonado*), an integrated tool for soil fertility assessment and fertilizer recommendations developed by *Fertiberia*.

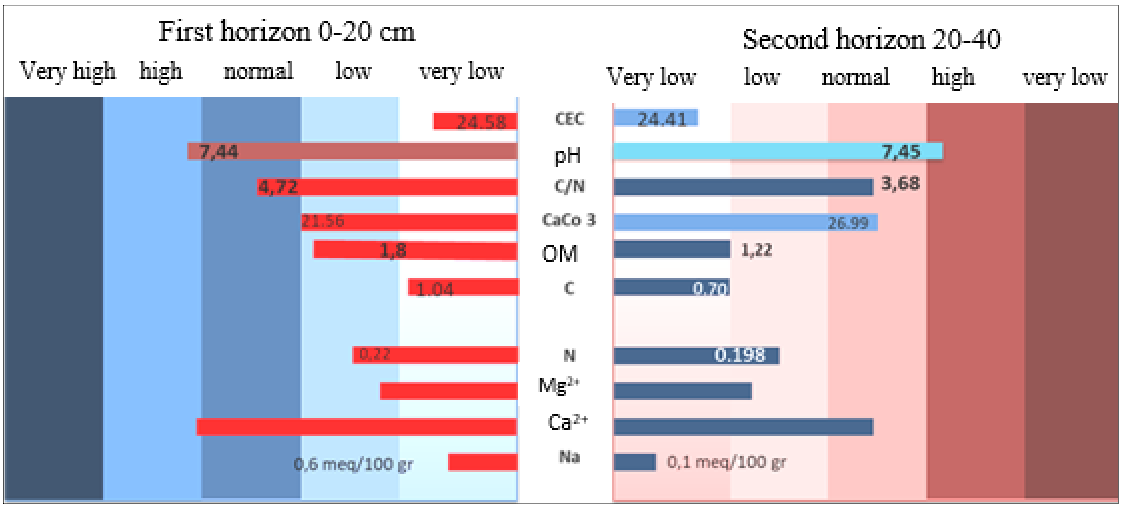


Figure 2. The soil's chemical characteristics with SIDRA software.

EXPERIMENT SET UP

The research aimed to assess the development of the wheat root systems. A rotational experiment including durum wheat (*Triticum durum*, local cultivar Oued El Bared) and lentil (*Lens culinaris*, cultivar Syrie 229) was conducted over three (03) years under rainfed conditions. Wheat was grown under two tillage systems: direct seeding (DS) and conventional tillage (CT), while lentil was cultivated exclusively under CT. The design was randomised complete block with three replicates. Each of the three blocks measured 100 m × 18 m (1,800 m^2) and was split into two plots of 50 m × 9 m (450 m^2), one for each tillage treatment, giving six plots in total. Wheat was sown on December 15^{th} in the first and third seasons at 300 seeds. m^{-2} (130 kg ha^{-1}). Lentil occupied the intervening season. The harvest of both crops took place at 442the end of June each year.

MEASURED PARAMETERS

During the experimental period, soil parameters were measured in relation to wheat root system development. The RD and RSA were measured to assess durum wheat root development under the two tillage systems in tillering and heading stages. Root samples were collected from each experimental plot using a cylindrical soil sampler (30 cm in height and 10 cm in diameter). The soil samples were gently washed with water to remove soil particles and organic debris while minimizing damage to the roots. The total root length was measured manually using a ruler, while root surface area was estimated from the measured root length and the diameter of the largest root. For each tillage treatment, five root samples were collected from each of the three experimental blocks, resulting in 15 samples for DS and 15 samples for CT during each growing season. The same sampling procedure was followed throughout the three experimental seasons.

Table 01. Measured soil parameters.

Parameters	References
Wilting point (%)	SPAW Software, Saxton, USDA-ARS (2006)
Field capacity (%)	
Saturation point (%)	
Soil moisture content (%)	Gravimetric method Mathieu Clément et Pieltain Françoise (1998)
Soil porosity (%)	Dwery et *al.*, 1995
Soil penetration resistance (MPa)	Mathieu Clément et Pieltain Françoise (1998)
Soil infiltration rate ($mm.h^{-1}$)	Colombani et *al.*, 1973

DATA ANALYSIS

Statistical analyses were conducted using Python, with the panda's library for data processing and the statsmodels package for statistical modelling (Seabold & Perktold, 2010). One-way

ANOVA was used to compare soil parameters between the two tillage systems, while three-way ANOVA was applied to root-related variables to evaluate the effects of tillage system, growing season, and crop growth stage, as well as their interactions. Pearson correlation analysis was used to explore the relationships between soil properties and root system development, with significance assessed using a Holm-adjusted p-value threshold of 0.05. In addition, multivariate linear regression was performed to identify the main drivers of root development at the 5% significance level.

Table 02. Studied parameters.

