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Full Length Article

Resilience of conservation agriculture to rainfall deficits: A long-term study on durum wheat yield in Tunisia

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ABSTRACT

Adopting climate-smart agriculture innovations, such as Conservation Agriculture (CA), is necessary in Tunisia to mitigate the impacts of climate change. The present study assessed the impact of CA on the resilience of durum wheat yield and water use efficiency (WUE) in the context of current climate change. The study involved a comparison of durum wheat yield stability and resilience over 12 successive years (from 2010 to 2022), between no-till (NT), minimum tillage (MT), and conventional tillage (CT), as influenced by precipitation and temperature variations across the crop cycle and year. The effect of tillage treatments on phenological stages (days to heading and grain filling duration) and soil organic carbon and nitrogen were assessed. Weather variables analysis revealed a significant decrease in precipitation and a significant increase in the number of rain-free days and temperature over the years. Results showed that durum wheat yield and aboveground biomass decreased over time in all three tillage treatments, but the rate of grain yield decreased differed significantly between the treatments. NT showed the smallest decrease rate in yield, followed by MT and CT, as well as the smallest coefficient of variation, indicating better yield stability. A highly significant relationship between weather variables and yield response ratios was observed, where the NT-to-CT ratio increased as precipitation decreased. Analysis of yields, soil water content, and phenology revealed that NT did not significantly outperform CT across all experimental years but showed a significant advantage only during years with low precipitation. Analysis of the relationships between variability in yield and variability in weather variables revealed that the NT system was less sensitive (more resilient) to changes in weather variables, especially with regard to the autumn and late spring precipitations. This is of great importance in emphasizing the necessity of the adoption of NT. The study demonstrated that the benefits of CA are particularly pronounced in years with extreme drought events, highlighting the importance of adopting such agriculture innovation to mitigate the impacts of changes in weather variables on durum wheat yield.

1. Introduction

Climate change is one of the major concerns of our time, and the associated implications for agriculture and food security are far-reaching (Arora, 2019; Abd-Elmabod et al., 2020; Zong et al., 2022). For instance, the global average temperature over land has risen by 0.9 °C since the nineteenth century. Average temperatures are estimated to increase by 1.5 °C by 2050 (Eftekhari, 2022). This increase will lead to a rise in the number of hot and rain-free days, along with changes in the frequency and severity of extreme weather events

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(Anderson et al., 2020). In the Mediterranean region, particularly in North Africa, climatic indices may reach critical thresholds (Santillán et al., 2020). Future warming in the Mediterranean region is expected to exceed global rates by 25 %, with the pace of summer warming being 40 % greater than the global mean (Cramer et al., 2018). Tunisia will likely experience an average temperature increase of 2.1 °C and a 20 % decrease in annual rainfall by 2050 compared to the 1961–1990 reference period (INDC, 2015; Meddi and Eslamian, 2021). Such predicted changes are expected to drastically affect soil water availability, carbon storage, and crop production (Malhi et al., 2021). According to these estimates, if the current rate of climate change continues, by the year 2100 there will be a decline in the production of major cereal crops, such as wheat (Arora, 2019). Indeed, for each degree of global temperature increase, wheat yields are expected to reduce by 4–6 % (Anderson et al., 2020). In this context, Tunisia's situation is particularly critical due to its economic dependence on the agricultural sector, dominated by durum wheat crop. This crop is the most widely cultivated staple crop in this country, representing 54 % of the cereal growth area (~1.5 M ha) (Ayed et al., 2022) and is sown mainly under rain-fed conditions (Ouessar et al., 2021). This cereal is considered a staple food in Tunisians' diets, providing the main source of calories (258 kg capita^{-1} year^{-1}) in the country (Ayed et al., 2021). Tunisian wheat yield is highly variable from year to year (1 Mg ha^{-1} to 6 Mg ha^{-1}), closely linked to the variability and distribution of annual precipitation during the growing season as well as high temperatures during the grain filling stage (Annabi et al., 2019; Bouatrous et al., 2022). In this region, vulnerability is further increased by the other components of global change, including soil degradation (more than 3 M ha) as a result of intensive conventional production systems based on intensive tillage (Annabi et al., 2017; Bahri et al., 2019).

Adaptation to future changes, associated with increased climate variability may require attention to maintain the stability and resilience of production, rather than simply improving its absolute levels. In this way, the adoption of "climate-smart" agriculture innovations, such as Conservation Agriculture (CA), are urgently needed to build the resilience of agricultural production systems. Such cropping systems have evolved to provide farmers with stability of production and thus steady income in the face of uncertain weather. The objective of measuring resilience in agriculture is to identify the capacities of cropping systems to thrive despite perturbations and ensure sustainability (Lamichhane et al., 2020). CA is based on three principles: i) minimum soil disturbance (e.g., no-tillage, NT), ii) permanent soil cover, and iii) crop diversification and sequencing (Su et al., 2021). CA aims to maintain agricultural productivity, reduce vulnerability, and strengthen the resilience of agricultural systems to climate variability (Devkota, Singh et al., 2022; Rinaldi et al., 2022).

Studies report that with CA techniques, there is potential to sequester a substantial amount of carbon. For example Parihar et al. (2018) revealed that NT increased Soil Organic Carbon (SOC) stock (0–30 cm depth) by 7.22–7.23 Mg C ha^{-1}, whereas the CT system increased SOC by only 0.88 Mg C ha^{-1}. This leads to: (i) restoring soil quality and its ecosystem functions and services, (ii) improving water and nutrient retention capacity, reducing soil evaporation, increasing infiltration to deeper layers (iii) enhancing efficiency of inputs in soils of managed ecosystems, and (iv) creating climate-smart soils and agroecosystems (Lal et al., 2015; Gonzalez-Sanchez et al., 2021; Liebhard et al., 2022). These improvements allow crops to access more water in dry periods, resulting in increased yields and water use efficiency (WUE) compared to a conventional tillage (CT) system (Gonzalez-Sanchez et al., 2021). Moving to NT systems could also lead, by increasing carbon sinks, to significant climate change mitigation benefits and reductions in greenhouse gas (GHG) emissions per unit of agricultural product (Li et al., 2023). Based on data from 260 paired plots from 115 published papers, the rate of soil organic carbon (SOC) sequestration of no-till plots, relative to conventional tillage averaged 0.35 ± 0.05 Mg C ha^{-1} year^{-1} (Sun et al., 2020).

Souissi et al. (2020) provided evidence of the positive impact of NT on rainfed durum wheat, in terms of nitrogen use efficiency, under semi-arid Mediterranean conditions in Tunisia. Furthermore, Devkota et al. (2022) reported that, in Morocco, NT increased wheat grain yield by 43 % compared to CT. However, other authors working in agricultural semi-arid areas of Spain did not find significant differences between CT and NT in grain yield and straw biomass (Gandía et al., 2021). This large heterogeneity in experimental results not only highlights the significance of site specificity related to soil-climate conditions and agronomic practices (Su et al., 2021), but also of the experiment duration (Gandía et al., 2021).

Resilience analyses involve agricultural production indicators based on the mean and the inter-annual variability of crop production (Rosenzweig and Tubiello, 2007). Suitable indicators of system resilience can only be obtained in the context of long-term experiments (LTEs) spanning more than 10 experimental seasons (MacLaren et al., 2022). Such experiments can determine heterogeneity and include rare events (flood, drought), which are not detectable at short time scales (Müller et al., 2016). LTEs are required to account for the influence of different cropping seasons and to explore cumulative effects and processes that may take several years to become apparent (Giller et al., 2011). In this way, data from long-term experimental studies are needed to optimize the resilience framework and help identify optimal management systems for durum wheat to increase resilience in the long run. On the other hand, most of the studies comparing NT and CT have mainly focused on differences in soil quality and absolute yields, and only a few have investigated the yield resilience over time in the face of current climate change factors (Knapp and van der Heijden, 2018).

To assess the impact of weather variables on durum wheat production in Northern Tunisia, the present study aimed to compare durum wheat yield stability and resilience over 12 successive years, between NT, minimum tillage (MT), and CT, as influenced by precipitation and temperature variations across the crop cycle.

2. Materials and methods

2.1. Study area

A field study was carried out in the experimental fields of the National Institute of Agronomic Research of Tunisia located in the Boulifa region - Kef governorate (36°14′N, 8°27′E, 518 m). This region has a medium semi-arid bio-climate. The historical (1990–2010) average rainfall recorded in this region is 451 mm (AFD, 2021), and this high-altitude site is characterized by cold winters and hot, dry summers (Table S1, Table S2). The coldest month is January and the hottest is July. The soil is a silty clay, with 51 % clay, 30 % silt, 19 % sand, and a soil water pH of 8.2 was determined using a standard procedure in a 1:2.5 (w/v) soil:deionized water suspension.

