Conservation agriculture improves agronomic, economic, and soil fertility indicators for a clay soil in a rainfed Mediterranean climate in Morocco

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Conservation agriculture improves agronomic, economic, and soil fertility indicators for a clay soil in a rainfed Mediterranean climate in Morocco

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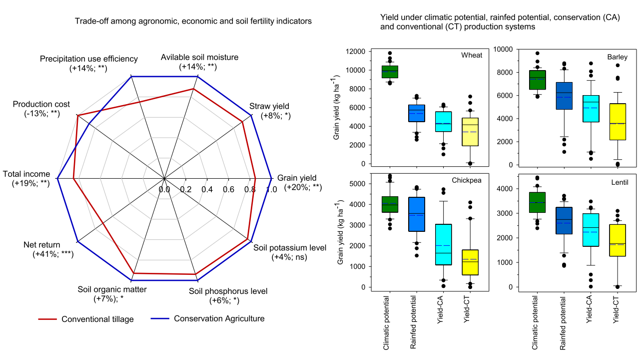
HIGHLIGHTS

- Rainfed Mediterranean region is facing higher rainfall and climatic variability
- Conservation agriculture (CA) can close wheat, barley, lentil, and chickpea yield gaps
- Experimental and long-term modeling approaches used to explore the impact of CA
- CA improves yields, soil fertility and resilience than conventional in rainfed drylands
- Cereal–legume rotation is more resilient than cereal monocrops under variable rainfall

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Declining rainfall with increasing variability, increasing temperature extremes, and declining soil fertility are threatening crop production and ultimately food security in the rainfed Mediterranean environment in Morocco. Conservation agriculture (CA) practices such as reduced tillage, soil cover, and appropriate crop rotation are recognized as a set of adaptive agricultural systems in such climate-sensitive regions. Systematic evaluation of agronomic, economic, and soil fertility indicators with medium-and long-term adoption of CA in different crop rotations in such variable climatic conditions is needed to drive wider adoption of CA in the region.
OBJECTIVE: The objective of this study was to systematically evaluate agronomic, economic, and soil fertility indicators under CA and conventional tillage (CT) using field experimentation (medium-term) and simulation modeling (long-term) for a clay soil of a rainfed Mediterranean environment.
METHODS: Methodologies included the following: 1) Field experimentation for 5 years (2015–2019), comparing CA and CT in four major food crops: wheat, barley, lentil, and chickpea, conducted in Merchouch, Morocco. The objective was to determine the effect of CA on crop productivity, yield stability, profitability, precipitation use efficiency, and soil fertility indicators of individual crops and cropping systems. (2) Dynamic simulation modeling to understand the long-term effect of adopting CA and CT under cereal–legume and cereal–cereal rotation systems. Using 5 years of experimental data, we calibrated and validated a Decision Support System for Agrotechnology Transfer (DSSAT) model for four crops; and ran the model for 36 years for two major rotations.

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RESULTS AND CONCLUSIONS: Across the five contrasting rainfall years, in comparison to CT, CA had greater yield stability and increased wheat grain yield by 43%, barley by 8%, lentil by 11%, and chickpea by 19%. In 5 years of cereal-legume rotation cycle, CA resulted in increased system yield (by 20%), total benefits (by 40%), precipitation use efficiency (by 13%), and available soil moisture (by14%) with production cost reduced by 14.5%. The CA system had higher soil organic matter (+7%), available phosphorus (+3%), and exchangeable potassium (+15%) than in CT, although all differences were non-significant. Our field experiment and long-term simulation results suggest that CA adoption improves a range of agronomic and economic, and soil fertility indicators compared to CT in the clay soil of a rainfed Mediterranean environment.

SIGNIFICANCE: The outcomes of this experimental and simulation study on the multiple benefits of CA provide evidence for extensionists, policymakers, and farmers to drive its wider adoption in Morocco and similar production environments.

1. Introduction

Agricultural production is predominantly rainfed in Morocco, representing >80% of the crop production area. In such a production environment, crop productivity greatly depends on the rainfall amount and distribution (Devkota et al., 2021b; Namdar et al., 2021). In recent years, the frequency of extreme events such as drought and temperature extremes has been increasing. Furthermore, the country is recognized as a "hotspot" for climate change and is predicted to have 20% reduced rainfall and a 2 °C increment in temperature by 2050 (IPCC, 2022). Also, previous studies from the major wheat-growing region in Morocco reported the existence of large attainable yield gaps, which are higher in rainfed than in irrigated environments (Devkota and Yigezu, 2020; Pala et al., 2011). This indicates that opportunities exist for enhancing crop productivity through better crop and soil management practices. Healthy soils, improved crop production practices, and choice of resilient crops and crop diversification are essential for sustainably closing yield gaps in such climatic conditions (López-Bellido et al., 1996; Vanlauwe et al., 2014). However, existing conventional tillage (CT) agricultural practices – i.e., intensive soil tillage, overgrazing and/or residue removal, and cereal mono-cropping – have a negative effect on soil health, resulting in declining productivity and resilience under such climatic conditions (Mrabet et al., 2012; Sombrero and De Benito, 2010). Hence, crop production practices that help improve crop yield, soil health, and utilization of available water are needed for sustainable crop production.

Conservation agriculture (CA) practice- i.e., minimum soil disturbance, permanent soil cover, and diversified crop rotation – has advantages over CT. It reduces production costs, runoff, and soil erosion, and increases water use efficiency and soil health resulting in similar or even higher crop yields compared to CT (Bashour et al., 2016; Devkota et al., 2021b; Moussadek et al., 2014; Mrabet, 2002). Previous studies have shown that the benefits of CA are more notable in rainfed drylands than in wet tropics (Kassam et al., 2012; Pittelkow et al., 2015). The CA system is not only effective in enhancing soil health and increasing farm income but also has been identified as a solution to the environmental challenges currently affecting crop production (Devkota et al., 2022a, 2022b; Fuhrer and Chervet, 2015; Mrabet et al., 2021). Thus, CA is becoming a major research and innovation pathway in the 21st century to achieve the SDGs by 2030, Paris agreement targets, and the outcomes of the COP-26 summit. In 2021, Morocco committed to achieving over 1 M ha of CA area by 2030 and has launched a national program to mainstream it under the new Green Generation strategy (2020−2030).

Despite several benefits of CA and efforts for scaling up, its adoption in Morocco and other Middle East and North African (MENA) countries is currently limited, i.e., <2% of the area is under CA (Kassam et al., 2019). Such a low adoption of CA in these countries stems from various barriers (Devkota et al., 2022a, 2022b). Several studies indicate that CA cannot be promoted as a blanket solution for management, but instead has to be tailored to the site- and context-specific management practices (Giller et al., 2009; Kirkegaard et al., 2014; Swanepoel et al., 2018). Also, for adoption at scale, the short-, medium-, and long-term effects of CA practices need to be well comprehended to design policy for better support and an enabling environment for farmers.

Proper crop rotation/crop diversification is one of the major pillars of CA. The yield and economic performance of different crops differ with the rotation system in CA under its medium to long-term adoption. Generally, farmers' primary concerns include short-term benefits from agriculture systems rather than longer-term sustainability. Hence, it is crucial to identify sustainable production practices that can provide both short-term benefits and long-term sustainability. Also, an increase in crop yield per unit area can be achieved through increasing yield potential and/or narrowing the attainable yield gaps. Generally, cereal-legume systems outperform cereal-monocropping systems in agronomic and economic indicators (Devkota and Yigezu, 2020; Yigezu et al., 2019). However, a systematic assessment of such benefits in long-term CA-based systems is yet to be further explored in MENA countries. The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM) can simulate the long-term effects of CA practice on yield, soil organic carbon, and soil moisture dynamics under different crop rotation systems (Devkota et al., 2022a, 2022b; Devkota et al., 2015). CERES model (for wheat and barley) and CROPGROW (for lentil and chickpea) within DSSAT framework can simulate the growth and development of these crops (Hoogenboom et al., 2019). These models have also been used to simulate the impact of CA-practices in rainfed maize in Malawi (Ngwira et al., 2014); to simulate the effect of long-term no-tillage in rainfed cereal systems in the Mediterranean area (De Sanctis et al., 2012); to simulate the growth and yield of irrigated rice-wheat systems in South Asia (Jeong et al., 2014; Timsina et al., 2008); to simulate the long-term impact of CA practices on wheat-based systems in Tunisia (Bahri et al., 2019) and performance of alternative crops for low input systems in a semi-arid region (Jing et al., 2021). Simulation modeling has been used to simulate the effect of management practices (Timsina and Humphreys, 2006), bundling agronomic solutions (Devkota et al., 2021a, 2021b), multi-criteria assessment (Topping et al., 2019), and policy formulation (Lalani et al., 2018). The DSSAT models have extensively been evaluated using experimental data and can accurately predicti yield variability caused by variable rainfall and different management practices (Hoogenboom et al., 2019; Timsina and Humphreys, 2006). The potential of CA-based practices for closing the yield gap in the Mediterranean rainfed production system, especially in wheat has been reported (Devkota and Yigezu, 2020).

As explained above, CA can be an alternative to the conventional production system in the context of increasing rainfall variability, temperature extremes, and declining soil health which directly affects crop productivity and farm profitability. Assessing the full benefits of CA requires a better understanding of its impact on agronomic, environmental, and soil fertility indicators with the adoption of CA practices, which will provide adaptation guidelines and ways forward to improve the resilience of rainfed drylands. However, available studies lack a systemic evaluation of those indicators at the system level with the medium and long-term adoption of CA systems. Ergo, the present study was designed with the objectives to understand yield variability and profitability of wheat, barley, lentil, and chickpea under rainfed

Table 1
Initial physical and chemical properties of soil in Merchouch research station, Morocco.