Variable	Definition	Statistical parameter
RSA	Root system area (RSA)	Dependent parameters
RD	Root density (RD)	
SMC (%)	Soil moisture content (SMC)	Independent parameter
SP (%)	Soil porosity (SP)	
SPR (MPa)	Soil penetration resistance (SPR)	
IR ($mm.h^{-1}$)	Infiltration rate (IR)	

RESULTS AND DISCUSSION

ANALYSIS OF SOIL MOISTURE CONTENT

Before examining the variation in SMC, it is important to consider the amount and temporal distribution of rainfall during the three growing seasons. The total rainfall recorded during the experimental period was 442.1 mm in 2017/2018 (Y1), 346.6 mm in 2018/2019 (Y2), and 241.96 mm in 2020/2021 (Y3). The estimated wilting point (WP) and field capacity (FC) of the experimental soil, determined using the SPAW model based on soil texture, ranged from 22.3% to 36.6%. Soil moisture content varied between tillage systems and among growing seasons (Table 3), reflecting differences in rainfall availability and its distribution throughout the crop cycle. In Y1, SMC remained consistently below the estimated WP under both tillage systems during emergence, tillering, full tillering, and heading. The cumulative rainfall recorded up to these growth stages was 47.4, 71.3, 161.7, and 243.0 mm, respectively. Despite the progressive accumulation of rainfall, SMC remained below the estimated WP, indicating limited soil water availability during the monitored growth stages. In Y2, SMC values generally fluctuated around the estimated WP under both tillage systems, with slightly lower values observed at the emergence stage. The cumulative rainfall up to emergence, tillering, full tillering, and heading was 87.9, 103.0, 129.8, and 173.6 mm, respectively. Compared with Y1, the distribution of rainfall resulted in SMC values closer to the estimated WP during the monitored stages, suggesting more favorable soil water conditions for crop development. In Y3, SMC was above the estimated WP and approached FC at the emergence stage. However, SMC declined markedly by the full-tillering stage, particularly under CT. The cumulative rainfall recorded up to emergence, tillering, full tillering, and heading was 75.91, 90.15, 124.87, and 139.67 mm, respectively. Despite the lower total seasonal rainfall in Y3, the relatively favorable SMC observed at emergence suggests that the timing and distribution of rainfall, rather than cumulative rainfall alone, influenced soil water availability. The decline in SMC during crop development, particularly under CT, indicates increasing water limitation as the season progressed. Throughout the experiment, SMC under DS was generally higher than that under CT, except in Y_2 when the two systems showed very similar values. Statistical analysis indicated significant differences in SMC under CT among years ($p = 0.05$), with Y_1 recording significantly lower values than the other two seasons. Under DS, year-to-year differences were not statistically significant (Table 3). The consistently lower SMC values recorded under CT, especially during dry periods, indicate that conventional tillage increased soil water loss compared with direct seeding. The higher moisture retention observed under DS is likely related to reduced soil disturbance and better conservation of surface residues, which limit evaporation. These results are in agreement with previous findings in semi-arid conditions (Lieskamp and Rieck, 2024), confirming the advantage of DS for soil water conservation in water-limited environments. The significant year effect observed only under CT further suggests that this system is more sensitive to inter-annual rainfall variability, while DS provides more stable soil moisture conditions across seasons.

Table 03. The mean SMC for each stage, year, and system.

Stage	Y_1		Y_2		Y_3	
	CT (%)	DS (%)	CT (%)	DS (%)	CT (%)	DS (%)
Emergence	21.12	21.62	19.23	18.68	25.08	26.35
Tillering	15.32	16.02	23.24	22.07	20.55	22.30
Full tillering	14.01	16.77	22.24	21.77	16.55	20.29
Heading	13.84	15.45	22.55	22.55	19.67	23.33

ANALYSIS OF SOIL PENETRATION RESISTANCE EVOLUTION ACROSS YEARS

SPR was generally higher under DS than under CT across the three experimental years, except during the emergence and heading stages of Y_3 (Table 4). Distinct temporal patterns were observed across growth stages. In Y_1, SPR increased progressively throughout the season under both systems, with consistently higher values under DS. In Y_2, both systems reached their highest SPR levels, showing a sharp increase across stages. In contrast, Y_3 was characterized by a declining trend in SPR, with a more pronounced reduction under CT.

One-way ANOVA indicated that year-to-year differences in SPR were not significant under CT ($p = 0.17$). Mean values were 0.493 MPa in Y_1, 0.557 MPa in Y_2, and 0.422 MPa in Y_3.

Under DS, however, significant year-to-year differences were detected ($p = 0.015$). The highest mean SPR was recorded in Y_2 (0.679 MPa), compared with 0.602 MPa in Y_1 and 0.413 MPa in Y_3. The higher SPR values recorded under DS is associated with the gradual development of soil compaction under long-term absence of mechanical disturbance. The experimental site had been managed under direct seeding for approximately ten years, which may have contributed to the observed soil resistance. In contrast, conventional tillage periodically disturbs and loosens the soil, resulting in lower penetration resistance. These findings are consistent with previous observations reported by Dusek et *al.*, (2021). The particularly high SPR levels observed under DS in Y_2 indicate that soil compaction was most severe during this season. The subsequent decline in SPR in Y_3, especially under CT, suggests a progressive improvement in soil structure under conventional tillage over time.

Table 04. The mean SPR for each stage, year, and system.