2.2. Weather data

During the experiment period (2010–2022), weather data were collected daily by an automatic agrometeorological station near the experimental site. Minimum temperature (Tmin), average temperature (Tave), maximum air temperature (Tmax) and precipitation were recorded. Yearly variation patterns of meteorological data were quantified. In addition, annually and seasonally derived indices were determined and used, such as the number of rain-free days (the sum of days without precipitation), for which we use the standard meteorological seasons (December to February, winter; March to May, spring; June to August, summer; and September to November, autumn) (Orlowsky et al., 2012). Growing season precipitation was determined as the sum of precipitation from September until May.

2.3. Experimental design and treatments

Three tillage treatments were tested during 12 cropping seasons in a durum wheat-faba bean rotation system using a completely randomized block design with three replicates. Each plot was 12 m wide and 20 m long and separated by a space of 10 m. Tillage treatments were: (i) CT: inversion of the first 30 cm depth of soil with two plough coulters and a moldboard, followed by clod fragmentation with an offset disc; (ii) MT: tillage without soil turning using a chisel with rigid tine, followed by a Canadian cultivator with vibrating tines; and (iii) NT: using NT seeder after the application of glyphosate N-(phosphonomethyl)-glycine. Glyphosate is applied 1 week to 10 days before the sowing date at a rate of 4 liters per hectare. The rotation scheme consisted of an annual succession of faba bean (*Vicia faba* L) and durum wheat (*Triticum turgidum* subsp. *durum* (Desf.) Husn). The analysis was performed on wheat crop plots, where wheat was grown every season in a biennial rotation. In NT, durum wheat and faba bean residues were left on the soil surface. In CT, residues were incorporated by ploughing.

2.4. Crop management

The experiment started in the 2010–2011 cropping season. The crop planted before the trial was faba bean (Chahbi variety), sown using conventional methods. The durum wheat variety used was Maali. According to the experimental treatments, the soil was tilled each year in October. The seeds were treated with fungicides (Flutriafol and Thiabendazole, 200 cc per 100 kg of seeds before planting. Just before planting, 100 kg ha^{-1} of Di-ammonium Phosphate (DAP) (18 − 46-0) was uniformly applied to the soil surface. Planting was done at a rate equivalent to 400 grains per m^2. Sowing dates are reported in the supplementary data (Table S3). NT seeder (SEMEATO SHM-15/17) was used for the NT system and a conventional seeder was used for the MT and CT systems. The seeding depth was 2 cm on average. Durum wheat received additional ammonium nitrate (33.5 %) at the BBCH22 (50 kg ammonium nitrate ha^{-1}) and BBCH50 (50 kg ammonium nitrate ha^{-1}) stages. Weeds were controlled chemically using Puma Evolution (8 g L^{-1} Iodosulfuron-methyl-sodium + 64 g L^{-1} Fenoxaprop-P-ethyl + 24 g L^{-1} Mefenpyr-diethyl, 1 L ha^{-1}) for durum wheat and Select Super (120 g L^{-1} Clethodim, 1 L ha^{-1}) + Basagran (480 g L^{-1} bentazone, 1.25 L ha^{-1}) for faba bean.

2.4.1. Sampling, measurements, and indices calculation

2.4.1.1. Soil sampling, total N and C content determination. Soil samples were collected in 2022 (12 years after the implementation of the experiment). The soil was sampled, during durum wheat maturity, using a soil auger at 0 to 20, 20 to 40, and 40 to 60 cm depth levels. Five soil cores were collected per plot and divided by depth; Coarse residues and visible roots were removed manually. The soil mass was recorded, and moisture content was determined gravimetrically. Subsamples were stored at 4 °C until use. After drying and finely grinding the soil samples, total organic carbon was measured using the Walkey and Black method (Sleutel et al., 2007). Total nitrogen content was determined using the Kjeldahl method (Pudełko and Chodak, 2020).

2.4.1.2. Wheat phenology and yield. The days to heading (BBCH 59) were counted from emergence to heading, which was recorded when in each plot spikes of at least 50 % of culms had emerged. The physiological maturity (BBCH 89) was recorded when 50 % of the spikes turned yellow. The date of the anthesis (BBCH 69) was recorded. The grain filling duration was estimated for each plot from anthesis to physiological maturity.

Wheat grain yield and aboveground biomass were determined at maturity. For aboveground biomass determination, samples for each plot were collected using a square meter sampler, with three replicates from a randomized distribution. Grain yield was determined from the entire plot area using an experimental combine harvester (Wintersteiger). Samples from each plot were weighed and values were converted to Mg ha^{-1}.

2.4.1.3. Yield stability, yield response ratio, and relationship with weather data. The trends in wheat grain yield and aboveground biomass during the study period were investigated and compared under the three tillage treatments. Interannual yield variability was assessed for both wheat grain yield and aboveground biomass by calculating the coefficient of variation (CV), which is the standard deviation divided by the mean, for each tillage treatment. The CV is widely used to quantify and compare the year-to-year yield stability or variability of crops, with a higher CV value indicating higher yield variability, i.e., lower yield stability and vice versa (Raseduzzaman and Jensen, 2017).

For each experimental season, the effect of tillage practices on yield was expressed as yield response ratio and calculated as a ratio between the respective yields with the defined treatment (NT or MT) to the respective yield of the control (CT) (Hedges et al., 1999). A ratio greater than one indicated a greater yield for the experimental treatment. Then we investigated the effect of different weather variables on the yield response ratio using linear regressions.

2.4.1.4. Resilience of crop yield to weather variability. To compare the impacts of tillage treatments on long-term yield resilience, we quantified the sensitivities of yield in each tillage system to variability in precipitation, and temperature by assessing the Pearson correlation coefficient between yield and weather variables (DeFries et al., 2016).

2.4.1.5. Water use efficiency. The Water Use Efficiency (WUE) (in kg m^{-3}) was calculated as the ratio between grain yield and the actual evapotranspiration (ETa in mm). The soil water content was determined by gravimetry at sowing and maturity of the durum wheat. The ETa of the crop was calculated based on the water balance method (Wang et al., 2011) as follows:

$$ETa\ (mm) = P + I + U - R - DW - \Delta S$$

where P is precipitation during the growing season (mm), I is the amount of irrigation (mm), U is upward capillary flow from the root zone (mm), R is runoff (mm), DW is downward drainage out of the root zone (mm), and ΔS is the change of soil water storage in the 0–60 cm layer (mm) before planting and after harvesting. No irrigation was used in this experiment (I = 0). The upward capillary flow, downward drainage out of the root zone, and runoff were negligible, since the plots are located on land with a slope of less than 2 % and the water table is far from the ground surface (Zebibi, 1975). Therefore, ETa was the sum of precipitation and the change in soil water storage.

For the determination of soil water storage, three soil samples per plot were used to measure the soil water content by the gravimetric method. Volumetric water content at 0–20 cm was calculated using the following bulk density values: 1.32 g cm^{-3} (CT), 1.39 g cm^{-3} (MT), 1.5 g cm^{-3} (NT). Volumetric water content at 20–40 cm was calculated using the following bulk density values: 1.48 g cm^{-3} (CT), 1.53 g cm^{-3} (MT), 1.56 g cm^{-3} (NT). Volumetric water content at 40–60 cm was calculated using the following bulk density values: 1.53 g cm^{-3} (CT), 1.48 g cm^{-3} (MT), 1.47 g cm^{-3} (NT). For measuring soil bulk density, undisturbed soil sample was obtained by a standard soil corer. Soil bulk density was determined using the measured mass of soil particles and the known volume of the standard soil corer according to (Ma et al., 2016).

2.5. Statistical analysis

All statistical analyses were performed using R (R Development Core Team, 2017). Normality and homogeneity of variances were checked using the Shapiro-Wilk and Levene tests, respectively, before analyses.

