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Climate change and agronomic management: Addressing wheat yield gaps and sustainability challenges in the Mediterranean and MENA regions

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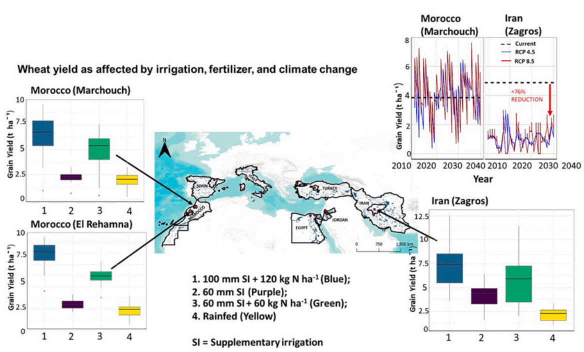
HIGHLIGHTS

- Wheat yields in MENA and Mediterranean may decline by 18–30% under RCP 4.5 and 20–28% under RCP 8.5.
- Irrigation and nitrogen application narrowed yield gaps by 30–50% and improved water use efficiency.
- Precision fertilization is needed as nitrogen losses often surpassed 60 kg N ha^{-1}, impacting sustainability
- Optimal seeding dates (Nov 1–30) maximize yields; reduce yield gap by up to 50%.
- Climate-smart precision agricultural practices are essential to sustain wheat production under climate variability

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Wheat is a crucial crop for food and nutritional security in Mediterranean and MENA regions, yet it faces significant challenges due to high yield variability, low average productivity, and substantial yield gaps. This highlights the urgent need for improved agricultural practices to enhance its productivity and resilience. The region's climate climate change, soil degradation, and water supply variability significantly impact wheat production, requiring innovative and integrated solutions to minimize yield gaps and improve sustainability.
OBJECTIVES: The primary objective of this study is to evaluate the impacts of climate change and agronomic management practices (supplementary irrigation, nitrogen fertilizer, planting date) on wheat yields across diverse agro-ecological zones in the Mediterranean region under current and future climate scenarios.
METHODOLOGY: Using advanced crops modeling DSSAT (Decision Support System for Agrotechnology Transfer) and scenario analysis, wheat yields were simulated under RCP 4.5 and RCP 8.5 climate scenarios for 11 representative sites of 7 countries, for the time periods 2010–2040, 2040–2070, and 2075–2099. Study countries and sites include: Morocco (Rabat-Salé and Marrakech-Safi), Spain (North Aragon), Egypt (Al Garbiyia and North Sinai), Italy (Sardinia), Jordan (Amman and Irbid), Turkey (Ankara and Edirne), and Iran (Zagros). The DSSAT model was calibrated and validated for 11 dominant wheat varieties (one variey per site) to simulate potential

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and attainable yields and the effect of agronomic practices such as supplemental irrigation, nitrogen application, and seeding dates to identify strategies for sustaining productivity across different locations and countries.

RESULTS AND DISCUSSIONS: Wheat yields across all regions are projected to decline by -18% to -20% under RCP 4.5 and RCP 8.5 by 2040, -28% to -27% by 2070, and -30% to -28% by 2099, compared to historical averages. Arid regions, such as North Sinai (Egypt) and Zagros (Iran), are projected to experience severe yield declines of 60–88% by the end of the century under RCP 8.5. Optimal agronomic practices, including supplemental irrigation (60–100 mm) and nitrogen application (60–120 kg ha^{-1}), improved yields by 30–50% (attainable yield exeeding 6 t ha^{-1}) and enhanced water productivity by 25–70%. Optimal seeding dates between November 1st and 30th were identified as critical, while delayed sowing reduced yields by up to 50%. Nitrogen losses exceeded 60 kg N ha^{-1} in regions with high nitrogen application rates.

SIGNIFICANCE: Climate change will lead to substantial yield losses compared to historical baselines, particularly under RCP 8.5, emphasizing the urgency of adaptation strategies and climate action. The study highlights the importance of integrated nutrient and water management for sustainable wheat production in the Mediterranean, offering context-specific agronomic recommendations for improving resilience in wheat production in the Mediterranean region. This study highlights the need to prioritize region-specific, data-driven interventions to sustain wheat production and ensure food security in the Mediterranean and MENA regions under changing climatic conditions.

1. Introduction

As delineated by the Intergovernmental Panel on Climate Change (IPCC) in its 2023 Sixth Assessment Report (AR6), the incontrovertible phenomenon of anthropogenic climate change brings forth a series of consequences worldwide for environmental systems, including agriculture (IPCC, 2023). In the Mediterranean region, where agriculture is vital, extreme weather events like droughts and extreme temperature have reduced crop yields significantly (Brouziyne et al., 2018; Bouignane, 2010). This vulnerability has necessitated policy interventions to enhance agricultural resilience, exemplified by initiatives such as Morocco's Green Morocco Plan (2020−2030) and the European Green Deal, aimed at improving the sustainability of agrarian livelihoods in the face of complex agro-environmental challenges (Sikora, 2021).

Given the Mediterranean's significant climatic variability, the future of wheat production is increasingly uncertain, demanding innovative approaches to ensure food security. Climate predictions for the Mediterranean region indicate significant environmental shifts, with an increase in average temperatures by 1.3 °C and a decrease in annual rainfall by 11 % by 2050 (Balaghi and Dahan, 2015, IPCC, 2023). Historical droughts in the mid-1990s severely reduced cereal production by more than 60 %, impacting the agricultural economy of rural communities (Bouignane, 2010; Lorite et al., 2023). The region's agriculture, mainly consisting of smallholder farms dependent on rainfall for growing cereals, legumes, and livestock rearing, faces challenges of water scarcity and soil erosion, which impact productivity and sustainability (Cammarano et al., 2019). Rainfall variability is the major reason for low and unstable yields, causing wheat yields in the Middle East and North Africa (MENA) region to be less than 2.3 t ha^{-1}, well below the global average of 4.0 t ha^{-1} (Jägermeyr et al., 2021; FAOSTAT, 2020). This disparity highlights the need for localized, science-driven, customized strategies to enhance wheat productivity in these vulnerable regions.