Stage	Y_1: 2017-2018		Y_2: 2018-2019		Y_3: 2020-2021	
	CT (MPa)	DS (MPa)	CT (MPa)	DS (MPa)	CT (MPa)	DS (MPa)
Emergence	0.438	0.560	0.433	0.553	0.524	0.449
Tillering	0.500	0.613	0.571	0.693	0.402	0.368
Heading	0.541	0.633	0.668	0.791	0.339	0.422

ANALYSIS OF SOIL POROSITY AND INFILTRATION RATE

Soil porosity (SP) and infiltration rate (IR) are closely linked. In general, higher porosity, especially with a greater proportion of macropores, typically leads to a higher infiltration rate, as water can move more easily through the soil. Conversely, lower porosity, often associated with compaction, reduces infiltration by limiting pore space and connectivity. Over the three years, SP under CT increased slightly, from 55.79% in Y_1 to 57.90% inY_3. Under DS, SP rose from 53.40% in Y_1 to a peak of 58.55% in Y_2, before declining to 52.65% inY_3. In most seasons, CT maintained higher SP than DS, except in 2018–2019. These differences were not statistically significant ($p = 0.68$ for CT and $p = 0.20$ for DS). IR under CT increased steadily, nearly doubling from 1.495 mm h^{-1} in Y_1 to 2.917 mm h^{-1} in Y_3. Under DS, IR increased from 1.538 mm h^{-1} in Y_1 to a maximum of 2.114 mm h^{-1} inY_2, then declined to 1.567 mm h^{-1} in Y_3. By the final year, infiltration was clearly higher under CT than under DS. The gradual rise in SP and IR under CT indicates that repeated mechanical disturbance improved soil structure and water entry over time, most likely through better aeration and reduced compaction (Lipiec et *al.*, 2006; Angon et *al.*, 2023). In contrast, the decline in SP observed under DS in Y_3 is consistent with the progressive compaction often reported in long-term no-tillage systems when soil remains undisturbed (Palm et *al.*, 2014; De'Anna et *al.*, 2024). Overall, the results show that CT provided more favourable conditions for water infiltration by the end of the three years under the semi-arid conditions of the study site.

ROOTS SYSTEM DEVELOPMENT

ROOT DENSITY

Figure 3 illustrates the variation in RD under CT and DS at the tillering and heading stages over the three growing seasons. RD was generally lower at tillering (approximately 10 - 12 cm/cm³) than at heading (14 -18 cm/cm³), with a clear peak recorded under CT inY_2. Under CT, RD at tillering remained relatively stable around 10 - 11 cm/cm³, whereas under DS it increased progressively from about 10 cm/cm³ in Y_1 to approximately 15 cm/cm³ inY_3. At heading, CT produced the highest values (up to 18 cm/cm³) in Y_2 before declining, while DS maintained more consistent densities of 14 -15 cm/cm³ across seasons.

A three-way analysis of variance confirmed these patterns, revealing highly significant effects of growth stage, year and tillage system on RD, together with significant two- and three-way interactions (all $p < 0.001$). RD was consistently higher at heading than at tillering. Year also exerted a strong influence, with overall means increasing from the first to the third season. Although the main effect of tillage system was significant, its impact varied markedly with year and developmental stage. CT produced substantially higher RD than DS in Y_1, the two systems were similar in Y_2, and DS outperformed CT in Y_3, particularly at tillering. The significant Stage x Year x Treatment interaction indicates that the relative performance of the two tillage systems depended on both the climatic conditions of each growing season and the growing stage of the crop. These differences are likely linked to contrasting effects of CT and DS on soil structure and water availability (Abebrese et *al.*, 2025).

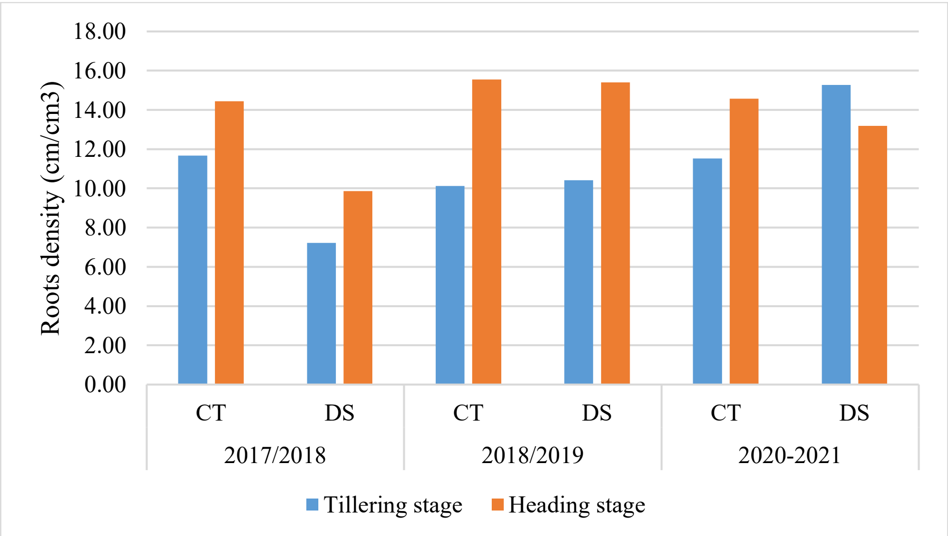


Figure 3. The variation of root density under DS and CT for Tillering and Heading stages.