Soil depth (cm)	Texture (%)			Bulk density (g cm^{-3})	LL (cm^3 cm^{-3})	DUL (cm^3 cm^{-3})	SAT (cm^3 cm^{-3})	RGF	SOC (%)	NH4-N (mg/ kg)	NO3-N (mg/ kg)	Total N (%)	Soil pH
	Sand	Silt	Clay										
0–10	11.4	41	47.6	1.12	0.4	0.54	0.59	1.25	1.65	3	4	0.10	7.6
10–40	11.1	41.3	47.6	1.125	0.4	0.53	0.58	1.0	1.25	3	3	0.09	7
40–70	9.5	42.9	47.6	1.113	0.35	0.54	0.59	0.75	0.81	2	2	0.08	7.8
70–95	11.3	41.1	47.6	1.113	0.35	0.54	0.58	0.25	0.81	2	2	0.08	7.9

LL = lower limit, DUL = drained upper limit, SAT = saturated soil water content, RGF = root growth factor, SOC = soil organic carbon.

conditions; to explore the potential of CA-based practices for closing yield gaps of these crops; and to explore the long-term impact of CA practices on crop productivity and soil moisture and organic carbon dynamics in a rainfed Mediterranean environment combining field experimentation and a crop simulation model.

2. Methodology

2.1. Experimental site

The field experiment was carried out in the experimental field of the International Center for Agriculture Research in the Dry Areas (ICARDA), Merchouch, Morocco (33°36′41″N, 6°42′45″W, 390 m a.s.l.), located in 75 km east of Rabat. The field experiment was conducted over five sequential growing seasons, i.e., 2014–15, 2015–16, 2016–17, 2017–18, and 2018–19, and the growing seasons henceforward invoke to as 2015, 2016, 2017, 2018, and 2019, respectively. The climate of the experimental site is typically Mediterranean with hot and dry summers and cold and wet winters. A full description of the experimental location, soil, and climatic condition is given in Devkota et al. (2021a, 2021b). The 47-year (1974–2020) average annual rainfall is 392 mm with a maximum of 665 mm and a minimum of 181 mm, and coefficient of variation (CV) of 31%. The mean annual air temperature is 18 °C with monthly minimum and maximum temperature ranges of 10–12 °C and 20–24 °C, respectively. The soil of the experimental location is classified as a Vertisol of clay-loam texture with 47.6% clay and 41% silt content. It has calcareous parent material (encrusted with loam and lime crust with limy pebbles) and is characterized by a depth of 90–100 cm and a clayey texture. Upon drying, the soil develops cracks and slickensides, and experiences temporary water stagnation if heavy rain occurs during the rainy season. The top 40 cm of soil has medium soil organic carbon (1.25–1.65%) and soil-pH 7–7.9 (Table 1).

2.2. Experimental treatments

The experiment was conducted for four major food crops barley *(Hordeum vulgare L)*, chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris,* Medik.), and wheat (*Triticum aestivum L.*) under CA and CT practice in a cereal–legume rotation. Tillage treatment was fixed, and the four crops were planted in a chain rotation of wheat – chickpea – barley – lentil sequence as presented in supplementary Fig. S1. The experiment was designed in a Randomized Complete Block design (RCBD) with four replications. Considering homogeneity of the experimental area and convenience in tillage operation, CT plots were allocated in one block. The individual plots were 25 m × 20 m. The experimental plot and crop rotational arrangement are given in Supplementary Material S1. Commercial varieties were used for this study: barley (Amalou), chickpea (Moubarak), lentil (Bakriya), and wheat (Arihane).

2.3. Crop management

For the CT treatments, land was prepared in accordance with local farmers' practices. This included a disk plowing of about 10–15 cm depth after crop harvest in August/September followed by two shallow cultivations using a tine cultivator before seeding in November. There was no soil tillage in CA treatments, and seeds and fertilizers were directly drilled into the undisturbed soil using a no-till planter (Wintersteiger Plotseed XXL). In CA plots, weeds were killed by applying glyphosate (@ 1.0 L ha^{-1} commercial product) before sowing. The same seeder was used for seeding and basal fertilizer application in both CA and CT plots for all four crops. Crops were seeded on the same row spacing of 25 cm but the seed was calibrated to maintain the seed rates of 300 seeds m^{-2} for wheat and barley, 150 seeds m^{-2} for lentil, and 50 seeds m^{-2} for chickpea. All four crops were seeded on the same day, and seeding was performed during 15–20 December for all years except in the 2018 season when seeding was on 7 January.

Crops received a basal fertilizer of 50:22:42 kg of nitrogen (N), phosphorus (P), and potassium (K) ha^{-1}; and 30:13:25 kg of N, P, and K ha^{-1} for legumes through complex fertilizer (15% each of N, P_2O_5, and K_2O). Cereal received an additional 50 kg N through ammonium nitrate (33% N) at the active tillering stage coinciding with precipitation events. Weeds were controlled by applying selective pre- and post-emergence herbicide and occasional hand weeding. In legumes, pre-emergence herbicide Stomp (455 g L^{-1} pendimethalin) was applied immediately after seeding in CT plots and Fusilade (0.75 L ha^{-1} Fluazifop-p-butyl), a post-emergence herbicide, was applied at 2–3 leaf stage of weeds in both CA and CT plots. Mustang 306 SE (2,4-D + Florasulam) was used at the tillering stage to control broad and narrow leaf weeds in wheat and barley in both CA and CT treatments.

Crops were harvested by plot-harvester leaving about 20 cm of straw height for cereals and 5–10 cm for legumes. About 60% of the loose residues were removed from CA plots for wheat, barley, and chickpea, while all residues were taken away from the CT field and also from the lentil plot in the CA.

2.4. Data collection and processing

2.4.1. Grain yield and biomass

Grain yield was measured by harvesting whole plots when the crop reached maturity using a plot harvester for wheat, barley, and chickpea, while lentil was manually harvested and threshed with a stationary thresher designed for lentil. Grains were air-dried under the low-humidity and high-temperature summer conditions in the experimental site. To measure total aboveground biomass yield, crops were harvested at the ground covering 4 m^2 of land area (four rows with 4 m length) from three different points in each experimental plot and threshed (using plot thresher) and separated to calculate total biomass, grain, and straw yield. Days to emergence and flowering were recorded when 50% of crops reached flowering for each crop from both CA and CT plots.

2.4.2. Soil moisture and fertility analysis

Soil moisture was measured for all plots before seeding and at harvest in each cropping season using a mechanical soil auger at 0–15, 15–30, and 30–60 cm soil depths. Soil samples were oven-dried at 105 °C for 24 h or until stable weight, and then gravimetric soil water content was measured. The gravimetric moisture content was converted to volumetric moisture content by multiplying the soil bulk density of the respective depth.

After four crop growing seasons, i.e., in June 2019 (after crop harvest) soil samples were collected from two depths (0–5 cm and 0–30 cm) in the CA and CT plots, with four different points in each plot to determine soil fertility parameters. Soil samples were then air-dried at room temperature. The soil organic carbon (SOC) content was determined using the Walkley and Black wet oxidation procedure. Total nitrogen content was ascertained using the Semi-Micro-Kjeldahl digestion method. Available phosphorus was determined using the Olsen P method, and exchangeable potassium using the procedure described by Knudsen et al. (1982).

2.4.3. Precipitation use efficiency (PUE)

The PUE was calculated considering the crop yield and evapotranspiration during the crop growth period. Daily precipitation was measured using a rainfall canister at the experimental station. Soil water content was measured at one location in each plot before sowing and during the harvest of each crop up to 60 cm depth in the soil profile in 0–15, 15–30, and 30–60 cm layers. The soil moisture content was determined using the oven-drying method. Volumetric moisture content for each depth was calculated by multiplying it by the corresponding soil bulk density. Evapotranspiration was calculated using the following equation (Eq. 1) (Peng et al., 2020).

$$\mathrm{ET} = \mathrm{P} + \mathrm{SWD} - \mathrm{R} + \mathrm{CR} - \mathrm{D} \quad (1)$$

where, ET is evapotranspiration during the crop growth period (mm), P is precipitation (mm), SWD is water storage (mm) at seeding minus that at harvest for the 0–60 cm depth, R is runoff, CR is capillary rise to the root zone, and D is drainage from the root zone. As the experiment was performed under rainfed conditions, no irrigation was applied to any crop in all years. Since the experimental site has a relatively flat and deep soil layer, CR and D were assumed to be zero. The PUE was calculated as the ratio of grain yield to evapotranspiration for each crop.

$$\mathrm{PUE} = \frac{\text{Grain yield (kg ha} - 1)}{\text{Evapotranspiration (mm)}} \quad (2)$$

2.4.4. Economic analysis

Economic analysis was conducted considering the total cultivation cost and gross return. Total cultivation cost was calculated from the input and machinery costs: seed, fertilizers, herbicides, and other inputs, labor, and machinery used (land preparation, seeding, harvesting, and threshing). Unit cost for each input was collected from the representative market information for the respective year. The gross return was computed from both grain and straw yield for all crops considering the market price at harvest in the respective year. In the case of CA plots, 40% of the residues were retained in the field and 60% were considered marketable for wheat, barley, and chickpea. Lentil was harvested close to the ground, and all straw was considered marketable for both tillage systems. All input and output costs were converted to US$ (1 US$ = MAD 8.9). Net return was calculated by subtracting total cultivation costs from the gross return. Total cultivation cost analysis did not consider the capital cost, for example, land rent and the cost of purchasing machinery and depreciation.