Spatial variability in annual rainfall across different regions results in distinct levels of precipitation, introducing unique agricultural challenges that necessitate targeted interventions (Luppichini et al., 2022). For instance, Morocco faces significant water resource challenges, with one of the lowest per capita water availabilities in arid regions, 730 cubic meters per person per year (Taheripour et al., 2020). Around 1.5 million hectares of Moroccan land are allocated for irrigation, predominantly using gravity systems (47 %), in contrast to sprinkler or drip irrigation methods Royaume du Maroc (2024). This scenario of water scarcity and reliance on inefficient irrigation systems is not unique to Morocco but is a global issue in semi-arid regions. Spain struggles with water scarcity, soil erosion, and increasing temperatures, all of which threaten agricultural productivity (Lorite et al., 2023). Egypt's agriculture heavily depends on the Nile for irrigation, with almost 98 % of its irrigation needs met by the river, facing challenges due to growing demand and declining water availability and soil fertility (Fouad et al., 2023). Italy is also affected by changing precipitation patterns, which influence crop growth and pest dynamics, alongside socio-economic issues in rural communities (Dettori et al., 2017). Jordan's severe water scarcity requires a careful balance between conserving water and maintaining food production (Al-Bakri et al., 2011). Turkey's agriculture is vulnerable to drought, soil erosion, and deforestation, highlighting the need for resilient farming methods (Yeşilköy and Şaylan, 2021). Iran faces challenges of water scarcity, soil salinity, and increasing temperatures, necessitating sustainable water management and adaptive farming strategies (Deihimfard et al., 2018; Eyshi Rezaie and Bannayan, 2012). Consequently, the MENA region is considered the most water-stressed globally, with two-thirds of the countries extracting groundwater faster than it can be replenished. Despite having the world's lowest water prices and spending about 2 % of GDP on water subsidies, the region suffers from low water productivity, only half the global average (World Bank, 2018; Abu-Hashim et al., 2021; Gatti et al., 2023). These challenges underscore the importance of adopting innovative water management practices that can significantly improve crop yields and sustainability in the region especially in the face of rainfall variability and climate change. To address these challenges and ensure sustainable wheat yields across the Mediterranean basin, various practices have been adopted to enhance organic matter (soil health) and water retention in the soil (Devkota et al., 2023; Huang et al., 2023). These include no-tillage and crop rotation with legumes, such as chickpeas and lentils, or the application of nitrogen fertilizers as single treatments (Fernandez-Garcia et al., 2024; Lago-Olveira et al., 2024). However, while these practices have shown promise, their effectiveness under future climate scenarios remains uncertain, necessitating further research that integrates advanced modeling techniques to predict outcomes under different environmental conditions.

The existing literature employs various process-based crop models, including Agriculture Production Simulator (APSIM) (Keating et al., 2003), Soil and Water Assessment Tool (SWAT), Decision Support System Agriculture Tool (DSSAT) (Jones et al., 2003), and ACQUACROP, a crop growth model developed by FAO (Busschaert et al., 2022; Halima et al., 2021; Bouslihim et al., 2016). These models particularly focus on evaluating water productivity and development of water-efficient and resilient good practices and solutions for semi-arid and arid regions. Considering the projected future climate scenarios, there is an anticipated challenge in water availability, necessitating a focus on efficient water use and the implementation of strategies to prevent adverse effects of water scarcity (Unnisa et al., 2022; Devkota et al., 2023). The DSSAT model, in particular, has been employed in the Mediterranean, West Asia, and North Africa (WANA) regions to evaluate different wheat management practices and predict crop yield. It has been used to investigate a variety of crop management practices such as planting dates, choice of cultivar, irrigation practices, and nitrogen fertilizer management (Bai and Gao, 2021; Hoogenboom et al., 2023). DSSAT model is recognized for its ability to simulate crop growth, development, and yield at the plot and landscape level by accounting for weather conditions, management practices, and changes in soil water, carbon, and nitrogen levels over time. The DSSAT version, 4.8.2, is capable of simulating more than 42 different crops, using inputs such as daily weather data, initial soil conditions, soil profile characteristics, comprehensive management practices, and specific cultivar coefficients (Hoogenboom et al., 2023; Jones et al., 2003). The model has proven effective in predicting potential yields of wheat, especially in terms of optimizing irrigation schedules and nitrogen fertilizer management, as demonstrated in studies by Gameh et al. (2020).

Climate change poses a significant threat to crops like wheat and barley, with significant negative impacts on their yield and resilience. Research using the DSSAT model has extensively analyzed yield responses under various climate scenarios across the Mediterranean and MENA regions (Malik and Dechmi, 2019; Cammarano et al., 2019; Kheir et al., 2021). Also, simulation model has been used to understand how different wheat genotypes withstand prolonged unfavorable conditions and to analyze the effects of climate variability on productivity (Devkota et al., 2022a, 2022b; Mamassi et al., 2023; Ishaque et al., 2023). A notable concern is the observed yield gap in wheat production within the MENA region, attributed to factors like diminishing rainfall patterns (Caloiero et al., 2018; Luppichini et al., 2022). Egypt's situation is particularly critical due to its dependence on the Nile Delta for irrigation and the heavy reliance on nitrogen fertilizers, which presents increasing challenges for nutrient use efficiency (NUE) (Elrys et al., 2019). Countries in the Mediterranean and MENA regions face significant challenges with water scarcity and efficient use of water resources, further compounded by soil erosion that diminishes crop yields over time. Consequently, the primary objectives of this study are to: (i) identify and analyze the major production drivers (e.g., nutrient, water use, seeding date) affecting wheat yield and yield gaps across diverse agroecological zones; (ii) evaluate the impact of supplementary irrigation and nitrogen fertilization on narrowing yield gaps, improving water productivity, and minimizing environmental risks such as nitrogen losses; and (iii) assess the effects of climate change under RCP 4.5 and RCP 8.5 scenarios on wheat yields, inter-annual variability, and resource use efficiency in the MENA and Mediterranean regions. By integrating crop modeling with localized climate scenarios, this study aims to identify region-specific, climate-smart agricultural practices to sustain wheat productivity, ehnance resource efficiency, and address the challenging climate variability and resource scarcity.