ROOTS SURFACE AREA

The RSA under CT and DS is presented in Figure 4. At the tillering stage, RSA under CT increased from 2.65 cm² in Y_1 to 6.64 cm² in Y_3. Under DS, values started lower (1.41 cm²) but rose more sharply, reaching 9.52 cm² in the final year (Y_3) and surpassing CT from the second year (Y_2) onward. At the heading stage, both systems showed a clear increase over time. RSA under CT rose from 6.68 cm² to 12.03 cm², while under DS it increased from 3.05 cm² to 14.67 cm², exceeding CT in the third year.

A three-way ANOVA (Year × Stage × Tillage) confirmed these trends. RSA differed significantly among years ($p < 0.001$) and between growth stages ($p < 0.001$), with consistently higher values at heading than at tillering. A significant Year × Tillage interaction ($p < 0.001$) indicated that the effect of tillage system changed over time: CT produced higher RSA in the first year, whereas DS clearly outperformed CT in the later years of the experiment. Overall, both systems showed an increase in root surface area over time, but the gains were more pronounced under DS, particularly at the tillering stage. The greater increase in RSA observed under DS may reflect an adaptive response of wheat roots to improved soil moisture conservation under reduced soil disturbance. Similar responses have been reported by Rahnama et *al.*, (2024), who showed that wheat root architectural traits are strongly influenced by water availability and contribute to drought adaptation. Therefore, the higher RSA observed under DS may reflect a root morphological response that promotes greater soil exploration and improves water acquisition under semi-arid conditions. In the heading stage, DS outperforms CT by Y_3, indicating potential long-term advantages, possibly due to reduced soil disturbance preserving root growth conditions.

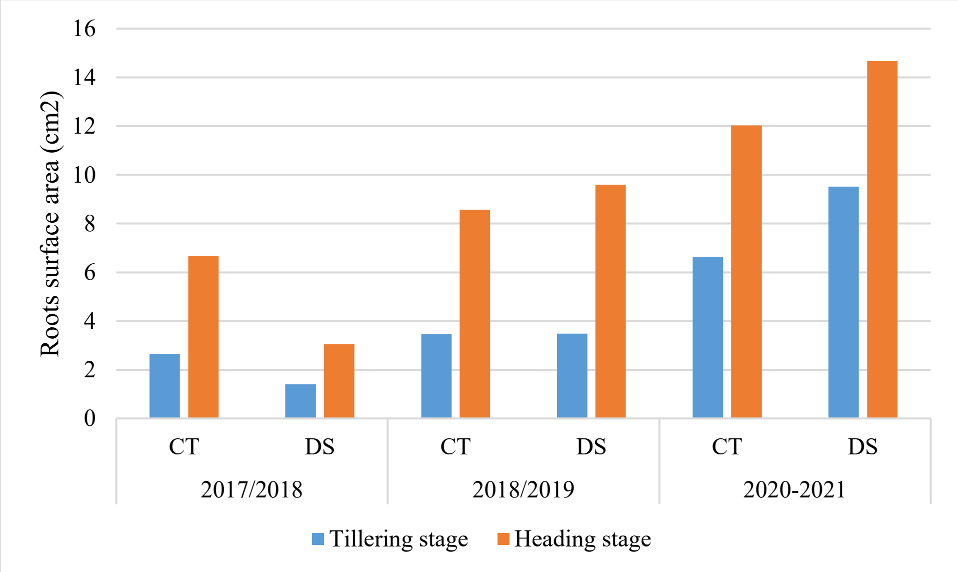


Figure 4. The variation in root surface area across DS and CT for tillering and heading stages.