2.4.5. System-level yield and economic benefits

To compare system-level yield and economic benefits of adopting CA and CT, total yield, production cost, and total income from five growing seasons in a rotation sequence of wheat–chickpea–barley–lentil–wheat were computed. For total yield, the wheat equivalent yield was computed for all crops and summed up to total yield. Total production cost was computed by adding the costs for individual crops, and the total income was computed by adding income from grain and straw from all five seasons.

Wheat equivalent yield (kg ha^{-1}) =.

$$\frac{\text{Respective crop yield (kg ha} - 1\text{) X Minimum market price of respective crop}}{\text{Minimum market price of wheat}} \quad (3)$$

2.5. Simulating long-term impacts of CA

2.5.1. Input data

Initial soil and crop management data: Initial soil conditions, i.e., soil moisture, nitrate, and ammonium content for each soil layer are shown in Table 1. In the initial condition, in both CA and CT, the initial amount of root biomass of 500 kg ha^{-1} was retained, while in the CA plot, wheat residue of 1.5 t ha^{-1} was retained. Cultivar-specific parameters, planting date, emergence date, planting method, density, distribution, seeding depth and row spacing, fertilizer types and application rates, harvesting date were recorded during the experimental period in different years. Organic amendments (amount of crop residues retention) and tillage practice varied across CA and CT and were recorded for the individual plots.

Daily weather data: The daily weather data required for DSSAT: rainfall, minimum and maximum air temperature, solar radiation, relative humidity, and wind speed were derived from NASA Power Project (NASA POWER, 2021) for 1984–2015 and for 2015–2020, all required data were obtained from the weather station in the experimental station.

2.5.2. Model calibration and validation

For wheat, chickpea, and lentil, two years of data (2017 and 2019) were used for calibration, and three years of data (2015, 2016, and 2018) were used for validation. For barley, data for 2015 and 2016 were used for calibration and 2017 data were used for validation. For model calibration and validation, growth and development parameters such as days to anthesis, days to maturity, maximum leaf area index, grain yield, and total aboveground biomass weight were used from CA and CT treatments. The cultivar coefficient (Table S2) for all four crops was derived using repeated iterations until a close match was obtained between simulated and measured growth and yield parameters.

2.5.3. Model performance

The model findings were assessed based on the mean, the ratio between simulated and measured values, standard deviation (SD), coefficient of determination (R^2), absolute root mean square errors (RMSEa), normalized root-mean-square errors (RMSEn), and d-stat (d) for the growth and yield parameters. It was assumed that the model reproduced experimental data best when the ratio between simulated and measured was close to 1.0, and R^2 and d-stat were also close to 1.0 (Timsina and Humphreys, 2006; Yang et al., 2014).

$$\mathrm{RMSE_a} = \left(\frac{1}{n}\sum (\mathrm{Y_i} - \mathrm{X_i})^2\right)0.5 \quad (4)$$

$$\mathrm{RMSE_n}(\%) = 100 \times \frac{\left(\left(1/n\right)\sum(\mathrm{Y_i} - \mathrm{X_i})2\right)0.5}{\sum \mathrm{Xi}/n} \quad (5)$$

$$d = 1 - \frac{\sum_{i=1}^{n}(\mathrm{Yi} - \mathrm{Xi})^2}{\sum_{i=1}^{n}\left(\left|\mathrm{Y}_i'\right| + \left|\mathrm{X}_i'\right|\right)^2} \quad (6)$$

where, Y_i and X_i are simulated and measured values, respectively; X_i is the mean of all measured values; and n is the number of measurements.

2.5.4. Simulating long-term impact of CA in different crop rotations

After the satisfactory calibration and validation, the model ran for 36 years (1984–2020) in the weather and soil of Merchouch research station to explore (1) reasons for yield differences across different years

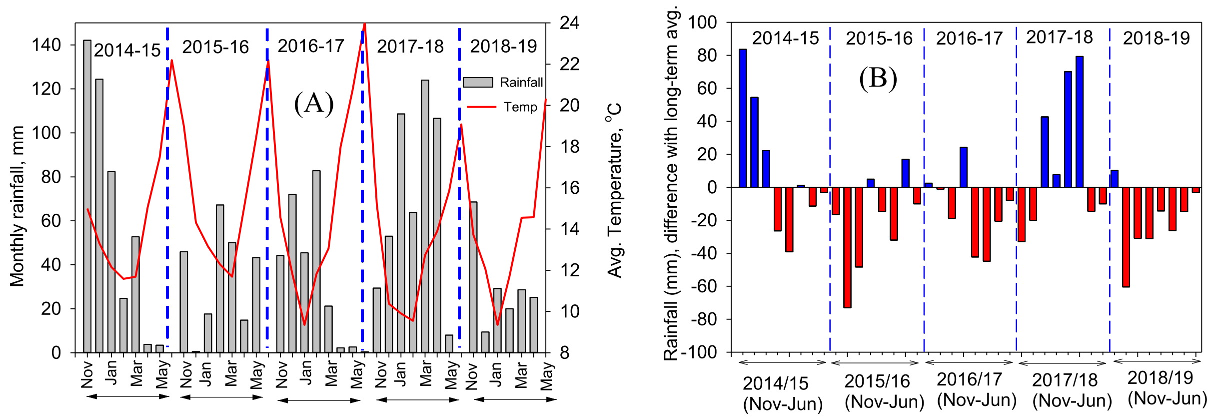

Fig. 1. Monthly rainfall and mean temperature (A) and monthly variability of rainfall compared to long-term (1974–2019) average for each month (B) during the five different crop growing seasons (November–June) at the experiment site in Merchouch, Morocco. Tick in X-axis represents months starting from November to June. Vertical dashed lines indicate growing seasons of 2014/15, 2015/16, 2016/17, 2017/18, and 2018/19.

(mostly soil moisture and SOC content), (2) climatic potential yield, (3) potential yield under rainfed (water-limited) condition, and (4) the impact of CA practices on yield, SOC sequestration, and available soil moisture dynamics in wheat–wheat and wheat–chickpea cropping systems in Morocco. For the dynamic simulation of SOC and soil moisture, the CENTURY (Parton) option of the model was used for all treatments and crops (Gijsman et al., 2002). The CENTURY model was initialized once in the beginning. In each season, the crop in the CA treatment was harvested leaving 60% vegetative biomass; in CT, 80% vegetative biomass was removed.

2.6. Statistical analysis

The experimental study compared CA and CT systems for five growing seasons for four different crops. A crop-based combined analysis of variance (ANOVA) was performed for all four crops, using GenStat 21st edition, to assess the yearly variation in crop yield, precipitation use efficiency, total production cost, and net benefit under the CA and CT systems. There was a significant year variation; hence pairwise comparison of the difference between individual treatments was performed using Fisher's Protected Least Significant Difference (LSD) for yield, economics, PUE, and soil fertility parameters. Combining the multiple sets of data available for pair comparison of CA

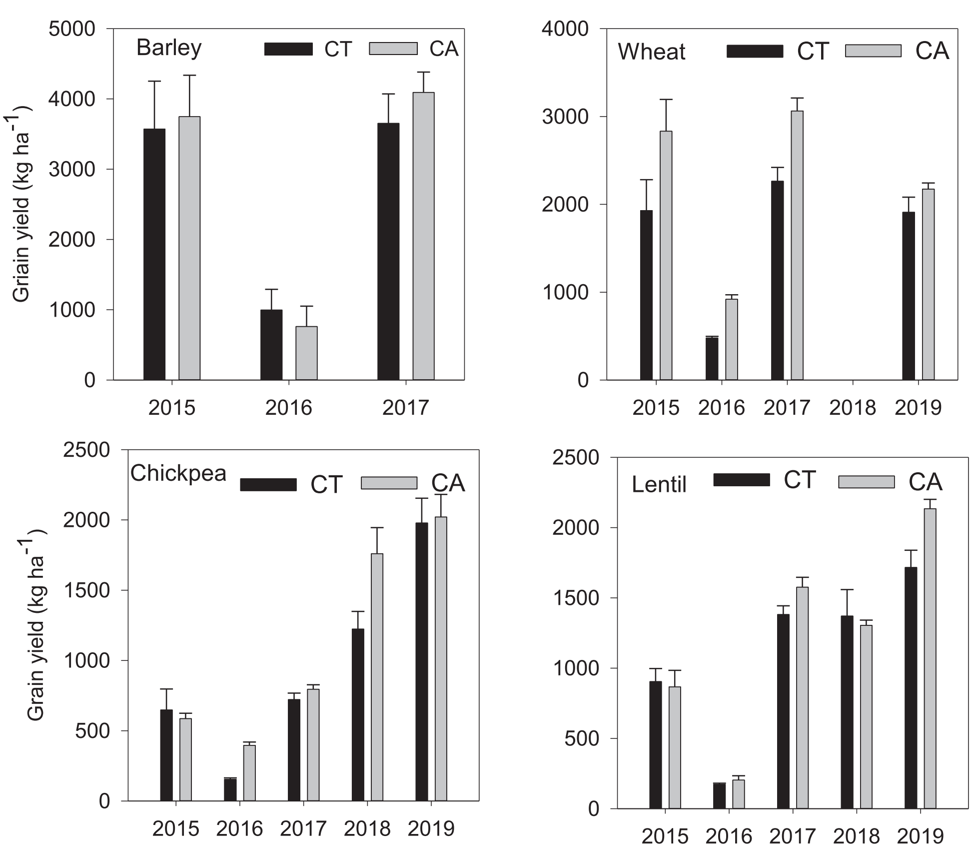

Fig. 2. Grain yield of chickpea, lentil, barley and wheat under conventional (CT) and conservation (CA) agriculture system in in on-station experiment at Merchouch, Morocco during 2015–2019.