2. Materials and methods

2.1. Description on study location and its soil and climatic characteristics

This research involved modeling wheat growth and yield using an experimental dataset collected from peer-reviewed published papers from different agroecological zones of Mediterranean countries (Table 1). Given the critical role of wheat in the Mediterranean diet, the study employed DSSAT crop simulation model CSM-CERES-Wheat to simulate its response as affected by soil and climatic conditions across Mediterranean countries. These included Morocco (specifically, the Rabat-Salé and Marrakech-Safi regions), Spain (in the North Aragon area), Egypt (covering Al Garbiyia and North Sinai), Italy (Sardinia), Jordan (Amman and Irbid regions), Turkey (Ankara and Edirne), and Iran (the Zagros region). Country wise detail soil and climatic parameters used for simulation is presented in Table 1 and Fig. 1.

2.1.1. Morocco

In a comprehensive study by Devkota et al. (2023a), the multi-year on-station experiment was conducted at the International Center of Agriculture Research in Dry Areas (ICARDA) experimental field in Marchouch, Morocco (33°36" W, 390 m asl). This location, located approximately 75 km east of Rabat, recorded an average annual rainfall of 451 mm over the 37 years from 1987 to 2023, with yearly variations ranging from 181 to 665 mm, a coefficient of variation (CV) of 35 %. The mean annual air temperature is 19 °C, with monthly minimum and maximum temperature ranges of 10–15 °C and 20–30 °C, respectively.

Table 1

Climate and soil characteristics of seven countries and eleven sites used for model calibration and validation. Data source NASA Power Project (2023) for climate, ISRIC (Batjes et al., 2024) for soil, and review of the published literatures.

Country	Site	Latitude e Longitude	Annual precipitation (mm) ± Coefficient of variation (%)	Average annual temperature (°C)	Average maximum temperature (°C) ± CV (%)	Average minimum temperature (°C) ± CV (%)	Soil class (FAO Taxonomy)	Sand (%)	Silt (%)	Clay (%)	SOC (%)	Soil pH
Turkey	Ankara-Ikizce	39.36N-32.40E	(377±18)	11 °C	(18±54)	(5±142)	Cambisols	12.1	37.7	50.1	0.48	8.2
	Edirne	41.68N-26.55E	(571±24)	14 °C	(20±48)	(7.7±94)	Cambisols	44.7	24.28	31	0.67	6.9
Jordan	El Mashuqqer	31.77N-35.80E	(267±30)	22 °C	(29±27)	(14±41)	Chromic Luvisol	8.8	36.8	54	0.96	7.9
	Irbid	32.64N-35.57E	(367±27)	21°C	(28.9±27)	(13±44)	Vertisol	8	45.98	53	0.37	8.1
Morocco	Marchouch	33.61N-6.71W	(451±35)	19 °C	(26± 23)	(13±36)	Vertisol	11.4	41.00	47.60	1.13	7.6
	El-Rehamna	32. 3 N-7.97W	(363±35)	21 °C	(27± 23)	(13±38)	Eutric Regosol	59.8	18.5	21.75	0.77	8.5
Egypt	North Sinai	31.08 N-33.49E	(121±52)	21 °C	(25±21)	(17±30)	Calcaric Regosol	34.3	39.65	26.1	0.32	8
	Tanta	30.8N-31.1E	(62±98)	23 °C	(30±23)	(15±34.7)	Vertisol	34.1	21.4	44.4	0.7	7.8
Italy	Ussana	39.24N-9.5E	(499±44)	18 °C	(20±27)	(16±31)	Vertic Cambisol	56.4	21.5	22.1	0.83	7.9
Spain	Violada	42.04N-0.40E	(476±21)	14 °C	(32±57)	(10±229)	Gypsic Haploxerept	31.5	40.3	28.3	0.56	7.8
Iran	Zagros	32.20N-50.14E	(229±44)	16 °C	(22±45)	(9.5±81)	Calcaric Regosol	15	30	55	0.96	8