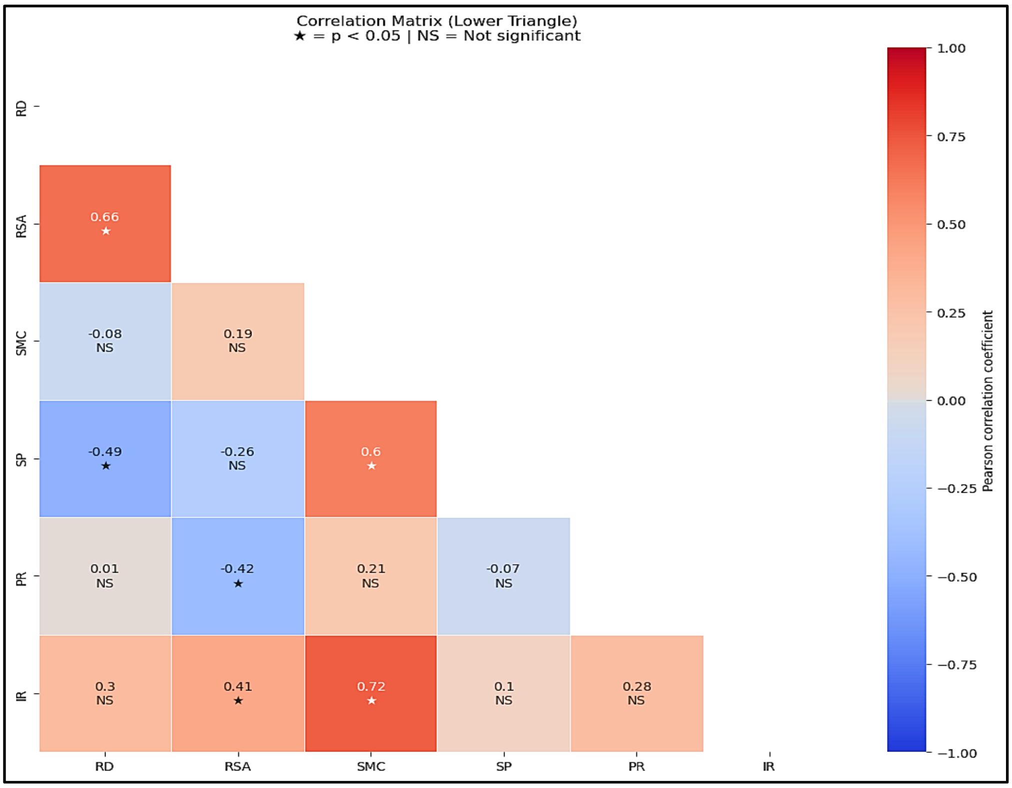
IDENTIFICATION OF CONTROLLING FACTORS

BIVARIATE ANALYSIS

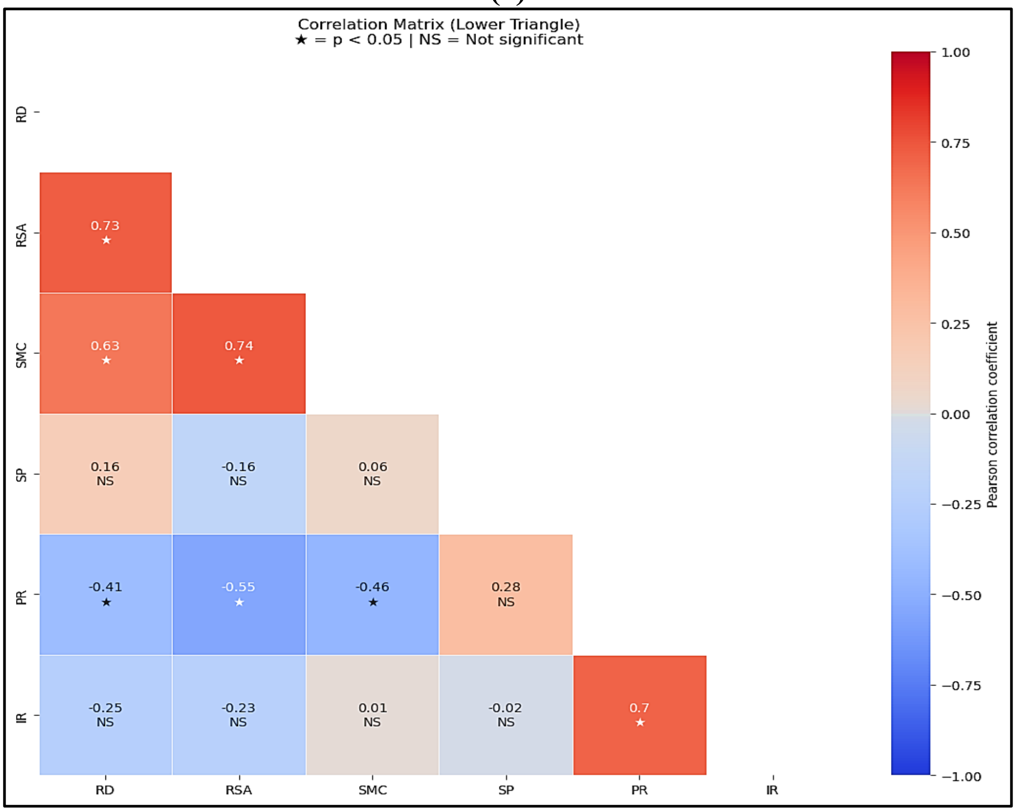
The correlation matrices (Figure 5 a -b) present the Pearson correlation coefficients among RD, RSA, SMC, SP, SPR and IR. In the context of CT on loam-clay soils characterized by low organic matter content and a basic pH, the significant positive correlation between RD and RSA ($r = 0.66$, $p < 0.05$) indicates that tillage was associated with root system development. This response is most likely linked to reduced soil compaction, which allowed roots to proliferate more readily in these relatively dense and nutrient-poor soils. The moderate negative correlation between RD and SP ($r = -0.49$, $p < 0.05$) suggests that the increase in porosity resulting from tillage may have reduced RD by limiting anchorage within the looser soil matrix typical of such textured soils with limited organic binding. The significant negative relationship between RSA and SPR ($r = - 0.42$, $p < 0.05$), together with the positive association between RSA and IR ($r = 0.41$, $p < 0.05$), points to mechanical impedance as a constraint on root surface expansion, while improved water infiltration facilitated by the soil's basic pH and low organic matter supported root growth. In addition, the strong positive correlations between SP and SMC ($r = 0.60$, $p < 0.05$) and between IR and SMC ($r = 0.72$, $p < 0.05$) underline the influence of tillage-induced porosity and water movement on soil moisture dynamics, reflecting a close interplay among the physical and chemical properties of the soil.