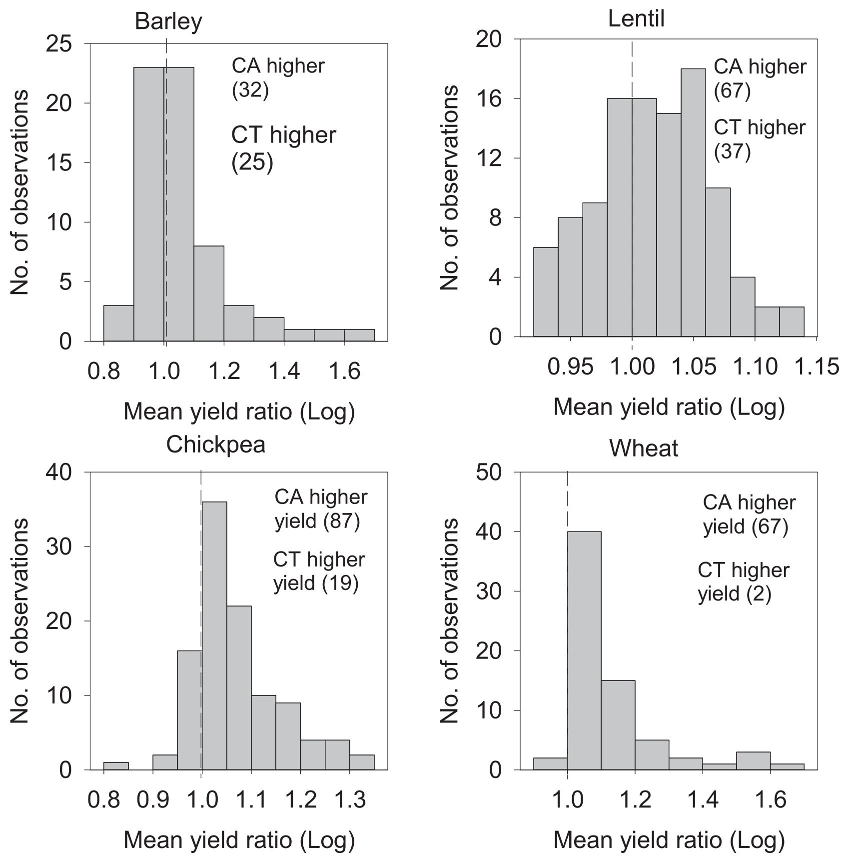

Fig. 3. Mean yield ratio of chickpea, lentil, barley and wheat under conventional (CT) and conservation (CA) agriculture system in in on-station experiment at Merchouch, Morocco during 2015–2019.

vs. CT, the mean yield ratio for all four crops was calculated by dividing the CA plot grain yield by the CT plot's yield, and the values were log-transformed. Mean, SD, coefficient of variation, and percentage difference were calculated wherever necessary. Multi-criteria analysis was also conducted using the normalized (0–1) scale spider diagrams to examine the relative trade-offs among the productivity, profitability, and soil fertility indicators in 5 years (2015–2019) of adoption of CA and CT practice.

3. Results

3.1. Weather conditions

Monthly rainfall and mean temperature at the experimental field over the five growing seasons (2015–2019) are presented in Fig. 1. Compared to the long-term (1974–2020) mean annual rainfall of 392 mm at the experimental station, 2019 was the driest year (181 mm) followed by 2016 (239 mm) and 2017 (271 mm), and 2018 (494 mm) and 2015 (434 mm) were wet years (Fig. 1A). The monthly rainfall had high variability between and within growing seasons, which is characteristic of the region's climate. In the 2016 and 2019 growing seasons, there was an early-season drought with almost no rainfall in December and only about 20 mm during January, which affected uniform crop establishment and early crop growth. In the 2016 and 2017 growing seasons, most of the months received low rainfall compared to the regional long-term monthly average (Fig. 1B). In 2017, seasonal rainfall was uniformly distributed during the growing season; hence yield performance was not as affected as it was in 2016 for all four crops. The average monthly air temperature had lower variability among years than the total rainfall. Air temperature for the grain-filling and maturity period (April–June) was lower in 2018 than in 2016 by 2–3 °C and in 2017 by 4–5 °C (Fig. 1A).

3.2. Grain yield performance, mean yield ratio, and stability

Significant differences in grain yield across the five growing seasons for all four crops were associated with high inter and intra-annual rainfall variation (Fig. 1). In all crops, grain yields were significantly low during 2016, the year with severe early-season drought with little or no rainfall in December–January. The average yield ranges from 0.62 to 2.0 t ha^{-1} with 68% coefficient of variability in chickpea, 0.19–1.9 t ha^{-1} with 57% variability in lentil, 0.89–3.87 t ha^{-1} with 60% variability in barley, and 0.7–2.67 t ha^{-1} with 45% variability in wheat (Fig. 2).

Across the growing seasons, barley under CA produced 8% higher grain yield than under CT, with a significant yield advantage observed in 2017, a growing season with low but well-distributed rainfall. For wheat, grain yield was significantly higher under CA in all four years. Averaged across all growing seasons, CA produced 43% higher wheat yield than the CT system. Similarly, averaged across the five growing seasons, chickpea and lentil grown under the CA system produced 19% and 11% higher yields than in CT, respectively.

For barley, out of the 57 multiple paired comparisons, 56% (32 observations) had a greater yield in CA than CT. For wheat, out of 69 multiple paired comparisons, 97% (67 observations) had greater yield in CA than CT. For lentil, out of 104 multiple paired comparisons, 65% (67 observations) had greater yield in CA than CT. For chickpea, out of 106 multiple paired comparisons, 82% (87 observations) had a greater yield in CA than CT (Fig. 3). All these indicate that all major crops grown under CA produced either similar or higher yields compared to CT. Comparatively, higher yields of wheat and chickpea with low CV under the CA system indicated that wheat and chickpea produced higher and

Table 2
Average grain yield (kg ha^{-1}), standard deviation (Std) and coefficient of variation (CV) for barley, wheat, chickpea and lentil grown under conservation agriculture (CA) and conventional agriculture (CT) system.

Crop	Mean yield		Std (kg ha^{-1})		CV %	
	CT	CA	CT	CA	CT	CA
Barley	2667	2878	1648	1845	62	64
Wheat	1617	2308	967	1056	61	46
Chickpea	777	923	644	622	80	61
Lentil	1026	1135	756	873	77	77

more stable yields under CA than in the CT system (Table 2).

3.3. Precipitation use efficiency (PUE)

The PUE varied with year, crop, and tillage practices. For barley, cultivation practices did not significantly affect PUE in all years. In average, the PUE was greater in 2017 and lowest in 2016 (Fig. 4). For wheat, PUE was significantly higher by 2.24, 1.95, 3.12, and 1.71 kg grain/mm water for CA compared to CT during 2015, 2016, 2017, and 2019, respectively. Similarly, for chickpea, PUE was significantly higher under CA during 2016 (very dry) and 2018 (very wet) than in CT, but similar during 2015 and 2019. For lentil, PUE did not significantly differ between CA and CT in 2015, 2016, and 2017, however, PUE was significantly higher under CA in 2019 but in wet year (2018) was higher in CT than CA (Fig. 4).

3.4. Economic benefits

The economic benefits varied with year, type of crop, and cultivation practice adopted. In a dry year (i.e., 2016), economic benefit was negative or negligible in crops under both systems, while benefits were greater in good rainfall years. In most years, the economic benefit from lentil, barley, and chickpea was higher than from wheat. Growing lentil under CA had significant economic benefits of 100–500 US\$ ha^{-1} in three growing seasons compared to CT, while economic benefit was similar between CA and CT in the first year of CA implementation. Similarly, the economic advantage of growing barley was higher under CA by 100–130 US\$ ha^{-1} compared to CT, except in 2016. There was no significant difference in the economic benefit of growing chickpea under CA and CT, except in the extreme drought year of 2016, when growing chickpea under CT had negative economic gain while the average economic gain was 368 US\$ ha^{-1} under CA. Growing wheat under CA had a greater benefit, with an average of 125–300 US\$ ha^{-1} greater than for CT (Fig. 5). The economic advantage with CA was mainly associated with increased grain and straw yield and reduced land preparation costs compared with CT.

Our analysis of individual crops and system-level productivity, total production cost, and net return highlighted the significant effect of CA over CT. Wheat, chickpea, and barley produced significantly higher yield and net return under CA than in CT, while yield and net return were similar in lentil. The 5-year total wheat equivalent yield and net return in the cereal– legume rotation system were higher under the CA system than CT. Overall adoption of CA increased system total productivity (in terms of wheat equivalent yield) by 20% and net return by 41% while reducing the total production cost by 13% compared to CT (Table 3).