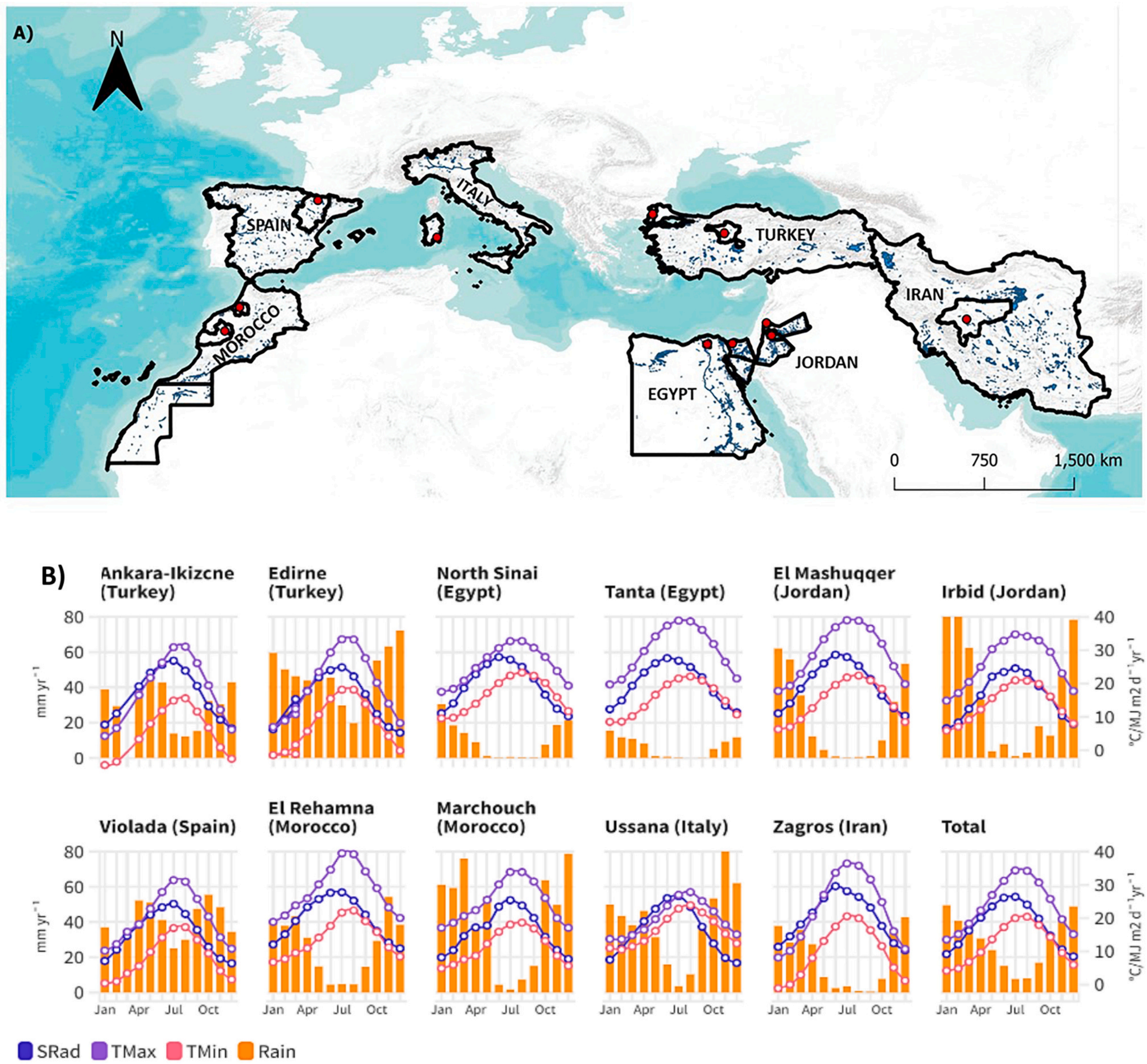

Fig. 1. Study sites location (red dots) and national boundaries in black (A). The climate characteristics of the study sites showing solar radiation (SRad, blue), maximum temperature (Tmax, purple), minimum temperature (Tmin, pink), and amount of rainfall (Rainfall, orange) from the long-term average (1986–2023) (B). Data source: NASA Power Project (2023).

The soil at this site is classified as a Vertisol with a clay-loam texture, comprising 47.6 % clay and 41 % silt, with medium soil organic carbon (1.1–1.65 %) and a soil pH range of 7–7.9.

Second site El-Rehamna Province lies in Marrakesh Safi region in Central Morocco (Briak and Kebede, 2021). This province, representing 16.81 % of Morocco's farmland, experiences variable climate conditions. Over a 7-year study period from 2013 to 2019, the mean annual rainfall in El-Rehamna was 168 mm, with precipitation concentrated in November (42.24 mm) and minimal in July (0.2 mm). The annual average daily maximum and minimum temperatures were 27.03 °C and 13.0 °C, respectively. The soil in El-Rehamna is predominantly sandy clay loam, reddish-brown in colour, with alkaline pH and moderate levels of nitrogen and cation exchange capacity (Briak and Kebede, 2021).

2.1.2. *Spain*

In Spain, the experimental data of Malik and Dechmi (2019) from the Violada Irrigation District in Northeast was used to simulate wheat yield. This site is located in the Ebro River basin, covers an area of 5231 ha. Soils in the experimental site were classified as Typic Xerofluvent fine-silty and Gypsic Haploxerept (Malik and Dechmi, 2019). The location has Mediterranean climate characterized by concentrated precipitation in spring and autumn. The mean annual precipitation value recorded at the nearest meteorological station of Tardienta (for the years 2005–2017) were 361 mm (Malik and Dechmi, 2019). In this study (Table 1), for the years 1986-2023, the mean annual precipitation was 476 mm (with a CV of 21%). The mean temperature was 14 °C, with the hottest month being July (mean temperature of 38 °C) and the coldest month December (mean temperature of −5.6 °C) (Table 1).

2.1.3. *Italy*

In Italy, experimental data from the study conducted by Dettori et al. (2017) was used. The location,Ussana (39.24N-9.5E) experimental farm of San Michele in Southern Sardinia was used for simulating durum wheat. Ussana has the Mediterranean climate with warm and dry summers and mild winters. The Ussana site, located in a hilly area, features sandy clay loam soil with a sand exceeding 50 %, and according to the FAO taxonomy soil is a Vertic Cambisol. The average annual temperature was 18 °C (Table 1), the hottest month being August (mean temperature of 28 °C) and the coldest month January (mean temperature of 11 °C). Furthermore, the average rainfall trend in the last thirty years corresponds to about 499 mm mm with a coefficient of variation of 44 %.(Table 1).

2.1.4. Turkey

Data from the experiment conducted by Yeşilköy and Şaylan (2021) at Edirne, Northwestern Turkey in winter wheat during 2014–2018 was used for model calibration. The second dataset used were from the field trials conducted at the Ankara-İkizce Research Farm (Aydoğlu, et al., 2023). In Edirne, the long-term average temperature was 14.0 °C and annual precipitation of 571 mm (Table 1). The experimental site Ankara-Ikizce had an average temperature of 11 °C and annual precipitation of 377 mm (Table 1). The predominant soil is silty-clayey with 0.48 % and 0.67 % soil organic carbon, respectively in Ankara-Ikizce and Edirne (Aydoğdu et al., 2023).

2.1.5. Jordan

Two sites, El Mashuqqer and Irbid were chosen in Jordan. Field experimental data conducted by Al-Bakri et al. (2011, 2021) at Irbid (32.64N 35.57E) and by Elgadi (2020) at El-Mushaqqer Agricultural Research Station Southwest Amman (31°46′24.7″ N, 35°47′47.3″ E, 800 m above sea level) were used. Jordan's part of the Yarmouk River basin has the semi-arid Mediterranean ecosystem (Al-Bakri et al., 2011, 2021). According to the FAO taxonomy, the soils are Chromic Luvisol and Vertisol, with an higher value of clay and sand. The region experiences variable rainfall and temperature gradients, with mean annual minimum and maximum temperatures ranging from 13 °C to 29.0 °C. The average annual temperature is 21 °C and the coefficient of variation correspond to the 44 %. The hottest month being July (mean temperature of 29 °C) and the coldest month December (mean temperature of 11 °C). The average rainfall trend in the last 37 years corrsesponds to 367 mm with a variance of 27 % in Irbid and 267 mm with coefficient of variation of 30% in El Mashuqqer.

2.1.6. Egypt

Data from the experiments reported by Fayed et al. (2015) and Kheir et al. (2021) from experimental sites of Suez Canal University in North Sinai, Egypt (31°08′04.300 N, 33°49′37.200 E), and in the middle Delta of Egypt, Tanta (30.8 N, 31.0 E) were used. Those experiments had used bread wheat cultivar. These regions experiencing variable rainfall and temperature gradients, with mean annual minimum and maximum temperatures ranging from 15 °C to 30.0 °C. The average annual temperature is 22 °C with the coefficient of variation of 21-30 %. The hottest month being July (mean temperature of 30 and 25 °C) and the coldest month January (mean temperature of 15 and 17 °C). The average rainfall trend in the last 37 years corrsesponds to 62 mm and 121 with a variance of 98 % and 52%. Soils of the experimental sites were Calcaric Regosol and Vertisol, with an higher value of silt and sand in North Sinai and silt and clay in Tanta.