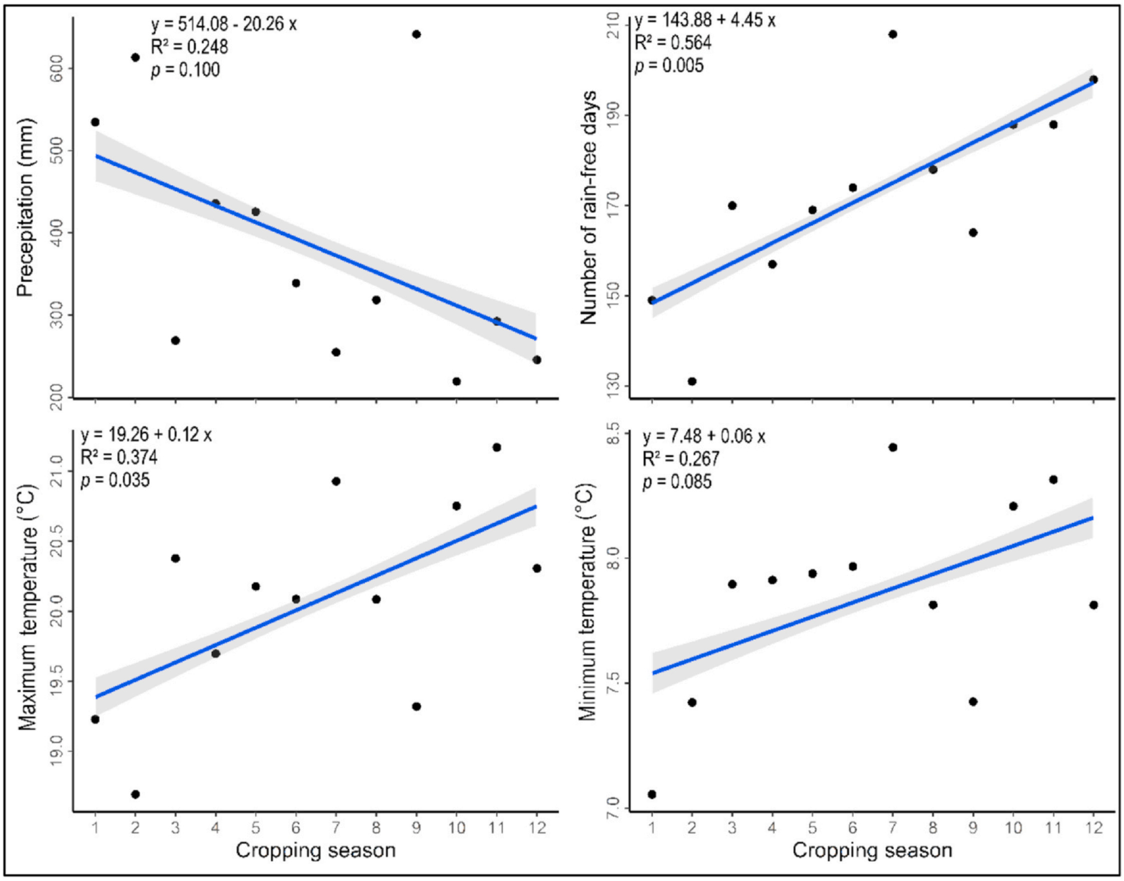

Fig. 1. Linear regression model showing the trend of mean cropping season precipitation, number of rain-free days, and maximum (Tmax) and minimum temperatures (Tmin) in El Kef-Tunisia experiment site from 2011 (1) to 2022 (12). Solid lines represent the best fit of linear regression trends ($p < 0.05$); shading represents the 95% confidence interval of the regression.

Homogenous groups were tested with the per-term linear model from aligned rank transformed data ($P = 0.05$) using the EMMEANS package (Lenth, 2018). A Tukey's post hoc test was performed to determine the significant differences between treatments. To compare the slopes of the regression line, the lsmeans::lstrends function, which performs an interaction test within an analysis of covariance (ANCOVA) framework, was used.

A Pearson correlation analysis was performed to test the relationships between agronomic and weather variables. For graphical visualization, the original data were plotted using R-package ggplot2 (Wickham, 2009).

3. Results

3.1. Weather variables change during the experiment

The cropping season precipitation (cumulative precipitation during the durum wheat cropping season) varied considerably over the 12 years of the study (Fig. 1). The average precipitation was 382 mm. The 2011–2012 and 2018–2019 (numbered 2 and 9, respectively) seasons experienced the highest precipitation levels, 60 % and 68 % above average, respectively. The 2019–2020 (numbered 10) season was an exceptionally dry year, with total precipitation levels 35% below average and experiencing the highest overall number of rain-free days. Similarly, the 2012–2013 (numbered 3), 2016–2017 (numbered 7) and 2021–2022 (numbered 12) seasons were categorized as dry seasons. These particularly dry years are categorized in the present study as extreme drought events.

Linear trends were examined to investigate the interannual variation pattern of the cropping season precipitation, the number of rain-free days per cropping season, the maximum temperature, and the minimum temperature across the 12 years of the study (Fig. 1). Significant warming trends were observed for maximum temperature ($p = 0.035$). The linear regression equations showed positive slope values of 0.12 °C/yr and 0.06 °C/yr and R^2 values of 0.374 and 0.267, respectively, for maximum and minimum temperature (Fig. 1). Results showed a decreasing trend of cropping season precipitation in the studied region ($p = 0.100$). The linear regression equation of cropping season precipitation showed a negative slope value of -20.26 mm yr^{-1} and an R^2 value of 0.248. A significant increasing trend ($p = 0.005$) was shown for the number of rain-free days per cropping season, with a positive slope value of 4.45 d yr^{-1} and an R^2 value of 0.564 (Fig. 1).

3.2. Tillage effect on soil organic carbon, total nitrogen, and water storage

Statistical analysis revealed significant effects of tillage treatment, soil depth, and their interaction on soil organic carbon (SOC) and total nitrogen (TN) (Table 1). Results revealed that, after 12 years of experimental implementation, the tillage treatments induced significant changes in the SOC and TN content only in the surface layer (Table 2). The NT treatment increased the SOC and TN content over CT at a depth of 20 cm by 24% and 34%, respectively. The MT treatment increased the soil SOC and TN content by 9% and 21%, compared to CT (Table 2).

Analysis revealed significant effects of season, tillage treatment, soil depth, and their interactions on soil water storage measured at durum wheat sowing and harvest (Table 1). Compared to CT, the NT treatment significantly increased soil water content (SWC) measured at sowing at only the third, seventh, tenth, and eleventh years of the experiment (Fig. 2). Compared to CT, NT significantly increased the SWC at the 0–20 cm depth at wheat sowing by 66%, 53%, and 69%, respectively in

Table 1
p values determined by analysis of variance for soil water content at the beginning (**SWC_0**) and the end (**SWC_f**) of the cropping season, soil organic Carbon (SOC) and Nitrogen (TN),and TN, and durum wheat phenology, aboveground biomass (AGB), grain yield (GY), harvest index, and water use efficiency (WUE).

Source of variation	df	SWC_0	SWC_f	SOC	TN	Days to heading	Grain filling duration	AGB	Harvest index	GY	WUE
Season (S)	11	0.0001	0.0001			0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Tillage (T)	2	0.0001	0.0001	0.022	0.0001	0.095	0.025	0.011	0.247	0.05	0.01
Soil depth (D)	2	0.0001	0.0001	0.0001	0.0001						
S × T	22	0.032	0.966			0.01	0.0001	0.036	0.657	0.0001	0.0001
S x D	22	0.0001	0.026								
T x D	4	0.007	0.107	0.131	0.002						
T x D x S	44	0.7	0.980								

df for error variance for SWC_0 and SWC_f = 216; df for error variance for SOC and TN = 18; df for error variance for phenology = 72; df for error variance for AGB, GY, harvest index, WUE = 108.

the third, seventh, and eleventh years. At the 20–40 cm depth, significant differences were found in the tenth (+48%) and eleventh years (+27%). A significant difference between treatments at the 40–60 cm depth was only observed in the eleventh year (+11%).

At harvest, significant differences between tillage treatments were observed only in the first, sixth, seventh, eighth, eleventh, and twelfth years, where SWC under NT was 31%, 77%, 99%, 165%, 60%, and 66% higher than CT, respectively (Fig. 2).

3.3. Tillage effects on wheat yield and phenological stages

Statistical analysis revealed significant effects of the season and the tillage x season interaction on wheat above-ground biomass and grain yield (Table 1). However, tillage treatment showed no significant effect on the harvest index (Table 1). Compared to CT, NT treatment significantly increased the above-ground biomass only in the sixth (+31%) and twelfth years (+24%) of the experiment, and grain yield only in the sixth year (58%) (Table 3).

Significant effects of the season and the tillage x season interaction on the duration of the phenological phases of durum wheat were revealed (Table 1). Tillage treatments significantly influenced the durum wheat phenology only during the seventh, eighth, and eleventh years of the experiment (Fig. 3). During these years, NT led to earlier heading and longer grain filling compared to CT and MT. In the seventh, eighth, and eleventh years, plants in NT headed 8 days, 15 days, and 9 days earlier, respectively, compared to CT. In these years, NT treatment resulted in a 5-day, 4-day, and 10-day increase in grain filling duration compared to CT (Fig. 3).