3.5. Soil fertility indicators under CA and CT

In four years of crop rotation, none of the measured soil fertility parameters significantly differed between CA and CT. However, the CA plot had higher SOC, which was 11% and 7% higher in the top 5 and 30

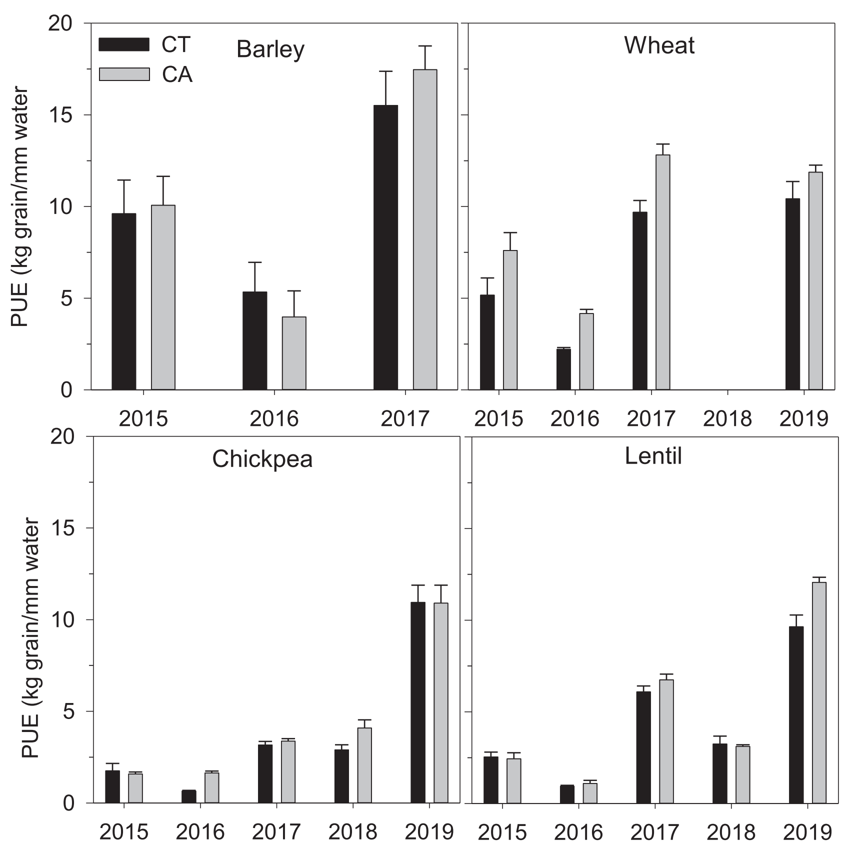

Fig. 4. Precipitation use efficiency (PUE) of chickpea, lentil, barley and wheat under conventional (CT) and conservation (CA) agriculture system in on-station experiment at Merchouch, Morocco during 2015–2019.

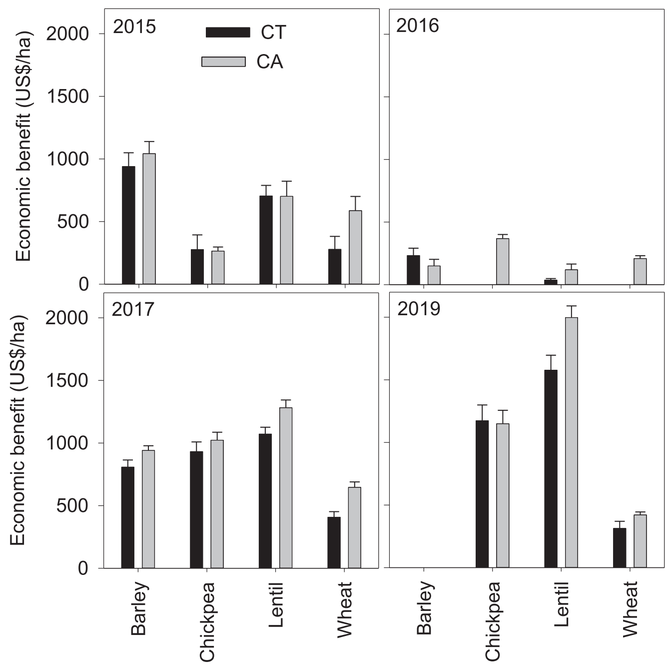

Fig. 5. Economic benefit (US\$ ha^{-1}) of chickpea, lentil, barley and wheat under conventional (CT) and conservation (CA) agriculture system in on-station experiment at Merchouch, Morocco during 2015–2019.

Table 3
Grain yield (t ha^{-1}), total production cost (US\$ ha^{-1}) and net return (US\$ ha^{-1}) in wheat, chickpea, barley, lentil, wheat, and in terms of the wheat equivalent yield (WEY) in five year cereal–legume rotation systems (2015 to 2019) under conservation and conventional agriculture system. Values are mean ± standard deviation (Std).

System	Wheat (2014/15)	Chickpea (2015/16)	Barley (2016/17)	Lentil (2017/18)	Wheat (2018/19)	Total WEY (2015–2019)
Productivity (t ha^{-1})						
CT	1.930^{b} ± 0.7	0.153^{b} ± 0.02	3.610^{b} ± 0.46	1.370^{a} ± 0.37	1.910^{b} ± 0.39	11.44^{b} ± 2.39
CA	2.832^{a} ± 0.72	0.375^{a} ± 0.02	4.077^{a} ± 0.33	1.304^{a} ± 0.07	2.170^{a} ± 0.28	13.75^{a} ± 0.46
Total production cost (US\$ ha^{-1})						
CT	343	240	310	305	318	1516
CA	304	210	272	258	280	1324
Net return (US\$ ha^{-1})						
CT	279^{b} ± 205	-13^{b} ± 34	788^{b} ± 136	883^{a} ± 327	313^{b} ± 93	2250^{b} ± 410
CA	588^{a} ± 226	339^{a} ± 38	935^{a} ± 97	882^{a} ± 67	423^{a} ± 64	3167^{a} ± 203

cm of soil depth, respectively compared with CT. Similarly, under CA available phosphorus was 13% and 6% higher in the top 5 and 30 cm of soil, respectively compared with CT. Exchangeable potassium in CA plot was 4% higher in the top 30 cm soil compared with CT, while was lower in CA at top 5 cm depth. There was a negligible difference between CA and CT plots in total nitrogen content in topsoil (Table 4). A higher level of SOC, available phosphorus, and exchangeable potassium under CA in the top 30 cm of soil indicated that CA adoption could gradually improve soil quality and overall fertility for this Vertisol in the medium to long-term compared with plowed soil.

Table 4
Soil organic matter (SOM), available phosphorus (P_2O_5), exchangeable potassium (K_2O) and total nitrogen content at the top 5 cm and 30 cm soil profile under conservation (CA) and conventional (CT) system after four years of rotation system in Merchouch, Morocco.

Soil component	Top 5 cm			Top 30 cm		
	CT	CA	Chnage over CT	CT	CA	Change over CT
SOM (%)	1.77 ± 0.43	1.97 ± 0.65	+0.2 (11%)	1.5 ± 0.38	1.61 ± 0.6	0.11(7%)
Phosphorus (mg/kg)	74.2 ± 25.1	84.1 ± 24.9	+9.9 (13%)	60.1 ± 24	63.7 ± 30	3.6 (6%)
Potassium (mg/kg)	427 ± 110	417 ± 231	−10 (2.3%)	292 ± 129	304 ± 180	12 (4%)
Total nitrogen (%)	0.12 ± 0.06	0.13 ± 0.12	+0.01 (8%)	0.13 ± 0.06	0.13 ± 0.12	0

3.6. *Trade-off among agronomic, economic, and soil fertility indicators*

In 5 years of a cereal–legume rotation sequence comparing CA and CT practice with contrasting growing seasons (variable rainfall amount and distribution) in rainfed drylands, adoption of CA had higher system-level grain yield (by 20%) and straw yield (by 8%), improved soil fertility (SOC by 7%, P level by 6%, K level by 4%), higher PUE (by 13%), improved available soil moisture (by 14%), lower production cost (by 13%), and greater income (by 19%) and net return (by 41%) compared to the CT field (Fig. 6). The trade-off among those indicators showed that with the medium-term adoption of CA in this variable rainfed dryland improved agronomic-, economic-, and soil fertility-related performance indicators compared to CT practice.

3.7. *Simulating long-term impact of Conservation Agriculture*

3.7.1. *Model calibration and validation*

The goodness-of-fit parameters of the calibration and validation results (Table 5) showed that experimental and simulated parameters matched well for the major parameters of phenology, growth, and yield, indicating that the model satisfactorily simulated wheat, barley, chickpea, and lentil yield in rainfed ecologies of this Mediterranean region. There was close matching between simulated and measured results for days to anthesis and physiological maturity, grain yield, and total aboveground biomass accumulation differing by <12 days, by <0.3 t ha^{-1} and <0.7 t ha^{-1}, respectively (Fig. 7; Table 5).

3.7.2. *Simulated seasonal total stored soil water in wheat*

Simulated seasonal water stored in the top 95 cm of the soil profile varied with seasonal rainfall and production practice. In the growing seasons with high early-season rainfall followed by low late-season rainfall [e.g., in 2015 (397 ± 55 mm in CA vs. 364 ± 63 mm in CT) and 2019 (454 ± 20 mm in CA vs. 434 ± 23 mm in CT)], stored soil moisture was higher under CA than CT. However, stored soil moisture did not differ between CA and CT in the wet year (2018) and the year with well-distributed rainfall (2017) (Fig. 8).