2.1.7. Iran

Data from experiments reported by Dokoohaki et al. (2015) conducted at Zagros, Southwest Iranwere used in this study. Soil of the experimental site was Calcaric Regosol with an higher value of silt and sand. The experimental area, characterized by the topography and climatic conditions, experiences a long-term average annual precipitation of 229 mm with rainfall variability of 44%. This precipitation is primarily concentrated in the winter and spring months, and influences vegetation growth. The average annual temperature is 16 °C and the coefficient of variation correspond to 45-81 %. The hottest month being July (mean temperature of 22 °C) and the coldest month January (mean temperature of 8.87 °C).

2.2. Model input and crop management data

All experimental data required for the calibration and evaluation of DSSAT model were gathered from a comprehensive review of papers by Al-Bakri et al. (2011), Aydoğdu et al. (2023), Briak and Kebede (2021), Devkota et al. (2022a, 2022b, 2023a), Fayed et al. (2015), Kheir et al. (2021), Yeşilköy and Şaylan (2021), Dettori et al. (2017), Dokoohaki et al. (2015), Elgadi (2020), Malik and Dechmi (2019), and Moradi et al. (2022), who conducted experiments in wheat in those 7 countries. Input data required for model calibration such as irrigation amount and application method, fertilizer rate, source and time of application, planting date, variety, and initial conditions in these respective experiments were reviewed and tabulated (Table 2). Most of these studies provided detail information on growth and yield, such as aboveground biomass, leaf area index, days to emergence, days to flowering, and days to maturity.

In Morocco, wheat was seeded at the spacing of 20 cm, with seed rates adjusted to 300 seeds m^{-2}. Sowing was from November 15 to 20 in each year. Basal fertilizer of 50:22:42 kg of N, P, and K ha^{-1} were applied during precipitation events to enhance nutrient uptake. In Marchouch, supplemental irrigation ranging from 55 to 100 mm ha^{-1} were aplied via drip irrigation, while in Rehamna, it was 120 to 200 mm ha^{-1} using the drip irrigation(Table 2). Crop was harvested on June 1st in both locations (Briak and Kebede, 2021; Devkota et al., 2022a, 2022b).

In Violada Irrigation District, northeast Spain, irrigation management was evaluated by comparing actual farmer practices with optimal scenarios. This study had different fertilizer rates applied and wheat was sown using no-tillage practices at density of 560 seeds m^{-2}. Crop was harvested on June 21st (Malik and Dechmi, 2019). Similarly, long-term (1973–2004) durum wheat agronomic management data were sourced from Italian Durum Wheat Variety Trials, Ussana, Italy (Table 2). In this experiment, wheat was seeded using 350 seeds m^{-2} with 18 cm row-row spacing, planted on 04 December, and harvested on 30 June (Dettori et al., 2017). In Ankara-İkizce Research Farm, Turkey, nitrogen application rates (60 and 120 kg ha^{-1}) were compared. Fertilizer DAP was used as base and ammonium nitrate for topdressing in April, where the crop was planted on October 24th in Ankara and October 20th in Edirne, with a density of 400 seeds m^{-2} at 16 cm row-row distance, and crop was harvested on 20 June (Aydoğdu et al., 2023; Yeşilköy and Şaylan, 2021).

Wheat yield data from Irbid Governorate in Jordan from 2006 to 2016 were gathered from the Department of Statistics in Amman (Table 2). The crop was sown at a density of 300 seeds m^{-2} with a spacing of 16 cm between rows. Two distinct planting date experiments were conducted: one in El Mashuqqer, where wheat was planted on 15 November and another in Irbid, where it was planted on February 1st (Al-Bakri et al., 2011; Elgadi, 2020). In Egypt, seed rate of 300 seeds m^{-2} was used in both North Sinai and Tanta and the crop was harvested on 23 April and May 15, respectively (Fayed et al., 2015; Kheir et al., 2021). In Iran, wheat was planted in a field with adequate water and nitrogen fertilization rates of 60 and 120 kg ha^{-1} were applied with diammonium phosphate (DAP) and ammonium nitrate fertilizers (Table 2). Seeding density was 300 seeds m^{-2} and row-row spacing of 15 cm, planted on 11 November and harvested on 20 July (Deihimfard et al., 2018; Dokoohaki et al., 2015; Moradi et al., 2022). Detail crop production and management practices are summarized in Table 2.

2.3. Climatic data

The historical daily weather data of 37 years (1986–2023) for all locations (Northern Morocco, Spain, Italy, Jordan, Egypt, Turkey, Iran; as provided latitude and longitude of the experimental site) were derived from NASA, AgCFSR (https://data.giss.nasa.gov/impacts/agmipcf/agcfsr/) climate dataset. The daily climatic data comprised of maximum and minimum temperatures, solar radiation, and rainfall.

Table 2
Location, irrigation amount and fertilizer management practices and yield of wheat in the study sites (data extracted from review of 12 papers).