3.4. Tillage effects on wheat yield trends over time, stability, and water use efficiency

The time trend analysis showed a decrease in wheat aboveground biomass and grain yield over the years in all three tillage treatments (Fig. 4). However, wheat yield trends differed significantly between the three tillage treatments, as indicated by significant tillage-by-year interaction (Table 1) as well as by a significantly different slope (Table 4). Notably, the rate of yield decreases differed across the tillage treatments.

For aboveground biomass, no significant differences in slopes were observed between the systems, indicating similar trends over the experimental period (Table 4). However, for grain yield, the comparison between NT and CT revealed a marginally significant difference (p = 0.096), suggesting that NT might have a slightly distinct yield trend. For grain yield, the decrease rate was higher in CT (−259 kg ha^{-1} per year) than NT (−170 kg ha^{-1} per year). Comparing the CV, the results revealed that wheat yields varied the least in NT, as indicated by the smallest CV. Water use efficiency was significantly influenced by tillage treatment, season, and their interaction (Table 1). Regression analysis revealed that WUE decreased over the years (−0.031 kg m^{-3} per year, p = 0.015) in CT, while there was no significant trend in NT and MT (Fig. 4). The NT vs. CT comparison indicated a potential improvement in WUE trends under NT compared to CT (p = 0.053) (Table 4).

3.5. Yield response ratio of tillage treatments over years

For each experimental season, the effects of tillage practices on yield were expressed as yield response ratio and calculated as a ratio of the yield under NT or MT to the yield under CT (Fig. 5). From the first to the seventh years of the study, there was a progressive increase in the NT-to-CT ratio of grain yield, indicating that NT results in increased yield over time compared to CT. For the grain yield, the NT-to-CT yield ratio was significantly greater than one only during the seventh, the eighth, and the tenth years. In the seventh and tenth years, the NT grain yield was more than twice that of CT (NT-to-CT ratio = 2.5 and 2.1, respectively). For the aboveground biomass, the NT-to-CT yield ratio was significantly greater than one only during the seventh year of the experiment.

3.6. Effects of weather variables on NT and MT performance

The relationships between yield response ratios (NT-to-CT and MT-to-CT) and weather variables were analyzed to assess the effect of weather variables on the relative yield performance of the tillage treatments. Yield response ratios positively correlated with the number of rain-free days and the maximum temperature, and negatively correlated with precipitation (Fig. 5). The strength and significance of the

Table 2
Soil Organic Carbon and Total Nitrogen across soil layers under different tillage treatments at the end of the experiment.

	Soil Organic Carbon (g kg_{soil}^{-1})			Soil total Nitrogen (g kg_{soil}^{-1})		
	0-20 cm	20-40 cm	40-60 cm	0-20 cm	20-40 cm	40-60 cm
NT	12.56 a	9.79 a	6.99 a	1.07 a	0.77 a	0.66 a
MT	10.98 b	8.15 a	6.13 a	0.97 a	0.77 a	0.69 a
CT	10.09c	9.79 a	7.45 a	0.8 b	0.68 a	0.64 a

Letters indicate significant differences in each layer between tillage treatments using the Tukey HSD test at the 5% level. NT = no-till; MT = minimum till; CT = conventional till.

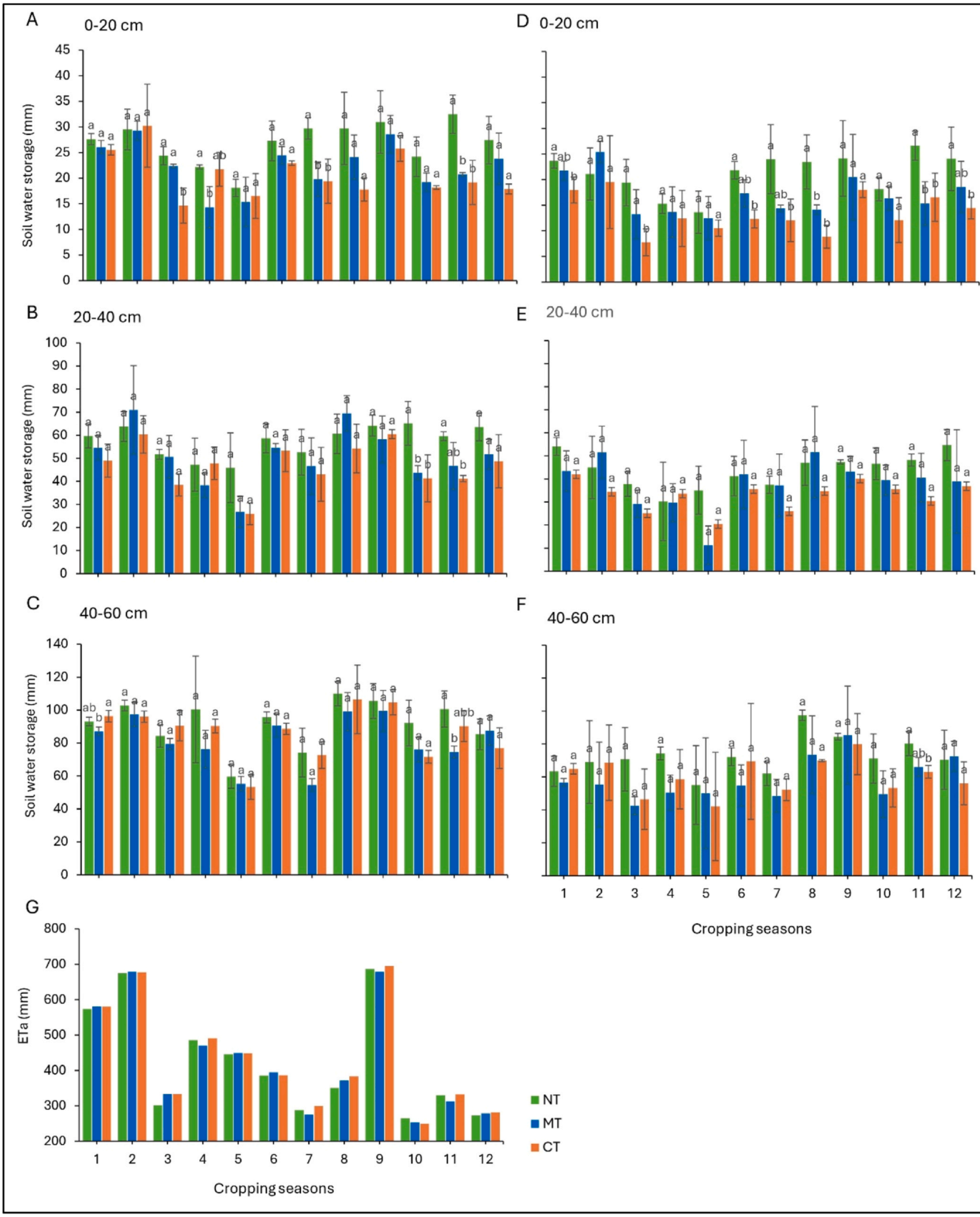

Fig. 2. Soil water storage (mm) at the beginning (A, B, C) and the end (D, E, F) of the cropping season at 0–20 cm, 20–40 cm, and 40–60 cm soil depth, and the actual evapotranspiration (ETa, G) in different tillage treatments across 12 cropping seasons. Different letters indicate significant differences between the three treatments in each cropping season using the Tukey HSD test at the 5% level. NT = no-till; MT = minimal till; CT = conventional till.

Table 3
Average above-ground biomass, grain yield and harvest index of durum wheat according to the 12-cropping season.