3.7.3. *Simulated potential yield of wheat, barley, lentil, and chickpea*

The simulated long-term average climatic yield potentials for wheat, barley, lentil, and chickpea were 9.87 ± 0.82, 7.42 ± 0.93, 4.01 ± 0.61, and 3.41 ± 0.53 t ha^{-1}, respectively. The average water-limited yield gap was highest for wheat (4.55 t ha^{-1}) followed by barley (1.53 t ha^{-1}), lentil (0.78 t ha^{-1}), and chickpea (0.57 t ha^{-1}). The result from the multi-year simulation supported the results from the experiment showing that the average grain yield of all four crops was higher for CA compared to CT. The average long-term simulated grain yield under CA was 24%, 38%, 48%, and 32% higher for wheat, barley, chickpea, and lentil, respectively than for CT (Fig. 9). This indicates that practicing CA can reduce the attainable yield gaps of these major food crops in the

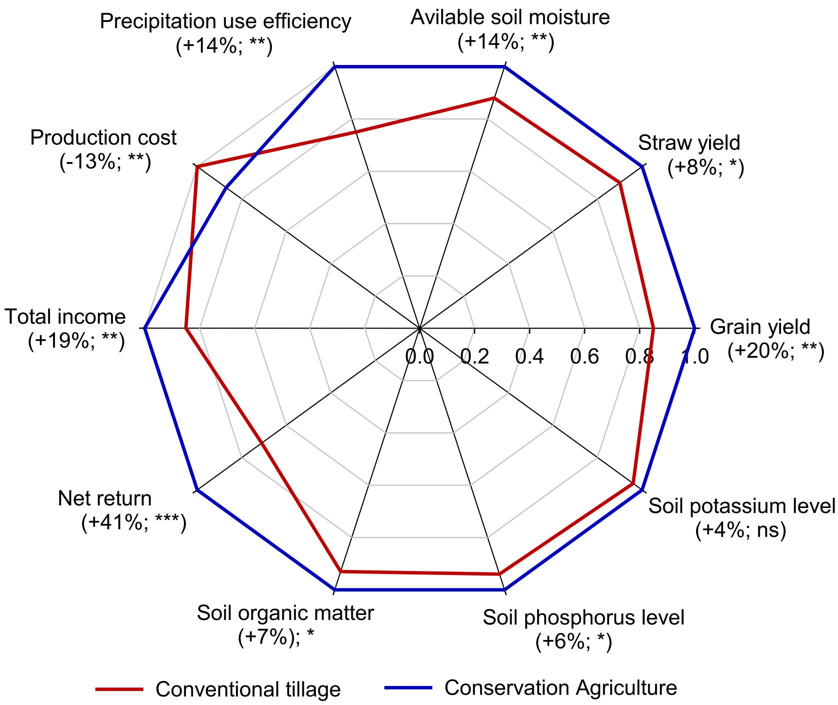

Fig. 6. Trade-off among agronomic, economic and soil fertility performance indicators under CA and CT system. Data averaged for five growing seasons in cereal-legume rotation sequence (wheat – chickpea – barley – lentil – wheat). Notes: Symbols and units for the parameter used: Grain yield: five years total wheat equivalent yield (kg ha^{-1}); Straw yield: the total amount of straw yield in five different growing seasons (kg ha^{-1}); Production cost = total production cost in five growing seasons; precipitation use efficiency = total amount of biomass yield with total available seasonal precipitation for five growing seasons. Soil indicators after four years rotation cycle at top 30 cm soil depth. Soil organic matter content, soil available phosphorus, and exchangeable potassium. Values in bracket denote percent higher or lower in CA than in CT. *, ** and ns denote significant at $p = 0.05$, 0.01 and non-significant, respectively.

Table 5
Statistical analysis of model calibration and validation parameters of wheat, barley, chickpea and lentil.

Parameters	Mean			Standard deviation		r-square	Mean Diff.	RMSE	RMSEn	d-Stat.	Used Obs.
	Observed	Simulated	Ratio	Observed	Simulated						
Wheat											
Anthesis (day)	105	92	0.88	15	4	1	−12	17.3	17	1	8
Maturity (day)	142	154	1.09	9	48	1	12	11.5	8	0.8	8
LAI maximum	2.53	2.68	1.06	0.93	1.10	0.66	0	0.5	20	0.67	8
Grain yield (kg ha^{-1})	2037	2296	1.13	905	472	0.72	259	683	22	1	8
TAGB wt. (kg ha^{-1})	5290	5912	1.12	2348	1291	0.73	622	1463	24	0.65	8
Barley											
Anthesis (day)	112	104	0.93	14	9	0.97	−8	10.5	9	0.51	6
Maturity (day)	156	156	0.99	13	12	0.83	0	8.3	5	0.54	6
LAI maximum	2.62	2.05	0.78	1.74	1.68	0.86	−1	0.6	22	0.80	6
Grain yield (kg ha^{-1})	2804	2677	0.95	1503	1995	0.98	−127	524	19	0.98	6
TAGB wt. (kg ha^{-1})	6525	6102	0.94	3530	3048	0.98	−423	796	12	0.90	6
Chickpea											
Anthesis (day)	108	109	1.01	11	21	0.81	1	23.7	22	0.81	10
Maturity (day)	164	184	1.13	16	11	0.61	12	27.1	17	0.46	10
LAI maximum	2.14	2.16	1.01	0.87	0.83	0.63	0	0.42	19	0.55	10
Grain yield (kg ha^{-1})	1094	974	0.89	794	468	0.74	−120	295	24	0.61	10
TAGB wt. (kg ha^{-1})	3820	4145	1.09	2373	2223	0.64	325	683	18	0.54	10
Lentil											
Anthesis (day)	110	116	1.05	13	3	0.89	6	13.7	12	0.61	10
Maturity (day)	159	161	1.01	11	9	0.81	1	7	4	0.58	10
LAI maximum	2.68	2.86	1.07	2.21	2.79	0.85	0	0.67	24	0.74	10
Grain yield (kg ha^{-1})	1239	1417	1.14	736	933	0.77	178	369	21	0.53	10
TAGB wt. (kg ha^{-1})	3375	3080	0.91	2058	2145	0.73	−295	482	14	0.68	10

LAI = leaf area index, TAGB = total above ground biomass.

region.

3.7.4. *Simulated long-term impact of CA on crop yield, SOC and available soil moisture in two rotation systems*

Long-term simulation to determine the impact of CA practices on grain yield, total SOC, and available soil moisture was carried out for two major rotation systems: cereal- cereal (wheat-wheat) and cereal-legume (wheat-chickpea). As expected, grain yield and available soil moisture in both production systems were associated with seasonal rainfall under both rotation systems. In 36 years of simulation for wheat-chickpea rotation (18 harvest seasons for each wheat and chickpea) in CA and CT system, CA outyielded CT in 22 years (60% growing season) and had a similar yield in 14 years for both crops. Where, grain yield in CA was higher by 8–95% (2.99 ± 1.81 t ha^{-1} in CA and 2.64 ± 1.68 t

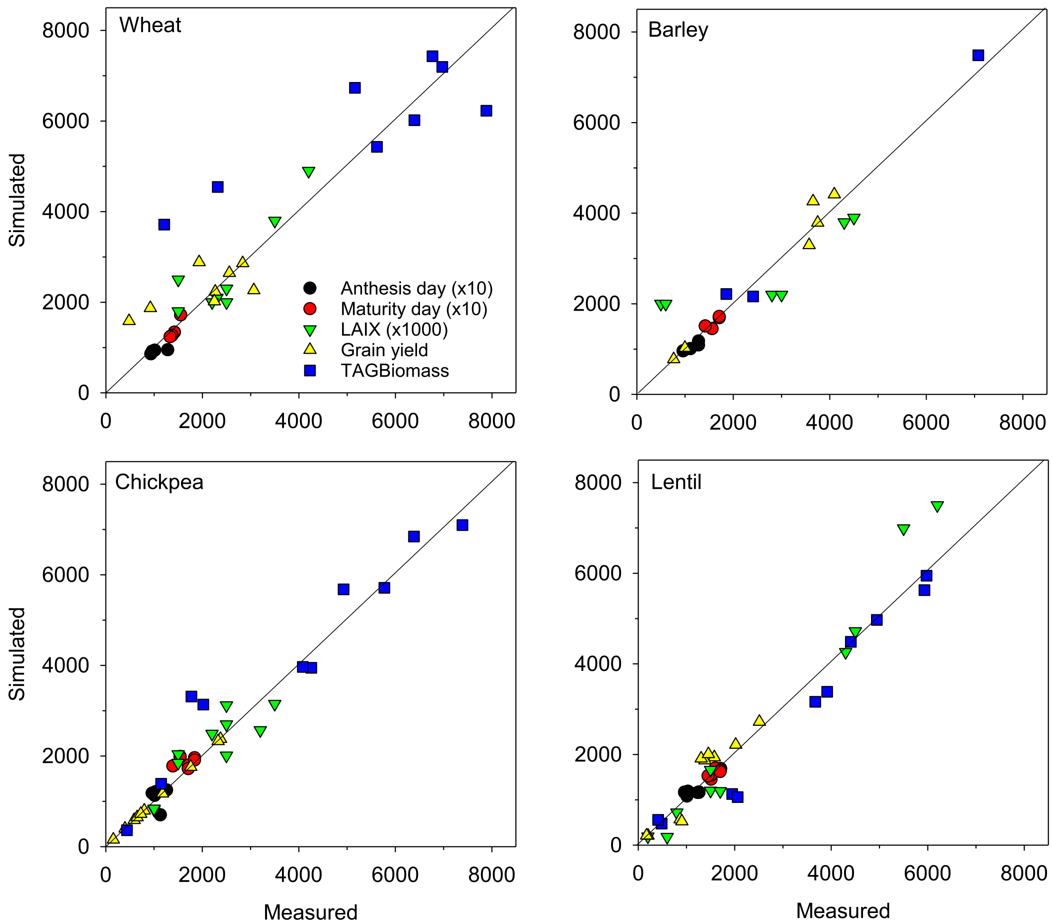

Fig. 7. Measured and simulated days to anthesis and maturity days, maximum leaf area index (LAIX), and grain and total aboveground biomass (TAGBiomass) (kg ha^{-1}) in wheat, barley, chickpea, and lentil. 1:1 line of observed and simulated data.

ha^{-1} in CT) in wheat and chickpea by 7–72% higher (1.59 ± 0.81 t ha^{-1} in CA and 1.41 ± 0.82 t ha^{-1} in CT) in chickpea than in CT. Similarly, under cereal-cereal rotation, 72% of years produced higher wheat yield (range from 30 to 200% higher) under CA (2.89 ± 2.05 t ha^{-1}) than in CT (2.13 ± 1.76 t ha^{-1}), the wheat crop failed due to drought in four years and 14% of years had higher yield (6–12% higher) under CT than CA (Fig. 10).