Country	Location	Irrigation amount (mm)	Nitrogen fertilizer rate (kg ha^{-1})	Planting date	Grain yield (kg ha^{-1})	References
	Marchouch	0	50	15-Dec	3000	Devkota et al., 2022a, 2022b; Devkota et al., 2023
		100	50	15-Dec	3100	
		60	60	15-Dec	5250	
		100	120	15-Dec	6410	
Morocco	El Rehamna	100	50	4-Dec	3500	Briak and Kebede, 2021
		120	50	4-Dec	4800	
		120	60	4-Dec	7000	
		200	120	4-Dec	7800	
	North Sinai	100	25	15-Oct	5000	Fayed et al., 2015
		140	50	15-Oct	5500	
		140	120	15-Oct	7000	
Egypt		240	180	15-Oct	7500	
	Tanta	100	140	15-Nov	3500	Kheir et al., 2021
		140	140	15-Nov	4500	
		140	120	15-Nov	7000	
		240	180	15-Nov	7500	
Turkey	Ankara -Ikizcne	0	50	15-Nov	2000	Aydoğdu et al., 2023
		100	50	15-Nov	3500	
		55	60	15-Nov	5500	
		100	120	15-Nov	6500	
	Edirne	0	50	24-Oct	5000	Yeşilköy and Demir, 2023; Yeşilköy and Şaylan, 2021
		100	50	25-Oct	5250	
		55	60	25-Oct	5750	
		100	120	25-Oct	7250	
Jordan		0	100	20 Oct	4500	Al-Bakri et al., 2011;
	Irbid	140	100	20 Oct	5000	Department of Statistics of Amman
		140	60	20 Oct	6110	
		240	120	20 Oct	7150	
		0	60	1 Feb	4000	Elgadi, 2019; Department of Statistics of Amman
	El Mashuqqer	140	100	1 Feb	4500	
		140	60	1 Feb	6000	
		240	120	1 Feb	7500	
Iran	Zagros	0	50	11-Nov	2200	Dokoohaki et al., 2015; Moradi et al., 2022; Deihimfard et al., 2018
		120	60	11-Nov	4250	
		120	80	11-Nov	4750	
		200	120	11-Nov	5250	
Spain	Violada District (Aragon)	0	50	29-Nov	4350	Malik and Dechmi, 2019
		100	60	29-Nov	5000	
		55	60	29-Nov	6000	
		100	120	29-Nov	7500	
Italy	Ussana (Sardinia)	0	60	4 -Dec	3000	Dettori et al., 2017; Martiniello, 2012
		100	60	4 -Dec	4500	
		55	90	4 -Dec	5250	
		100	120	4 -Dec	9000	

For the climate change projections, daily data were derived from Representative Concentration Pathways (RCPs) 4.5 and 8.5 from the MIROC5 (Model for Interdisciplinary Research on Climate, Version 5) pathway developed by the University of Tokyo for three time periods by the year 2100 (i.e., 2010–2040, 2040–2070, 2075–2100). Therefore, RCP were selected given the objective to determinate the impact of climate change on crop growth and yield that allows for developing forward-looking adaptation strategies. This general circulation models (GCM) was selected because it is widely used for modeling crop, soil, and water management practices. Those data were sourced from the MARKSIM DSSAT weather file generator (https://gisweb.ciat.cgiar.org/MarkSimGCM/#), a CGIAR tool used to create weather files for the DSSAT model (http://www.ipcc-data.org/ ar5/gcm_data.html).

2.4. Soil data

Soil data were extracted from both the cited literature complemented with ISRIC world soil database (https://data.isric.org/geonetwork/srv/eng/catalog.search#/metadata/a2379a76-4919-44c1-863e-90504b76ee10) for the missing parameters. Soil data collected comprises soil water content, wilting point, field capacity, saturation percentage, drainage and runoff factors, root growth factor, evaporation, and soil albedo.

2.5. Conceptual framework

CSM-CERES-wheat model of DSSAT Version 4.8 (Hoogenboom et al., 2019a, 2019b, Ritchie et al., 1998) integrates soil, weather, and crop datasets to simulate multi-year above- and under-ground crop-soil-water-climate related parameters under diverse crop management practices (Fig. 2). It has a dynamic feature which accounts for the interactions between crops, soil conditions, weather variations, and management practices.

2.5.1. Model calibration

Essential data for calibrating and validating the model such as soil characteristics, daily weather data, cultivar characteristics, and crop management practices were collected from the reviewed literature. Critical soil characteristics derived from those reviewes papers include bulk density, drainage water content at saturation and permanent wilting point, the proportion of sand, silt, and clay, pH, nitrate and ammonium content, and soil organic carbon content, and the missing information were filled from ISRIC soil database. Crop management practices such as irrigation (rates, amount, method, and dates), fertilization (rates, date, application method, and source), planting information (date, depth, geometry, and density), initial soil water and nitrogen levels, initial residue amount, planting date, harvesting date, harvesting method were mostly reported in those paper, and the missing information was filled using FAO Crop Calendar for the particular country (https://cropcalendar.apps.fao.org/#/home). During model calibration, cultivar specific parameters such as vernalization, photoperiod, thermal time, kernel number per unit, kernel growth rate, maximum stem dry weight, and phyllochron interval were derived for each variety for each region/country.

2.5.2. Model validation

The process of model evaluation includes fine-tuning of 7 genetic coefficients (P1V, P1D, P5, PHINT, G1, G2, and G3) (Table SI 3) to match with measured outputs in the study area (Oreskes et al., 1994, Mehrabi and Sepaskhah, 2020). The data collected from non-stress treatment were used (Table 2). The 'trial and error' or manual calibration method, commonly employed with the DSSAT model (Seidel et al., 2018), was used until a satisfactory match between measured and simulated crop parameters (grain yield and vegetative biomass) was achieved. Additional tools within the model, i.e., GENCALC (Genotype Coefficient Calculator) and GLUE (Generalized Likelihood Uncertainty Estimation) were also employed to refine phenological outputs (Jha et al., 2022). Model performance was assessed using coefficient of determination (R^2), root mean square deviation (RMSE), normalized root mean square deviation (nRMSE), and Wilmott index of agreement (d-stat) as:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{I}$$