Cropping season	Above-ground biomass (kg ha^{-1})			Grain yield (kg ha^{-1})			Harvest index (%)		
	CT	MT	NT	CT	MT	NT	CT	MT	NT
1	14500 a	11800 a	12625 a	4113 a	3171 a	3397 a	28.8 a	27.8 a	27.1 a
2	14220 a	16605 a	14370 a	4583 a	4817 a	4156 a	32.9 a	29.0 a	29.4 a
3	2050 a	1013 a	2573 a	290 a	124 a	318 a	27.3 a	10.7 a	12.1 a
4	11308 a	12913 a	12465 a	4450 a	4679 a	4163 a	39.8 a	36.8 a	34.0 a
5	10503 a	9933 a	11578 a	3193 a	2910 a	3613a	30.7 a	29.5 a	31.9 a
6	6350 b	5485 b	8330 a	1786 b	1362 b	2833 a	28.4 a	25.1 a	34.2 a
7	3503 a	4780 a	5683 a	327 a	508 a	869 a	8.97 a	10.1 a	15.6 a
8	606 a	480 a	564 a	94 a	117 a	157 a	15.6 b	23.5 ab	28.1 a
9	13618 a	14693 a	13783 a	3217 a	2917 a	3063 a	23.5 a	20.7 a	23.1 a
10	3385 ab	2628 b	4145 a	575 a	463 a	1211 a	17.8 a	18.3 a	28.1 a
11	4770 a	6410 a	7405 a	1248 a	1622 a	1800 a	41.6 a	25.0 a	24.3 a
12	6957 b	7880 ab	8613 a	1457 a	1675 a	1964 a	21.1 a	21.2 a	22.6 a

NT = no-till; MT = minimal till; CT = conventional till. Different letters indicate significant differences between the three treatments in each cropping season using the Tukey HSD test at the 5% level.

relationship largely varied according to the tillage treatment (NT and MT). The linear regression was only statistically significant for the NT-to-CT response ratio, whereas the MT-to-CT ratio was weakly related to weather variables (Fig. 6). Concerning the grain yield response ratio, regression indicates that, among all weather variables, precipitation ($R^2 = 0.48$, $p = 0.012$) and the number of rain-free days ($R^2 = 0.63$, $p = 0.002$) were the most important factor driving the response to NT, followed by and the maximum temperature ($R^2 = 0.5$, $p = 0.009$). Analysis revealed a decreasing NT-to-CT ratio with increasing precipitation, indicating that during the study period, the NT system outperformed the CT system – mainly in years with the lowest precipitation, whereby the highest relative grain yield benefits from NT were obtained in low rainfall conditions. This observation was confirmed by a positive and highly significant relationship between the NT-to-CT ratio and the number of rain-free days per year. Similarly, regression analysis revealed that the NT-to-CT ratio positively correlated with maximum temperature. Regarding aboveground biomass, the relationships between the NT-to-CT ratio and weather variables were similar to those for grain yield, with the temperature being the most critical factor governing the response to NT practice (Fig. 6).

3.7. Effects of tillage treatments on durum wheat yield – weather variables relationships

3.7.1. Wheat yield

Overall, significant positive correlations between precipitation and durum wheat yield (both grain yield and aboveground biomass) were reported in all tillage treatments (Fig. 7). The highest correlations were

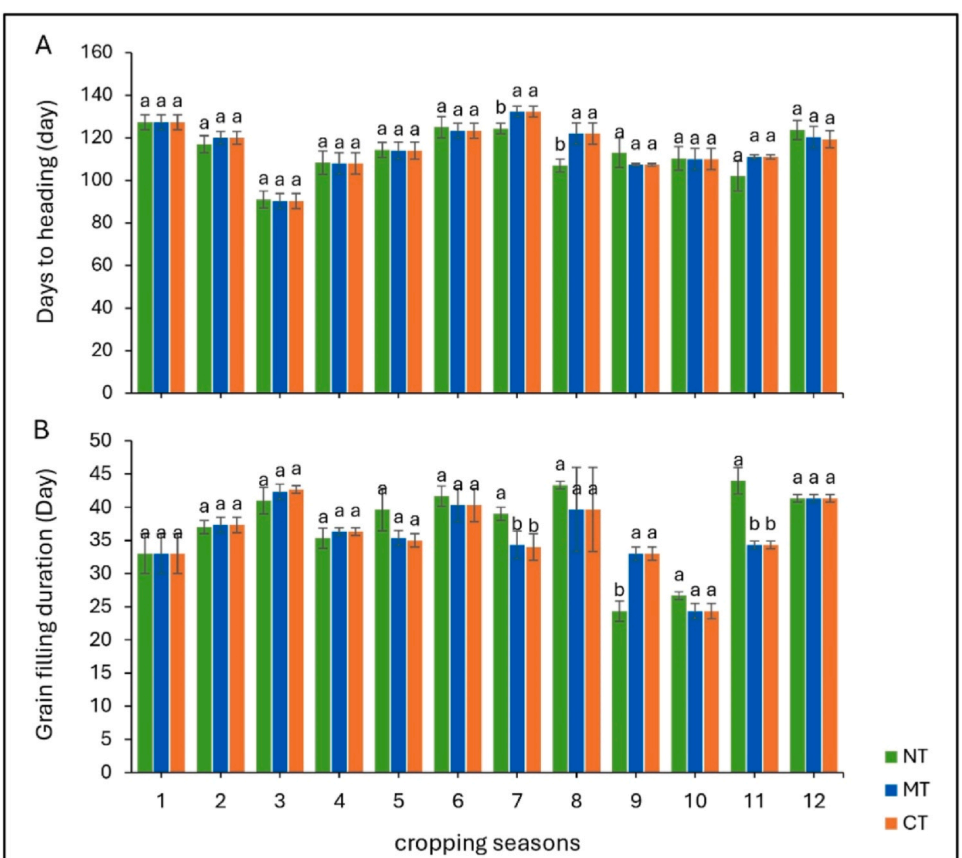

Fig. 3. Days to heading (emergence to heading) (A) and grain filling (B) duration of durum wheat plants in different tillage treatments across 12 cropping seasons. Different letters indicate significant differences between the three treatments in each cropping season using the Tukey HSD test at the 5% level. NT = no-till; MT = minimum till; CT = conventional till.

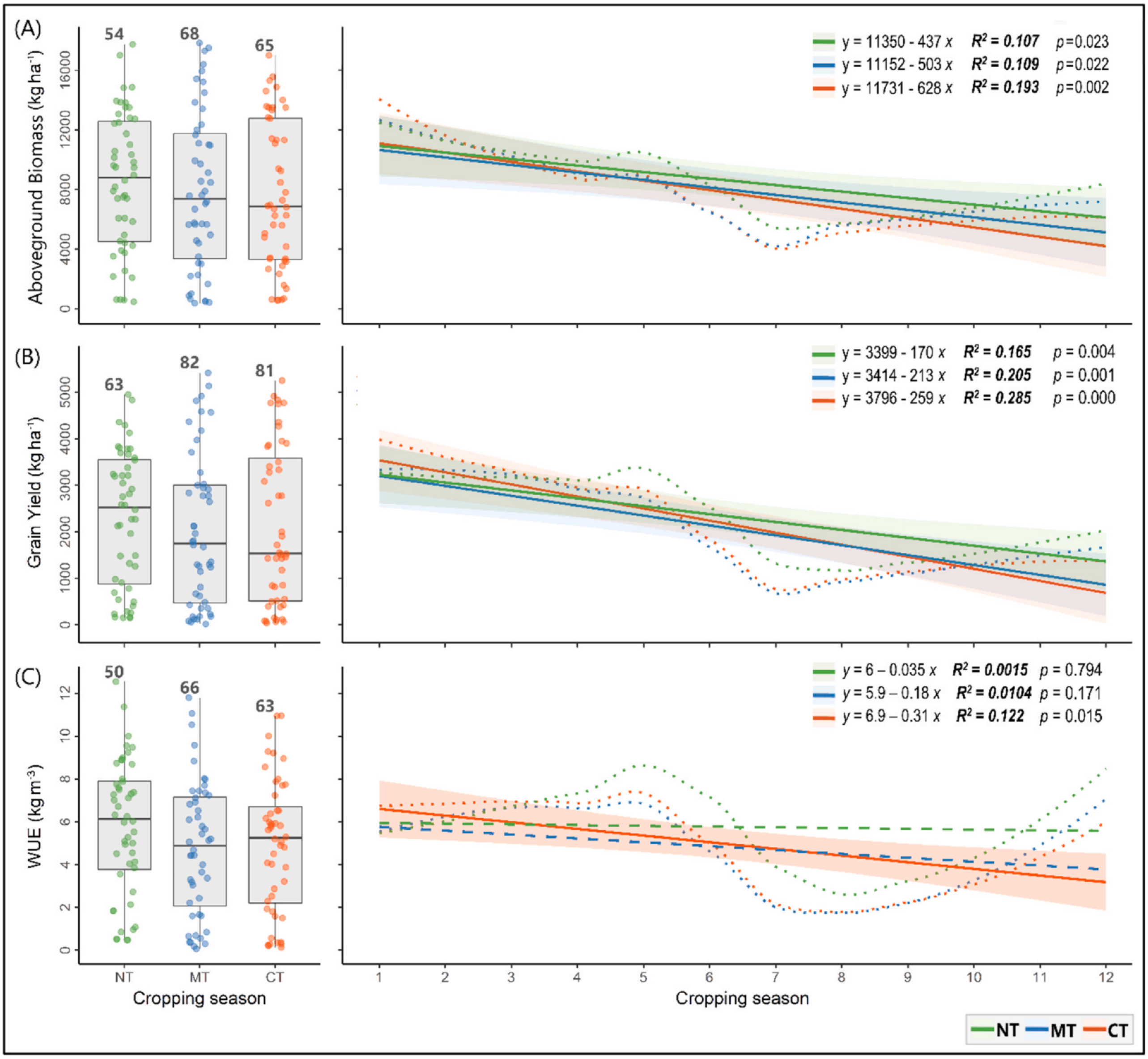

Fig. 4. Dot-plot with superimposed boxplot and observed linear trends of aboveground biomass (A), grain yield (B), and WUE (C) for each cropping system, during the experimental period from 2011 (1) to 2022 (12). Numbers on the top of the box plot indicate the coefficient of variation (CV, %); solid lines represent the best fit of linear regression trends among replicates (n = 48). Dashed lines represent no significant linear regression ($p > 0.05$); shading represents the 95% confidence interval of the significant regression; dotted curves are LOESS (locally-estimated scatterplot smoothing) curves. NT = no-till; MT = minimum till; CT = conventional till. df of the error variance = 138.