The trend of total SOC stock under cereal-cereal and cereal-legume rotation is presented in Fig. 10. The long-term simulation result for total SOC stocks showed a gradual increment of SOC in the top 30 cm of soil, and the increment was higher for the cereal-cereal than the cereal;-legume rotation in both production systems. In 36 years, the SOC stock built-up 9.6% higher under CA (from 49.9 to 54.8 t ha^{-1}) and by 3.8% higher under CT (from 49.9 to 52.2 t ha^{-1}) for the cereal- legume system. Similarly, in the same period, SOC increased by 16.6% under CA (from 49.9 to 58.2 t ha^{-1}) and increased by +12.6% under CT (from 49.9 to 56.2 t ha^{-1}) in cereal-cereal system (Fig. 10). Higher SOC content in cereal-cereal system than in cereal-legume system was mainly due to higher biomass with high carbon content in wheat than in chickpea. Despite higher SOC content in cereal-cereal system, the possibility of nutrient immobilization, decreasing soil fertility, and increasing disease and insect pressure might offset the benefit of higher SOC.

The simulated result for available soil moisture in the 95 cm soil profile under the two production systems is presented in Fig. 10. Out of 36 years, compared to CT, the available soil moisture was high under CA for 19 years (221 ± 21 mm in CA vs. 212 ± 23 mm in CT), was similar for 11 years, and was low for six years under cereal-legume rotation. In the same time period, it was higher under CA in 22 years (236 ± 14 mm in CA vs. 216 ± 13 mm in CT), was similar for eight years, and slightly lower for six years compared to CT under cereal-cereal rotation.

4. Discussion

Field experimentation comparing CA and CT practices in five contrasting rainfall years provided evidence that wheat, barley, chickpea, and lentil grown under the CA system had higher agronomic, economic, and soil fertility indicators compared to CT in this Mediterranean rainfed environment in Morocco. This study also confirmed that CA adoption for major cereal - legume-based rotation increased crop productivity, farm profitability, soil fertility, moisture availability, and PUE, while reducing total production cost as also reported elsewhere (Bahri et al., 2019; Bashour et al., 2016; Devkota et al., 2021a; Mrabet, 2011; Peng et al., 2020; Piggin et al., 2015). Economic incentives, yield stability, and resilience to varying weather (especially rainfall) are the major driving forces for the wider adoption of CA (Devkota et al., 2022a, 2022b; Kassam et al., 2019). The increase in gross revenue under CA was due to reduced total production costs, mainly associated with tillage operation and higher grain and straw yields (Fig. 6). Comparatively higher yield and resilience under the CA system can be explained by the greater available soil moisture, especially for low rainfall years (Fig. 8), and improved PUE and soil fertility indicators (Table 4). A simulation study by Bahri et al. (2019) also found that CA is more effective than CT for enhancing wheat yield and water use efficiency under semi-arid and sub-humid conditions in Tunisia.

Similar to the result from field experimentation, the long-term simulated average yield was significantly higher for the CA than the CT system by 24%, 38%, 48%, and 32% for wheat, barley, chickpea, and lentil, respectively (Fig. 9). This result further supports that the adoption

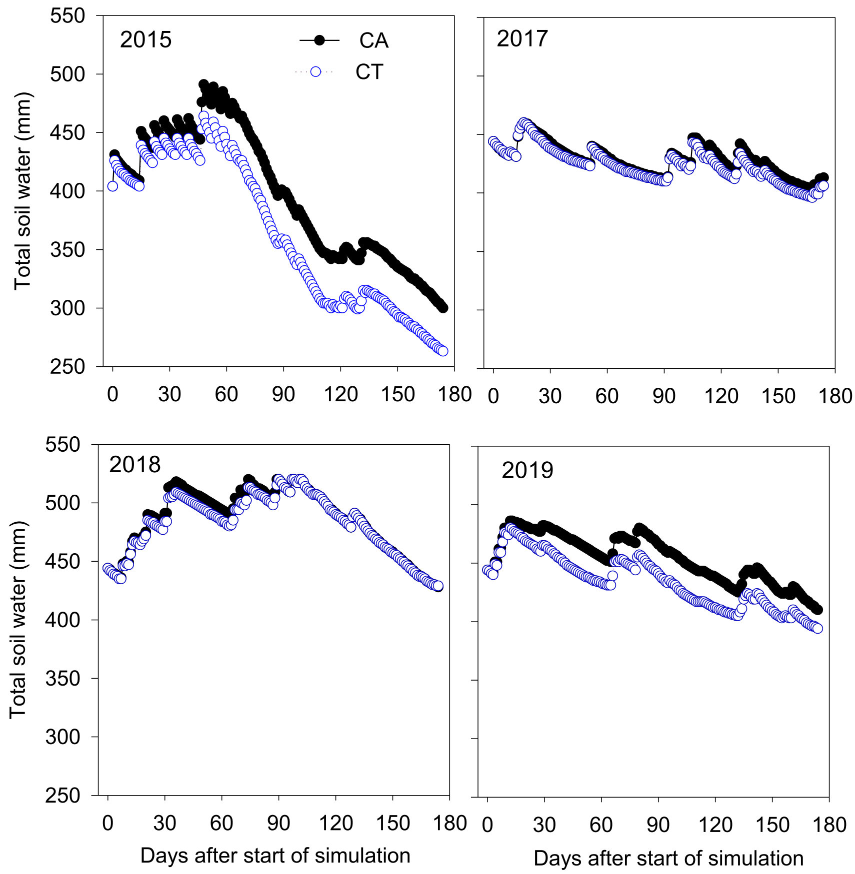

Fig. 8. Simulated total soil water (mm) on top 95 cm soil profile under Conservation Agriculture (CA) and Conventional practices (CT) in wheat during four different growing seasons.

of CA would help to minimize the existing attainable yield gaps for these major food crops in Morocco and similar production environments with Mediterranean rainfed conditions. Findings from a farmers' survey of 1901 households in the major wheat-growing region in Morocco also revealed that adoption of no-tillage practice helps to minimize attainable yield and profit gaps under farmers' management practices in rainfed systems (Devkota and Yigezu, 2020). These authors also highlighted the adoption of no-tillage is the major determinant for closing yield gaps for wheat in rainfed drylands in Morocco.

Comparatively higher PUE (Fig. 4) and soil moisture availability (Fig. 8) under CA compared to CT, especially in low-rainfall growing season, in our experiment indicates that CA can be more resilient in rainfed drylands with variable rainfall. In this region, drought and rainfall variability are expected to be more and is recognized as a "hotspot" for climate change (Driouech et al., 2013). Therefore, agricultural practices such as CA help to capture and utilize the maximum possible available water, which is crucial to sustaining crop production in such environments. In a review study from the Maghreb region, Mrabet et al. (2021) and in MENA (Devkota et al., 2022a, 2022b) summarized that CA systems help to increase uptake, conservation, and use of available soil water by reducing evaporation and runoff, enhancing water distribution in the soil profile, and improving plant-available water-holding capacity and nutrient availability of soils.

Improving SOC, available P, and exchangeable K in top 30 cm soil depth with 4 years of CA practice compared to CT (from the experimental study), and higher SOC content from long-term simulation indicated that soil fertility improves with CA practice in this clay soil of a rainfed Mediterranean climate in Morocco. In agreement with this result, Moussadek et al. (2014) found that after 5 years of CA in Central Morocco, SOC in the top 30 cm had increased by 10% in Vertisol and by 8% in Cambisol compared to CT. Similarly, Mrabet et al. (2001) reported that the CA system significantly improved soil content of total N, available P, and exchangeable K compared to CT in semi-arid regions of Morocco. Most soils in Morocco and the MENA region are low in SOC (<2%) and show declining soil fertility. The decline in soil fertility is mainly associated with poor fertilizer management and intensive soil tillage, which increases soil loss due to wind and water erosion (Mrabet et al., 2001). In this study, untilled soil and retention of crop residue in CA likely led to improved soil fertility indicators compared to tilled soil as observed elsewhere. The FAO estimated that about 71% of Moroccan agricultural soils are degraded and it requires proper conservation measures (Bot and Benites, 2005). However, the improvement in soil quality does not give immediate direct benefit to the farmers adopting CA. The initial incentive such as subsidy on equipment that requires high initial investment; sustainability (especially economic, environment) based cash incentive; carbon sequestration-based incentives; provision for alternative feed and forage for livestock to the farmers on practicing CA; and institutionalization of CA-based production system in the national agricultural research and extension system (Kassam et al., 2019) may help promote its adoption at a larger scale. Previous studies by Bell et al. (2018) and Ward et al. (2016) in Malawai reported that modest subsidies likely increase the adoption of CA practices. From a study on smallholder farmers in Syria Yigezu et al. (2018) found that free access to costly technology components for first-time users increases its adoption. Similarly, a recent study by Devkota et al. (2022a, 2022b) reported that creating policy and institutional incentive mechanisms that create interest, change mindset to make CA in general, and seeding service provision profitable to the private sector—thereby enhancing private sector participation, helps for wider adoption of CA in MENA region.