These findings align with earlier research on tillage systems. Bescansa et *al.*, (2006), working in Spain, reported similar patterns under CT. They observed a negative relationship between RD and SP in tilled soils, which they attributed to reduced bulk density. However, their correlation coefficients were weaker (r ≈ -0.3), likely due to differences in soil texture and organic matter content between sites.

Recent research by Kihara et *al.*, (2020) in sub-Saharan Africa supports the strong IR-SMC relationship (r = 0.72), showing that CT can enhance water infiltration in compacted soils, whereas no-till systems generally display weaker associations (r ≈ 0.4) because of surface residue effects. For DS, the significant positive correlations between RD and RSA (r = 0.73, p < 0.05) and between RSA and SMC (r = 0.74, p < 0.05) highlight the central role of moisture retention for root development when tillage-induced aeration is absent. The positive relationship between RD and SMC (r = 0.63, p < 0.05) further indicates that greater soil water availability promotes denser root systems under these conditions. In contrast, the significant negative correlations between RSA and SPR (r = -0.55, p < 0.05), between RD and SPR (r = -0.41, p < 0.05), and between SMC and SPR (r = -0.46, p < 0.05) show that the higher compaction typical of DS constrains both root proliferation and surface expansion while simultaneously reducing moisture availability within the denser soil matrix. The strong positive correlation between SPR and IR (r = 0.70, p < 0.05) suggests that compacted layers under DS can still promote preferential water flow, a process likely facilitated by the basic pH and limited organic matter, which reduce aggregation and encourage the development of continuous macropores. Pittelkow et *al.*, (2015) observed that DS on clay-loam soils can increase RD and RSA by 15-25 % relative to CT when SMC is adequate, a finding that aligns with the strong RD-RSA (r = 0.73) and RD-SMC (r = 0.63) relationships reported here. The somewhat larger effects in their work may reflect the higher organic-matter levels of the soils they examined. Verhulst et *al.*, (2010) documented a comparable negative association between RSA and PR (r ≈ -0.5) under DS in Mexico and attributed it to compaction in low organic matter soils conditions similar to those of the present loam-clay site and consistent with the RD-PR and SMC-PR correlations found in this study. Recent investigations by Thierfelder et *al.*, (2022) in southern Africa and Giller et *al.*, (2021) in West Africa reported PR-IR correlations ranging from 0.65 to 0.75 under DS, supporting the value of 0.70 obtained here. They noted that compacted soils can enhance infiltration through macropores continuity, whereas systems with heavier residue cover often display weaker associations (r ≈ 0.3-0.4).



(a)



(b)

Figure 5. Correlation Matrix of RD, RSA, SMC, SP, SPR, and IR in Conventional Tillage (a) and Direct Seeding (b).

MULTIVARIATE LINEAR REGRESSION ANALYSES

The analyses were conducted to assess the relationships between dependent variables: RD and RSA, and independent variables: SMC, SP, PR and IR.

Under CT, RD appears less responsive to individual soil properties. In contrast, RSA is more sensitive, with significant reductions linked to SP and PR, and a potential boost from SMC, reflecting the importance of moisture and mechanical conditions for root surface expansion (Table 05). These findings align with the correlation matrix results, where RD-RSA and RSA-PR relationships were significant, reinforcing the regression outcomes. Similar findings are reported by Blanco-Canqui et *al.*, (2017) for CT in the U.S., where they observed comparable negative SP-RSA trends due to reduced soil cohesion, although their PR effects were weaker ($p > 0.05$) in soils with high organic matter content. More recent work by Schjonning et *al.*, (2022) in Denmark found significant SMC and RSA links ($p < 0.05$) in tilled loamy soils, supporting our borderline result. Moreover, under DS, RD is significantly driven by SMC ($p = 0.004$), highlighting the critical role of SMC in supporting denser root systems in the absence of tillage-induced aeration. Also, RSA is strongly influenced by SMC ($p = 8.41E-05$), underscoring the importance of moisture in promoting RSA expansion in compacted soils. The importance of soil moisture as a driver of root development observed in this study is consistent with previous findings showing that root growth and architecture are highly responsive to environmental stress conditions (Rahnama et *al.*, 2011; Kaur et *al.*, 2026), emphasizing the role of root plasticity in accessing limited soil resources. In DS, both RD and RSA are significantly enhanced by SMC, reflecting the reliance on natural moisture retention in loam-clay soils with low organic matter and basic pH. The lack of significant effects from SP, PR, and IR on RD, and the borderline SP effect on RSA, suggest that DS maintains a stable soil structure where moisture is the primary driver of root development. This contrasts with CT, where RD was less responsive, and RSA was more affected by SP and PR, indicating tillage's role in altering soil mechanics. These findings align with global research on DS. For instance, Pittelkow et *al.*, (2015) noted that DS on clay-loam soils boosts RD and RSA with adequate moisture, supporting our SMC-RD ($p = 0.004$) and SMC-RSA ($p = 8.41E-05$) results, though their higher-organic-matter soils showed stronger effects. Thierfelder et *al.*, (2022) reported minimal PR impacts on RSA in DS ($p > 0.05$), consistent with our non-significant PR coefficient, attributing this to compaction stability. Recent work by Giller et *al.*, (2021) also found IR effects on RSA to be variable ($p > 0.1$), aligning with our non-significant IR result, likely due to soil texture and residue cover differences. These comparisons highlight that DS outcomes are modulated by local soil properties and management, necessitating tailored approaches.