Table 4
p-Values of the Pairwise Comparisons of treatment linear regression Slopes on aboveground biomass, grain yield, and WUE Across the experimental period from 2011 (1) to 2022 (12).

	df	Aboveground biomass	Grain yield	WUE
CT vs MT	138	0.540	0.525	0.441
CT vs NT	138	0.357	0.096	0.053
MT vs NT	138	0.683	0.476	0.309

seen mainly with January and February precipitation for aboveground biomass, and with February and March precipitation for grain yield (Fig. 7B). The sensitivity of wheat crop yield to autumn precipitation was related mainly to precipitation occurring in October. Correlation coefficients between durum wheat yield and precipitation varied among the tillage treatments. The main differences were revealed for autumn precipitation (specifically the October precipitation) and late spring precipitation (May). Significant correlations between October precipitation and aboveground biomass were recorded only under CT (R^2 = 0.636) and MT (R^2 = 0.592) treatments. Under the NT treatment, there was no significant correlation (Fig. 7). This indicates that, in contrast to CT and MT, wheat yield under the NT treatment was resilient to autumn precipitation variability. In contrast to CT, there was no significant correlation between wheat yield (both grain yield and aboveground biomass) and May precipitation in NT and MT. This indicates that wheat yield under NT and MT treatments was resilient to the variability of precipitation in the late spring. For winter precipitation, wheat yield under the NT treatment showed the lowest coefficient for both grain yield and total biomass, indicating that wheat yield under NT was less sensitive (more resilient) to winter precipitation variability. Differences among the tillage treatments were observed at a monthly timescale, mainly for February precipitation. The lowest coefficients were recorded with wheat yield under NT for both total biomass (R^2 = 0.690) and grain yield (R^2 = 0.611), and the highest coefficient was

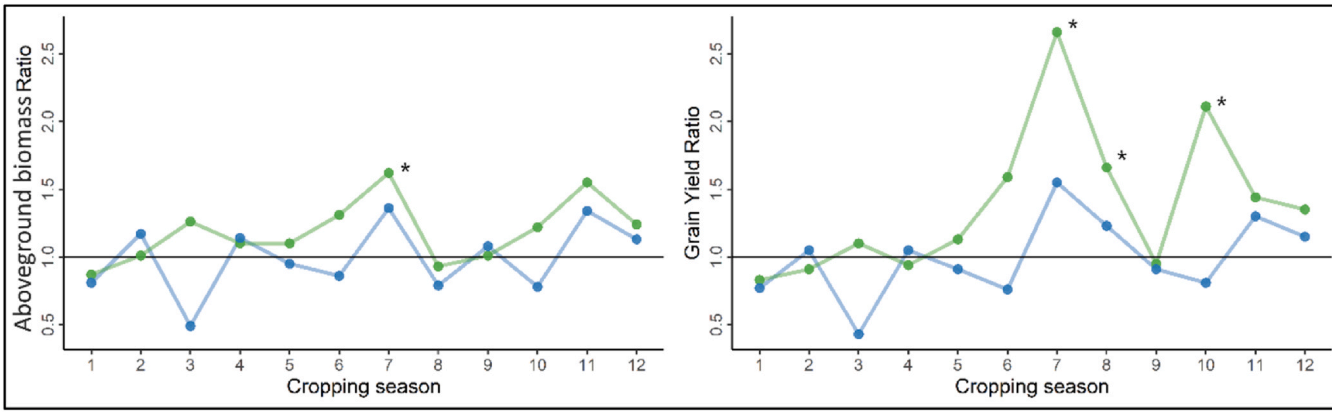

Fig. 5. NT-to-CT (green) and MT-to-CT (blue) yield ratios for aboveground biomass and grain yield during the experimental period from 2011 (1) to 2022 (12). Asterisks represent significant effects relative to the one value. The black line indicates a relative yield of one, i.e., with a yield equal to that of a CT system. NT = no-till; MT = minimal till; CT = conventional till.

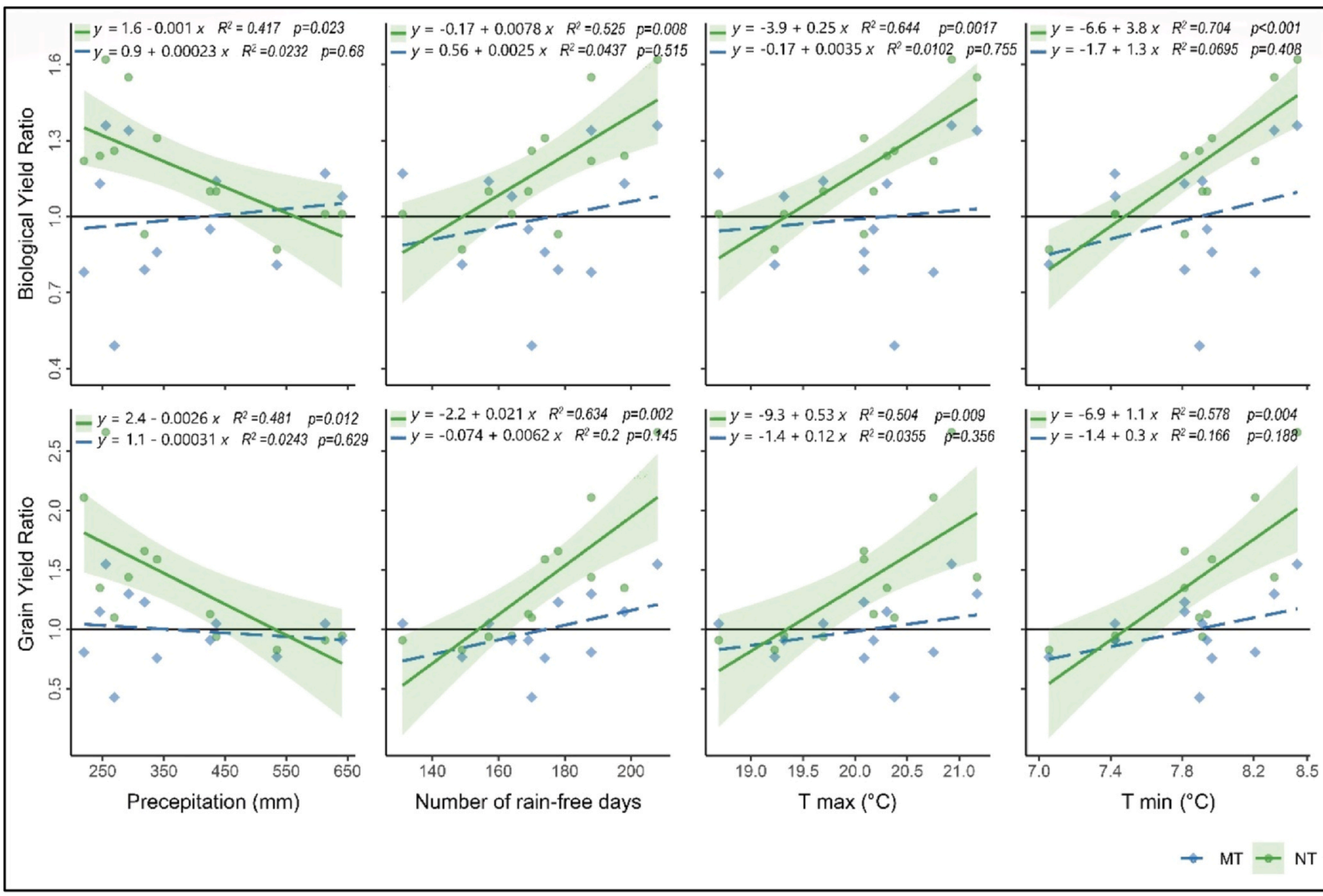

Fig. 6. Scatter plot with linear regression line of NT-to-CT (green) and MT-to-CT (blue) yield ratios for aboveground biomass and grain yield versus weather variables. Solid lines represent the best fit of linear regression trends among means. Dashed lines represent no significant linear regression; shading represents the 95% confidence interval of the significant regression. NT = no-till; MT = minimal till; CT = conventional till.

recorded with wheat yield under CT (R^2 = 0.812 and 0.763, respectively); indicating lower sensitivity of wheat yield under NT to February precipitation variability, relative to CT.