Where, the normalized RMSE (nRMSE) was expressed as the ratio

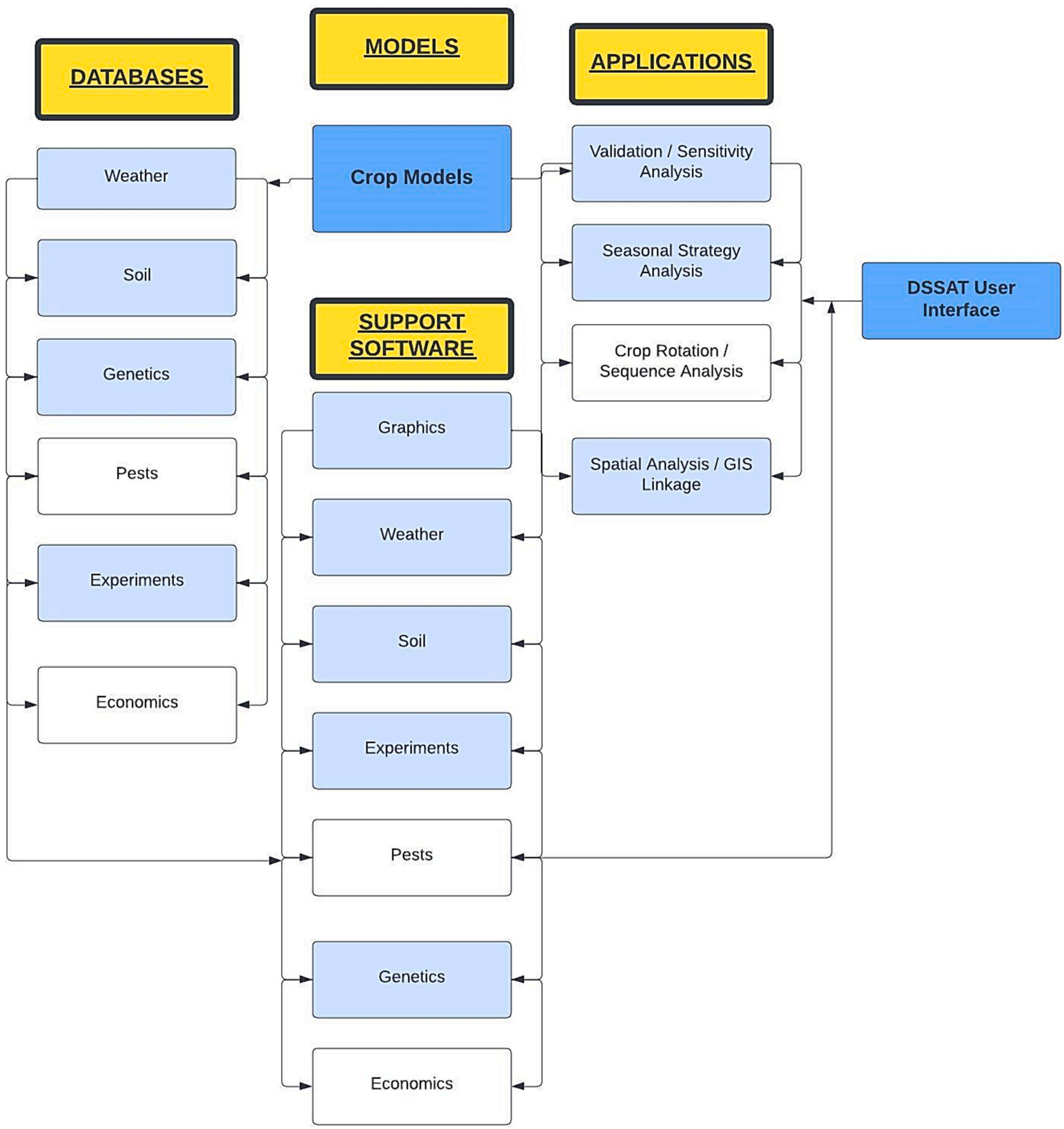

Fig. 2. Schematic representation of the database, application, and support software components and their integration with the DSSAT model (Jones et al., 2003).

between the RMSE and the average of the observed data and n = the number of observations, yi = actual/observed values, and xi = the predicted values. The model simulations were considered excellent, good, fair, and poor based on the nRMSE values of <10 %, 10–20 %, 20–30 %, and > 30 %, respectively, which were proposed by Kadiyala et al. (2015).

$$nRMSE = \frac{RMSE}{\overline{\sigma}} \times 100 \quad \text{(II)}$$

Where, σ¯ is the mean of standard deviation of the observed data. Finally, the index of agreement or d-stat (Willmott, 1982) was computed as follows:

$$d - stat = 1 - \frac{(yi - xi)2}{((|yi - \overline{y}| + |xi - \overline{x}|)2} \quad \text{(III)}$$

The coefficient of determination (R^2) of the linear regression was calculated between the simulated (x) —observed (y) values. The d-stat was developed by Willmott (1982) as a standardized measure of the degree of model prediction error which varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all (Willmott, 1982).

2.5.3. Model application

The calibrated and validated model was used to explore, a) climatic potential, water-limited and nutrient (nitrogen)-limited yield; b) explore seeding dates; and c) assess the impact of climate change in wheat yield. For the 1st applicaiton, model run for long-term (1986-2023) undere five treatments, T1) rainfed; T2) 60 mm supplementary irrigation; T3) 60 mm supplementary irrigation + 60 kg N ha^{-1}; T4) 100 mm supplemenary irrigation + 120 kg N ha^{-1}; and T5) climatic potenital yield. For the 2nd application, model run from 1st October to 1st of January at 15 days interval (7 seeding dates) in all 7 countires and ll sites. For the 3rd application, model run under three climatic conditions (historical, RCP 4.5 and RCP 8.5).

2.6. Climate change scenario analysis

Among different climate change scenarios, representing the possible average climatic conditions around the year 2100 (White et al., 2011), three time periods by the year 2100 (i.e., 2010–2040, 2040–2070, 2075–2100) were chosen for simulating the yield of wheat as affected by the long-term effect of climate change. Those three scenarios were based on the monthly temperature and precipitation projections of GCMs. Model run for RCP 4.5 (temperature changes of +1.5 °C) and RCP 8.5 (more than +2.5 °C). Changes in rainfall of 10 % and 20 % were incorporated in combinations with each level of the temperature increase. The effect of CO_2 fertilization was considered in all three conditions adjusting the yearly CO_2 increment rate.

2.7. Statistical analysis

Statistical analyses were conducted to determine the effect of irrigation, fertilization, seeding date, and climate change on yield of wheat across different locations of Mediterranean region. Simulated grain yield, total (irrigation and rainfall) water productivity (kg grain mm^{-1} water), crop water productivity (kg grain mm^{-1} evapotranspiration), nitrogen uptake (kg N ha^{-1}) and nitrogen losses (kg N ha^{-1}) in each of the the four treatment combinations in all countries and sites were computed and analyzed using analysis of variance (ANOVA). Annual nitrogen loss for all countries and sites were computed by adding simulated leaching, denitrification, and immobilization losses. In time series climate data, averages and the coefficient of variation (CV, %) are calculated to identify trends in the region and site. To better assess the efficiency of the treatments on the crop, the coefficient of crop water productivity (Chai et al., 2014) was computed and expressed as kg ha^{-1} mm^{-1} evapotranspiration. The combined use of descriptive statistics such as mean, median, standard deviation, coefficeint of variance, RMSE, nRMSE, R^2 were computed to investigate the effect of different treatments (scenarios) on simulated yield.