Chickpea and lentils are the major food legumes in the rainfed Mediterranean region. Cereal mono-cropping is the dominant cropping

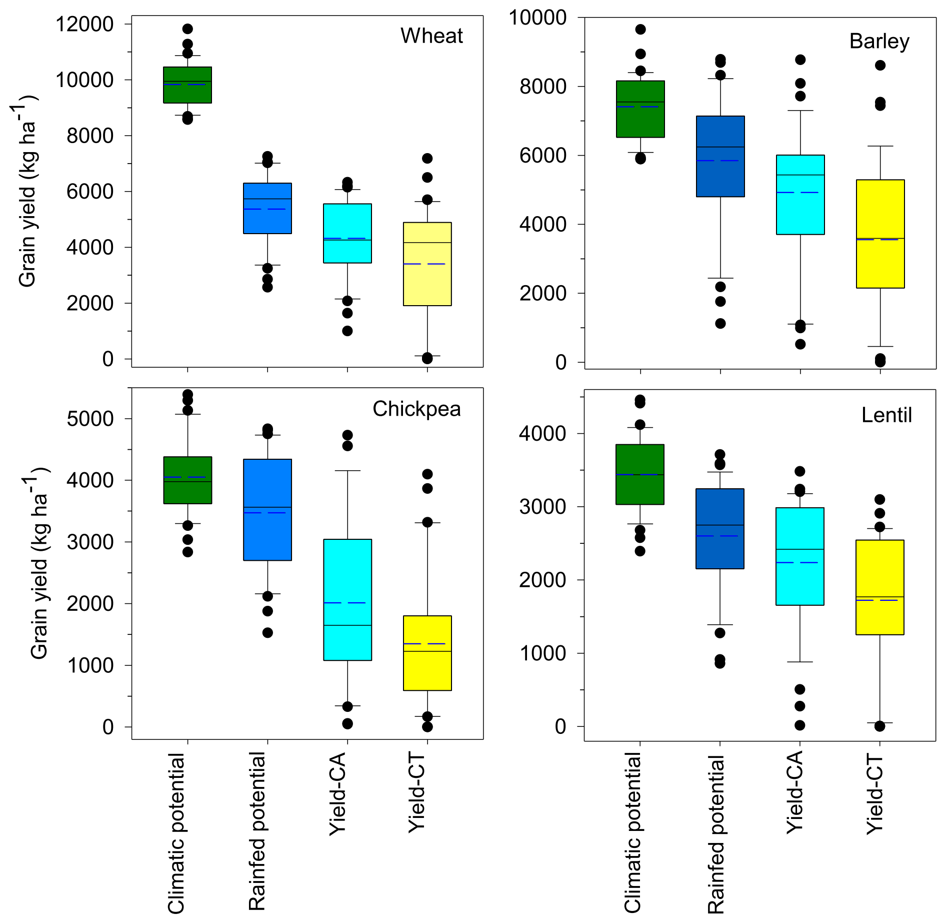

Fig. 9. Long-term (1984–2020) simulated wheat, barley, chickpea, and lentil yield (kg ha^{-1}) under climatic potential, rainfed potential, conservation (CA) and conventional (CT) production systems under rainfed condition in Merchouch, Morocco.

system, with >80% of field crops under cereal-cereal rotation. The inclusion of legumes in the cereal rotation has several benefits: it helps to improve soil health, reduces the amount of fertilizer and insect pest problems, and enhances family nutrition (Yigezu et al., 2019). Despite several benefits and increasing demand, the cultivated area and total production of legumes are decreasing, ultimately leading to a significant increase in the importation of those crops to meet the growing demand (FAOSTAT, 2021). Similar to the higher yield of lentil and chickpea, and significant yield and economic benefits of cereal-legume rotation under CA in this experiment provide evidence that lentil and chickpea under CA have economic benefits in rotation with cereal crops. Also, crop rotation is one of the major principles of CA; hence CA adoption also encourages farmers to grow legumes in rotation which can partly solve the problem of cereal mono-cropping, keeping land fallow and reducing imports in the region. Similarly, in long-term cropping system simulation, the chance of crop failure was lower for cereal-legume rotation compared to cereal-cereal rotation (Fig. 10), indicating that the inclusion of legumes in rotations improves yield stability and resilience of wheat yield compared to cereal mono-cropping especially in dry years.

Several analyses in this study including the trade-off indicated that adoption of CA with cereal-legume rotation leads to increased yield, farm profit, PUE, and soil fertility under variable rainfed environments in Morocco and locations with similar soil and climatic conditions in the MENA region. Hence, CA can be an alternative to the current conventional system in the MENA region, in which about 25–40% out of the 53 Mha of total arable land is estimated to be suitable for CA (Devkota et al., 2022a, 2022b); in Morocco 63% out of ~6.1 M ha is high to moderately suitable for CA (ICARDA, 2021; Moussadek et al., 2016). Despite several benefits of CA, <2% of the area is under CA practices in the MENA region (Kassam et al., 2020). However, >45% of the cropland area under CA in similar soil and climatic condition in Australia shows the possible success of CA at scale in Morocco and the MENA region. Therefore, effort on scaling out CA practice is important for the resilient and sustainable intensification of wheat-based systems in rainfed environments in Morocco and similar agro-climatic conditions in the rainfed Mediterranean environment.

5. Conclusions

A medium-term field experiment and long-term simulation studies suggested that adoption of CA at the individual crop and cropping system (cereal-legume rotation) level improved a range of agronomic, economic, and soil fertility indicators compared to CT in a clay soil with variable rainfall in a rainfed Mediterranean environment. Furthermore, CA adoption has the potential to improve resilience and close the existing yield gaps of the major food crops in the region. Because the MENA region including Morocco, is considered a hot spot for climate change, CA can be an alternative adaptation option to address this issue. However, future research on context-specific bundling of agronomic packages, disentangling the reasons for the slow adoption rate, formulation of policy incentives, and institutionalization of CA practices is required for its adoption at scale. The outcomes from this experimental and simulation study on CA with contrasting rainfall years provide much evidence for the extensionists, policymakers, and farmers to drive its wider adoption in Morocco and similar agro-climatic conditions.

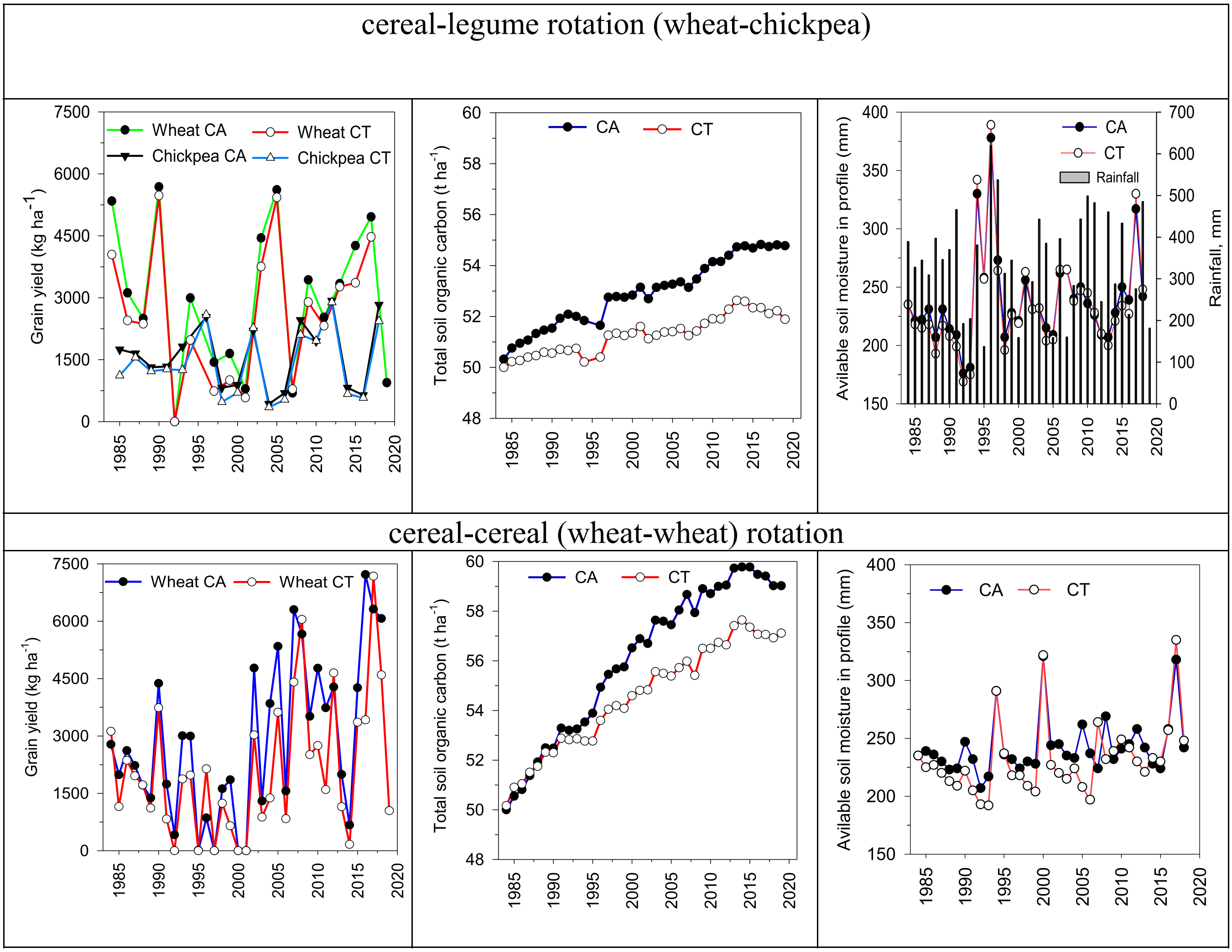

Fig. 10. Long-term (1984–2019) simulated grain yield (kg ha^{-1}), profile soil organic carbon at top 30 cm soil (t ha^{-1}), and available soil moisture in top 95 cm soil profile (mm) in cereal-cereal and cereal-legume crop rotation sequence in rainfed Mediterranean with clay soil in Merchouch, Morocco.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103470.

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