Wheat aboveground biomass and grain yield were significantly negatively correlated with the Tmin and Tmax recorded during the entire growing season (Fig. 7). Among the tillage treatments, the highest yield–temperature (Tmin and Tmax) correlation coefficients were observed under the CT treatment, followed by MT and NT. This indicates that wheat grain yield and aboveground biomass were most sensitive to changes in temperature under the CT treatment, followed by MT, and least sensitive under the NT system. Scaling to seasonal values, significant correlations were observed only with spring temperatures (p = 0.01). The strength of the negative relationship between spring Tmax and yield is greatest in CT, indicating that wheat yield under the CT treatment was more sensitive to changes in spring temperature than under NT and MT (Fig. 7).

3.7.2. Wheat WUE

The results revealed a significant positive correlation between precipitation and WUE in the CT treatment. There was no significant

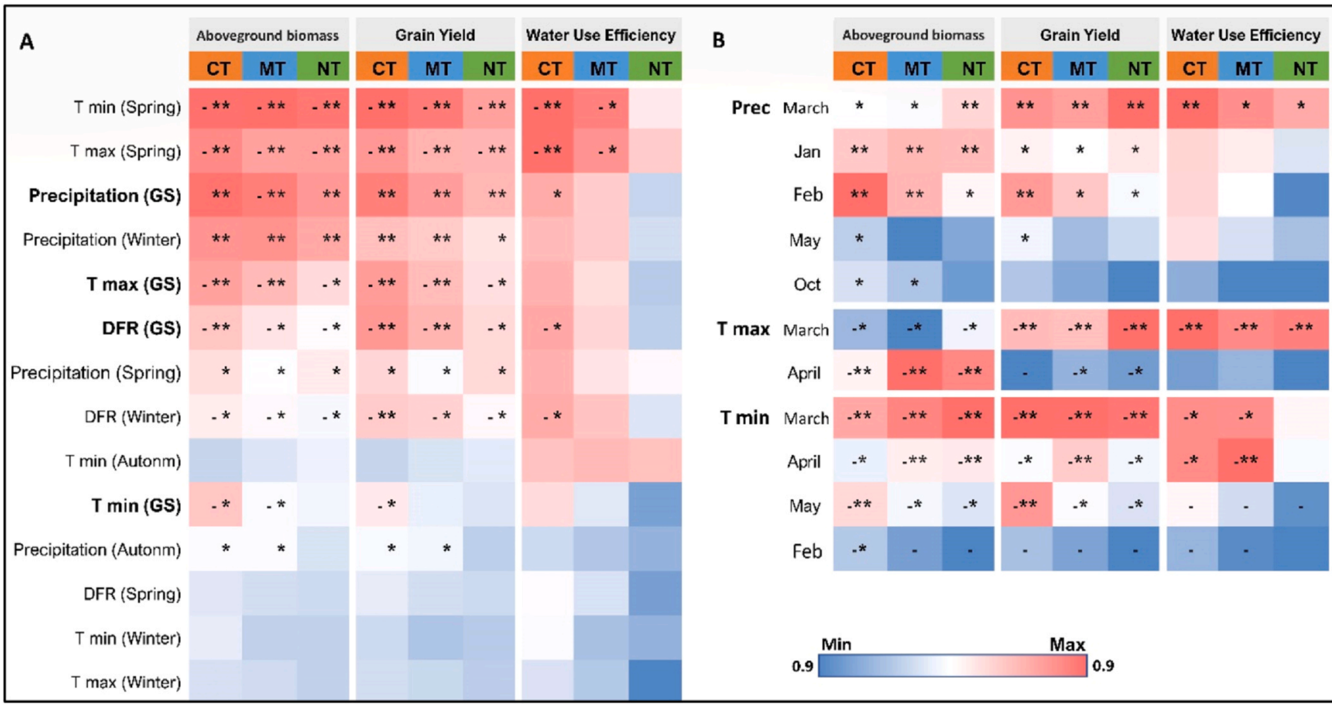

Fig. 7. Heatmap representing the strength and significance of correlations between weather variables and aboveground biomass, grain yield, and WUE within each cropping system. A: Weather variables at the growing season (GS) and season scale. B: Weather variables at the monthly scale (only months with significant correlation coefficients are shown). The absolute value of *R* is indicated by a color code explained in the legend within each cell. The weather variables scale is proportional to the strength of correlations. Significance levels $p < 0.05$, $p < 0.01$, and $p < 0.001$ are indicated by * , * *, and * ** respectively.

correlation between precipitation and WUE in the NT and MT treatments, indicating that WUE in these treatments was not sensitive to the interannual variability of precipitation during the study period (Fig. 7). At a seasonal timescale, the result revealed that WUE was related mainly to the spring Tmax and Tmin. This correlation was significant in CT and MT treatments while, interestingly, not significant in the NT treatment. Scaling to the monthly values, WUE was significantly positively correlated with precipitation that occurred in March for all three tillage treatments. The highest correlation coefficient was revealed in CT, followed by the MT and NT treatments. The WUE negatively correlated with Tmax in March for all three tillage treatments.

4. Discussion

Resilient cropping systems can be designed by better understanding the trends in yield variability over time and their interactions with crop management. A stable or increasing yield trend is a fundamental indicator of a sustainable cropping system. While this trend was not evident in our CA experiment (i.e., NT treatment), the comparison between NT and CT systems provided important insights, particularly regarding their yield decrease rate and sensitivity to weather variability. Our results showed that the NT system was more effective in increasing wheat yield resilience in the face of climatic variations – as evidenced by lower sensitivity to precipitation variability compared to the CT system. The NT system in our study showed the smallest decrease in grain yield over the years and the smallest CV compared to CT. This is in line with Bahri et al. (2019), who predicted that durum wheat yields under semi-arid conditions would be more stable under NT compared to CT. Our study indicates that NT, in comparison to CT, slows down yield losses resulting from changes in weather variables. This effect is primarily attributed to the mitigation of yield losses in years with low precipitation, which was demonstrated by a high NT-to-CT yield ratio in these years (Fig. 6). These effects were evident in the seventh (2016–2017), eighth (2017–2018) and tenth years (2019–2020) of the study, which was characterized by a low precipitation and a high number of rain-free days. In these conditions, the NT-to-CT grain yield ratio was significantly higher than one. This yield benefit under NT may be explained by the fact that NT management contributed to greater soil moisture conservation, as evidenced by a significant increase of SWC, at both the beginning and the end of the cropping season, during these years which allowed the crop to access more water in dry periods, and increased yield and WUE. In accordance with our results, previous studies reported that NT strongly enhances crop WUE by reducing soil evaporation (Badagliacca et al., 2021) and improving soil water content, compared to CT systems (Serraj and Siddique, 2012; Das et al., 2020; Gonzalez-Sanchez et al., 2021). However, we also found that WUE was significantly positively correlated with precipitation that occurred in March for all three tillage treatments. The fact that the correlation holds across all tillage treatments suggests that while tillage practices influence water dynamics, the benefits of rainfall in March were strong enough to improve WUE irrespective of the tillage type. March is often a key growth period for wheat, where water availability is critical for processes such as tillering and grain filling. Rainfall during this stage could boost biomass production and grain yield without necessarily causing a proportional increase in soil water content or evapotranspiration. The crops likely utilized the available water more efficiently for growth, leading to a higher yield response compared to the relative increase in soil moisture.

Based on the yield response ratio analysis over the 12 years, our study revealed that, in the first years of NT implementation, there was no benefit of NT over CT (NT-to-CT yield ratio lower or equal to one); and, that NT substantially outperformed CT during the seventh, the eighth, and the tenth years. In accordance with our results, Pittelkow et al. (2014) revealed that NT reduces yields in the first few years following adoption. Souissi et al. (2020) also showed that tillage practices did not affect durum wheat grain yield during a two-year experiment. However, our study demonstrated that the NT system yield increases with practice duration, as indicated by a progressive increase of NT-to-CT ratio over progressing years – thus highlighting the benefits of long-term NT management. Yield increases over time have often been attributed to gradually improved soil quality under NT versus CT, as indicated by a previous study (Jaziri et al., 2022). The decomposition of crop residues over the years releases nutrients into the soil, increases carbon and nitrogen storage, improves soil physicochemical properties, and helps conserve soil moisture, which allows for an increase in yields under CA (Bahri et al., 2018; Badagliacca et al., 2021). These important outcomes from NT allow for the development of a sustainable management agenda, which includes yield stability and environmental benefits. Previous studies suggest that the time required for a significant yield benefit from NT to occur varies from two to five years (Thierfelder et al., 2015); although others argue it may take much longer. The time lag between investment in NT and tangible benefits has been widely reported and varies widely between studies. For example, Thierfelder and Mhlanga (2022) revealed a significant change in maize yield for NT systems over CT following 10 years of implementation.