Table 05. Results of multivariate linear regression analyses.

	CT	DS	
	RSA	RSA	RD
	P value	P value	P value
SMC	0.063071173	8.41193E-05	0.004288523
SP	0.001982805	0,086681918	0.664946653
PR	2.06402E-05	0.606076273	0.735185355

Conclusions

This study evaluated the effects of conventional tillage and direct seeding on durum wheat root development under the semi-arid conditions of Sétif (Algeria), over three growing seasons (2017-2021). Direct seeding was associated with higher soil moisture content during key growth stages, which coincided with greater root density and root surface area. Multivariate regression confirmed that soil moisture was a significant predictor of both root density and root surface area under DS, suggesting that improved water availability supports root development under water-limited conditions. However, root development under CT showed greater variability across years, indicating a higher sensitivity to inter-annual climatic fluctuations. Overall, the results suggest that DS may promote soil moisture conservation and root growth, whereas CT improves soil physical properties. These findings provide practical support for the potential adoption of direct seeding by farmers in rainfed cereal systems, particularly where irregular rainfall is a major constraint. Nevertheless, the choice of tillage system should also consider crop yield, soil conditions, and local water availability.

REFERENCES

1. Abebrese, D.K., Matula, S., Báťková, K., Kara, R.S. & Miháliková, M. 2025. Contrasting long-term tillage treatments and their spatio-temporal effects on soil physicochemical signatures in a cropping season under a temperate climate in Central Europe. *J. Soil Sci. Plant Nutr.* **25(3)**: 3372–3390.

2. Adda, A., Sahnoune, M., Kaid-Harch, M. & Merah, O. 2005. Impact of water deficit intensity on durum wheat seminal roots. *C. R. Biol.* **328(10–11)** : 918–927.

3. Angon, P.B., Anjum, N., Akter, M.M., KC, S., Suma, R.P. & Jannat, S. 2023. An overview of the impact of tillage and cropping systems on soil health in agricultural practices. *Adv. Agric.* **8861216**: 1–14. https://doi.org/10.1155/2023/8861216

4. Awika, Joseph M. 2011. "Major Cereal Grains Production and Use around the World", Advances in Cereal Science: Implications to Food Processing and Health Promotion, Joseph M. Awika, Vieno Piironen, Scott BeanSociety :1–13.

5. Bescansa, P., Imaz, M.J., Virto, I., Enrique, A. & Hoogmoed, W.B. 2006. Soil water retention as affected by tillage and residue management in semiarid Spain. *Soil Tillage Res.* **87(1)**: 19–27.

6. Blanco-Canqui, H., Wienhold, B.J., Jin, V.L., Schmer, M.R. & Kibet, L.C. 2017. Long-term tillage impact on soil hydraulic properties. *Soil Tillage Res.* **170**: 38–42.

7. Boudiar, R., González, J.M., Mekhlouf, A., Casas, A.M. & Igartua, E. 2020. Durum Wheat Seminal Root Traits within Modern and Landrace Germplasm in Algeria. *Agronomy* **10 (5)**: 713.

8. Colombani, J., Lamagat, J. P., & Thiebaux, J. 1973. Mesure de la perméabilité des sols en place: Un nouvel appareil pour la méthode Muntz une extension de la méthode porchet aux sols hétérogènes. *Hyd. Sci. J.*, **18(2)**: 197-235.

9. Cookson, W.R., Murphy, D.V. & Roper, M.M. 2008. Characterizing the relationships between soil organic matter components and microbial function and composition along a tillage disturbance gradient. *Soil Biol. Biochem*. **40(3)**: 763–777.

10. De'Anna, R., Lieskamp, Abigail, M. Moseley, Isabelle M. R. Legrain, Cheyenne Kelly, Md Ariful Haque, Seockmo Ku, Samuel I. Haruna. 2024. No-till cover crop effects on the hydro-physical properties of a silt loam. *Soil Sci. Soc. Am. J.* **88**:764–778.

11. Dusek, D., Mašek, J., Kroulík, M., Kumhála, F. & Vítěz, T. 2021. Chiselling and wheeling on sandy loam long-term no-tillage soil: Compressibility and load-bearing capacity. *Soil Res.* **59(5)**: 462–472.

12. El Melki, M.N., Soussi, I., Al-Khayri, J.M., Al-Dossary, O.M., Alsubaie, B. & Khlifi, S. 2024. Future impact of climate change on durum wheat growth and productivity in Northern Tunisia. *Agronomy* **14(9)**: 2022

13. Giller, K.E., Witter, E., Corbeels, M. & Tittonell, P.A. 2009. Conservation agriculture and smallholder farming in Africa: The heretics' view. *Field Crops Res.* **114(1)**: 23–34.

14. Houshyar, E., Sheikh Davoodi, M.J. & Nassiri Mahallati, M. 2010. Energy use and economic analysis of wheat production in Iran: A case study from Ardabil Province. *J. Agric. Technol.* **6(4)**: 663–672.

15. Idowu, J., Angadi, S., Darapuneni, M., & Ghimire, R. 2017. Reducing Tillage in Arid and Semi-Arid Cropping Systems: An Overview. New Mexico State University Cooperative

Extension Service, College of Agricultural, Consumer and Environmental Sciences. Guide A52.

16. Kaur V, Yadav SK, Yadav B, Madaan S, Kheralia M and Chinnusamy V. 2026. Root system architecture and drought adaptation: emerging tools and genetic insights. *Front. Plant Sci.* **17**:1753086. doi: 10.3389/fpls.2026.1753086

17. Kihara, J., Martius, C., Bationo, A., Thuita, M., Lesueur, D., Herrmann, L., Amelung, W. & Sommer, R. 2020. Soil fertility and crop yield under conservation agriculture in sub-Saharan Africa: A review. *Agron. Sustain. Dev.* **40**: 24.

18. Labad, R., Mohammedi, Z., Echcherki, S., Beldi, Y., Bounedjar, A., Chachoua, A., Kebir, K., Kerimi, H., Tayeb Hamani, R., Taibi, S. & Feddal, M.A. 2023. Effect of tillage practices on durum wheat (Triticum durum) productivity under semi-arid climatic conditions. *Farm Manage.* **8**: 14–20.

19. Lampurlanés, J. & Cantero-Martínez, C. 2001. Tillage effects on water storage during fallow, and on barley root growth and yield in two contrasting soils of the semi-arid Segarra region in Spain. *Soil Tillage Res.* **65(3-4)**: 207–220.

20. Lieskamp, D.R., Moseley, A.M., Legrain, I.M.R., Kelly, C., Haque, M.A., Ku, S. & Haruna, S.I. 2024. No-till cover crop effects on the hydro-physical properties of a silt loam. *Soil Sci. Soc. Am. J.* **88(3)**: 764–778.

21. Lipiec, J., Kuś, J., Słowińska-Jurkiewicz, A. & Nosalewicz, A. 2006. Soil porosity and water infiltration as influenced by tillage methods. *Soil Tillage Res.* **89(2)**: 210–220.

22. Palm, C., Blanco-Canqui, H., DeClerck, F., Gatere, L., & Grace, P. 2014. Conservation agriculture and ecosystem services: An overview. *Agric. Ecosyst. Environ.* **187**: 87–105. https://doi.org/10.1016/j.agee.2013.10.010

23. Pittelkow, C.M., Liang, X., Linquist, B.A., van Groenigen, K.J., Lee, J., Lundy, M.E., van Gestel, N., Six, J., Venterea, R.T. & van Kessel, C. 2015. Productivity limits and potentials of the principles of conservation agriculture. *Nat. Plants* **1(6)**: 151–157.

24. Rahnama, A., Munns, R., Poustini, K., & Watt, M. 2011. A screening method to identify genetic variation in root growth response to a salinity gradient. *J. Exp. Bot.*, **62(1)**: 69–77. https://doi.org/10.1093/jxb/erq359

25. Rahnama, A., Fakhri, S. and Meskarbashee, M. 2019. Root Growth and Architecture Responses of Bread Wheat Cultivars to Salinity Stress. *Agron. J.*, **111**: 2991-2998. https://doi.org/10.2134/agronj2018.12.0795

26. Rahnama, A., Hosseinalipour, B., Farrokhian Firouzi, A., Matthew, Tom. H., Ghorbanpour, M. 2024. Root architecture traits and genotypic responses of wheat at seedling stage to water-deficit stress. *Cereal Res. Commun.*, **52**: 1499-1510. https://doi.org/10.1007/s42976-023-00481-4

27. Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J. & Qiang, Z. 2010. Managing water in rainfed agriculture: The need for a paradigm shift. *Agric. Water Manag.*, **97(4)**: 543–550.

28. Saxton, K.E. and W.J. Rawls. 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Sci. Soc. Am. J.*, **70**: 1569–1578.

29. Schjønning, P., Munkholm, L.J. & Lamandé, M. 2022. Soil characteristics and root growth in a catena across and outside the wheel tracks for different slurry application systems. *Soil Tillage Res.*, **221**: 105422. https://doi.org/10.1016/j.still.2022.105422

30. Seabold, S. & Perktold, J. 2010. Econometric and statistical modelling with Python. In: Proceedings of the 9th Python in Science Conference. Austin, Texas, USA. pp. 92–96.

31. Thierfelder, C., Paterson, E., Mwafulirwa, L., Daniell, T. J., Cairns, J. E., Mhlanga, B., & Baggs, E. M. 2022. Toward greater sustainability: how investing in soil health may enhance maize productivity in Southern Africa. *Renew. Agric. Food Syst.*, **37(2)**: 166-177.

32. Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P.C., Deckers, J. & Sayre, K.D. 2010. Conservation agriculture for wheat-based cropping systems under changing climates. *Field Crops Res.*, **117(3)**: 197–210.

33. Yin, L., Lv, Q., Wang, P., & Xie, H. 2024. Changes in the degree of lateral root trait plasticity and trade-offs of maize under long-term no-tillage. *Front. Plant Sci.*, **15**: 1345189.