An unexpected decline in NT-to-CT yield ratio (ratio = 1) was observed in the ninth year of the study, before it increased again in the tenth, eleventh, and twelfth years (ratio greater than one). The ninth year was characterized by the highest precipitation during the study period (precipitation was 68% above average). High rainfall under NT, which is considered to be a water-harvesting system, leads to prolonged waterlogging and anaerobic conditions in the soil, which negatively affect crop productivity (Thierfelder and Mhlanga, 2022). While NT systems offer several advantages, it is important to consider the potential challenges associated with their adoption. One significant issue is soil compaction. Over time, the continuous use of NT without proper management practices can lead to the formation of compacted layers (Moreno et al., 2010). This compaction can restrict root growth, hinder water infiltration, and reduce aeration in the soil, ultimately affecting crop performance (Wasaya et al., 2019). Another challenge is the difficulty in managing weeds. Without soil disturbance, NT systems can lead to an increase in weed pressure, as tillage, typically used to control weeds, is no longer employed (Nichols et al., 2015). This places greater reliance on herbicide applications or other alternative weed control methods. Thus, effective weed management strategies are essential to ensure the success of NT systems.

In our study, regression analysis confirmed highly significant relationships between weather variables and yield response ratios. For grain yield, among all environmental factors, precipitation had the strongest effect on yield response, which was also confirmed in research conducted by Grover et al. (2009). Analysis revealed a decreasing NT-to-CT ratio with increasing precipitation, indicating that during the study period the NT system outperformed the CT system, mainly during years with the lowest precipitation. The highest relative grain yield benefits from NT were achieved under conditions of low precipitation. This observation was further confirmed by a positive and highly significant relationship between the NT-to-CT ratio and the number of rain-free days per year. Mrabet et al. (2012) revealed that the positive effect of CA on crop yield is more observable when the degree of aridity is increased. Similarly, regression analysis revealed that the NT-to-CT yield ratio, mainly for aboveground biomass, is positively correlated with maximum temperature. The largest grain yield benefit from NT practice over CT occurred in years with the highest maximum temperature, which may be related to the reduced surface soil temperatures arising from NT practice (Corbeels et al., 2020).

In contrast to CT, wheat yield under the NT treatment was resilient to autumn precipitation variability. This is of great importance in emphasizing the benefits of CA adoption. Previously, Latiri et al. (2010) claimed that the risk of drought stress for durum wheat is high in autumn, when germination occurs. The autumn precipitation determines the first stages of crop growth (germination, radicle extension, and seedling emergence). If rainfall does not occur and soil water content is too low (thus not allowing a sufficient increase in seed water content), the process of germination and radicle growth is delayed or even inhibited. This reduces the percentage of germination, with serious consequences for planting density and overall crop development and growth (Latiri et al., 2010). In our study, these effects were mitigated under the NT system, which was resilient to decreased precipitation in autumn. This was probably due to the greater level of soil water conservation under the NT system, as explained above – meaning water is stored in a deep soil profile, preserved from evaporation, and remains available for the crop during the consumption period under the NT system (Lampurlanés et al., 2016). Under this system, there was a significant increase in soil organic carbon (SOC) and nitrogen (N) content, which are important indicators of soil quality. Higher concentrations of SOC and TN are generally associated with improved soil physical, chemical, and biological properties (Bohoussou et al., 2022). For example, the increase in soil organic carbon, as demonstrated in the NT treatment, can improve soil water retention function by increasing the slope of the soil water retention characteristic curve, Ks values, and water infiltration rate (Lin et al., 2023).

In conditions of low precipitation, higher soil water content at sowing under NT, as observed during the third, the seventh, the tenth and the eleventh years, can lead to greater and earlier seedling emergence, resulting in greater development and growth, as well as greater shoot biomass, tiller density, and leaf numbers, compared to CT (McMaster et al., 2002). When the soil surface is covered by plant leaves, water is mainly lost by transpiration rather than by soil evaporation, and this water movement through the plant maintains and increases growth and assimilation, thus contributing to crop development and dry matter production. Therefore, NT helps to reduce yield loss that can result from decreased precipitation in autumn. Furthermore, this greater canopy development (due to more favorable emergence conditions in autumn) under NT, relative to CT, reduced soil evaporation and increased soil water during the wheat growing cycle. As seen in previous research (McMaster et al., 2002), this effect continues into the late spring, which coincides with the grain-filling period. Moreover, we found that tillage treatments significantly influenced the durum wheat phenology only during the seventh, eighth, and eleventh years of the experiment, which were characterized by low precipitation. During these years, NT led to earlier heading and longer grain filling compared to CT and MT. This can be likely explained by the early emergence in NT systems, as outlined above, driven by better moisture retention and optimal soil temperatures, which might have allowed wheat to establish more quickly during these years. This early establishment can cascade through the crop's growth stages, leading to earlier heading compared to CT. Grain filling is the final stage of growth, and the duration and rate of seed filling affect the final seed weight (Ullah et al., 2022). Longer grain filling durations are a key to higher wheat grain yield (Mondal et al., 2020). Better soil water conservation during the wheat growing cycle, as evidenced by a higher SWC at harvest in the first, sixth, seventh, eighth, eleventh, and twelfth years, may offset such deficits, allowing some assimilation and grain filling (Latiri et al., 2010). This allows for the reduction of grain yield losses due to decreasing precipitation in spring; hence increasing wheat yield resilience in the face of precipitation variability – primarily the interannual variability of May precipitation, as evidenced in our study. NT allows for the mitigation of both early and late drought effects on durum wheat, which provides cropping system resilience in the face of decreased autumn and late spring precipitation, respectively. Accordingly, Aryal et al. (2016) proved that CA-based wheat production copes better with extreme climate events than conventional tillage-based systems. The results of our study revealed that the NT system was more resilient than CT to changes in weather variables, especially decreasing precipitation, which is becoming more frequent in Tunisia.

5. Conclusion

The adoption of conservation agriculture practices based on no till helps to increase the ability of durum wheat to adapt to adverse impacts of changing weather variables, especially extreme climate events, such as periods of severe drought. In Tunisia, these practices show better yield stability compared to conventional tillage over 12 cropping seasons and significant advantages mainly during periods of severe drought. The study also highlights the importance of considering long-term impacts when evaluating the effectiveness of conservation agriculture practices. Rainfall was found to be the most critical climatic factor influencing durum wheat yield benefit under the conservation agriculture. Tmax and Tmin also affected biomass and grain yields. Overall, our findings suggest that variation in weather variables is having a significant impact on crops in the study region, and this should be addressed in future agricultural planning and management through the adoption of climate-smart agriculture innovations, such as conservation agriculture. This study provides evidence of the positive impact of conservation agriculture on durum wheat yield resilience during periods of severe drought, offering a pathway to enhancing agricultural sustainability in semi-arid regions. However, these findings are specific to the experimental site and require careful consideration when generalizing to other regions in Tunisia due to the country diverse agroecological conditions. Future research should focus on scaling conservation agriculture practices across different zones. Furthermore, a comprehensive understanding of the long-term dynamics of soil fertility parameters, such as soil organic carbon and nutrient availability, necessitates field experiments extending beyond 20 years. Long-term monitoring combined with predictive modeling will be critical to understanding the sustainability and scalability of these practices.

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CRediT authorship contribution statement

Annabi Mohamed: Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Rinaldi Michele:** Validation, Supervision, Methodology, Funding acquisition. **Frija Aymen:** Resources, Project administration, Funding acquisition. **Barbouchi Meriem:** Investigation, Formal analysis, Data curation. **Bahri Haithem:** Validation, Resources, Investigation, Conceptualization. **REZGUI Mounir:** Resources, Investigation, Data curation. **Somrani Olfa:** Formal analysis, Data curation. **Toukabri Wael:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Ferchichi Nouha:** Writing – review & editing, Investigation. **Rezgui Mohsen:** Validation, Supervision, Investigation, Data curation, Conceptualization. **Cheikh M'hamed Hatem:** Writing – original draft, Validation, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wael TOUKABRI reports was provided by Institut National de la Recherche Agronomique de Tunisie (INRAT). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ijagro.2025.100031.

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