3. Results and discussion

3.1. Characterization of wheat production

Table 2 summarizes the average yield of wheat reported in reviewed papers across rainfed and irrigated conditions with different nitrogen rates and irrigation amount. Wheat yields across the Mediterranean sites showed significant increases with higher irrigation and nitrogen application. Rainfed conditions with low nitrogen consistently resulted in lower yields, such as 2.0–3.0 t ha^{-1}, while combined irrigation (up to 240 mm) and high nitrogen rates (120–180 kg ha^{-1}) achieved yields as high as 7.5–9.0 t ha^{-1}. It is noteworthy that yields increased by over 50% when irrigation was paired with optimal nitrogen. This analysis highlights the effectiveness of tailored integrated water-nutrient practices for maximizing wheat productivity in water-scarce regions.

3.2. Model calibration and validation

The model's prediction of P1V like (Saberali et al., 2022; Malin Grosse-Heilmann et al., 2024; Feng et al., 2024) highlighted that P1V ranges from 19 to 150 days, irrespective of climate type. The photoperiod coefficient (P1D) was determined within the range of 2 to 48 %, a range consistent with other studies that reported P1D values ranging from 30 % to 70 % (Saberali et al., 2022; Feng et al., 2024). Following the sensitivity observed in P1V, the model's prediction of maturity date was notably responsive to variations in P1D (Saberali et al., 2022; Feng et al., 2024). The grain-filling duration (P5) for wheat varieties ranged from 168 to 992 degree-days, while the coefficients for kernel number (G1) spanned from 17 g to a maximum of 55 g. Additionally, the kernel weight coefficient (G2) ranged from 10 to 80 mg day^{--1}, and the optimal value for the spike number coefficient (G3) was set within the interval of 1.5 to 8 g (Supplementary material, Table 2). Comparisons with previous studies indicated variability in G1 values between 15 and 50 kg^{--1} globally, and G2 values reported by various authors ranged between 36 and 76 mg (Saberali et al., 2022; Malin Grosse-Heilmann et al., 2024; Feng et al., 2024). The optimum value for PHINT, representing plant height, fell within the range of 30 to 120 for the wheat varieties (Supplementary material, Table 2).

The simulation of grain and vegetative biomass in 11 sites from 1986 to 2023 demonstrated strong linear relationships between simulated and observed yields. Aboveground biomass weight showed higher R^2 (0.92) values and lower RMSE compared to grain yield (0.91) (Fig. 3; Supplementary material, Table 3 and 4). The nRMSE values were 7 % for vegetative biomass and 6 % for grain yield across all locations. Deihimfard et al. (2018) and Moradi et al. (2022) reported successful simulation of wheat yield, with this study aligning closely with an RMSE of 540 kg ha^{-1} and an nRMSE of 7 % (Fig. 3; Supplementary material, Table 3 and 4). Discrepancies in results may arise from model calibration using literature review data and incorporation of diverse datasets from various studies and time (Fig. 4).

Compared with previous studies, an improvement in DSSAT calibration was observed when using replicated experimental data to modify genotype coefficients (Fig. 3). The RMSE for wheat grain yield decreased from 476 kg ha^{-1} to 413 kg ha^{-1} (Al-Bakri et al., 2011; Devkota et al., 2022a, 2022b). Trends of simulated grain yields were similar with measured, with minor differences in standard deviations and coefficients of variation. Differences between simulated and observed yields were expected, considering variations in soil and crop management practices.

3.3. Simulated potential yield

Long-term simulated grain yield captured yearly variations, with the lowest yield occurred in the driest years (1999, 2000, 2002, 2008, 2009, 2014, 2017, 2019, 2021), while the wetest year (2015) had the highest averaged potential yield of more than 12 t ha^{-1}. The average climatic potential yield varied from 7.6 to 12.0 t $ha^{-1.}$ The averaged rainfed yield (except El Mushaqqer, Jordan, El Rehamna, Morocco, and North Sinai and Tanta, Egypt) ranged from 1.5 to 5.3 t ha^{-1} (Fig. 4). With 60 mm supplementary irrigation, the averaged yield increased to 4.4 t ha^{-1} (18% increment). In addition to 60 mm supplementary irrigaiton, with 60 kg N ha^{-1} yield increased to 5.8 t ha^{-1} (31% increment). Compared to sub-optimal irrigation and fertilizer (T3), T4 increased yield by 20%. These results showed a significant water and nutrient limited yield gap, which varies across the country and sites; indicating a substantial impact of region-specific management practices and tailored agronomic interventions in optimizing wheat production. Simulation results, aligned with experimental data, demonstrated increased grain yields for all wheat varieties with irrigation and higher fertilization rates, approaching the potential yield. The average long-term simulated potential grain yields surpassed treatments with high irrigation and fertilization practices (T4) by 56 %, T3 by 43% and T2 by 31%, indicating a potential reduction in yield gaps through better water and nutrient management. These findings suggest that strategic enhancements in irrigation and fertilization practices could significantly narrow yield gaps, particularly in regions where these inputs are currently suboptimal.

It's noteworthy that in some countries, water constraints, such as in, Jordan, Morocco, and Southern Italy, seem to define the yield gap. In contrast, in Turkey and Iran, the trend suggests issues with management practices, as a reduction in irrigation and/or nutrients did not result in significant differences in attainable yield. This differential response highlights the importance of region-specific irrigation approaches, where water availability is a limiting factor, while in other areas, optimizing management practices could lead to substantial yield improvements.

3.3.1. Site-specific simulated yield under different irrigation and nitrogen

The 37-year average yields of the wheat varieties in good year under rainfed conditions, as assessed in this study, are as follows: 3.06 t ha^{-1} (Turkey), 4.4 t ha^{-1} (Jordan), 5.07 t ha^{-1} (Spain), 3.14 t ha^{-1} (Morocco), 5.29 t ha^{-1} (Italy), and 2.17 t ha^{-1} (Iran). Considering yield variability, it is essential to examine their performance under supplemental irrigation using furrow or drip irrigation systems and different rates of N fertilizers. The resulting yields with supplementary irrigation increased substantially and were 3.26 t ha^{-1} (Turkey), 5.3 t ha^{-1} (Jordan), 5.5 t ha^{-1} (Spain), 5.4 t ha^{-1} (Morocco), 5.6 t ha^{-1} (Egypt), 6.16 t

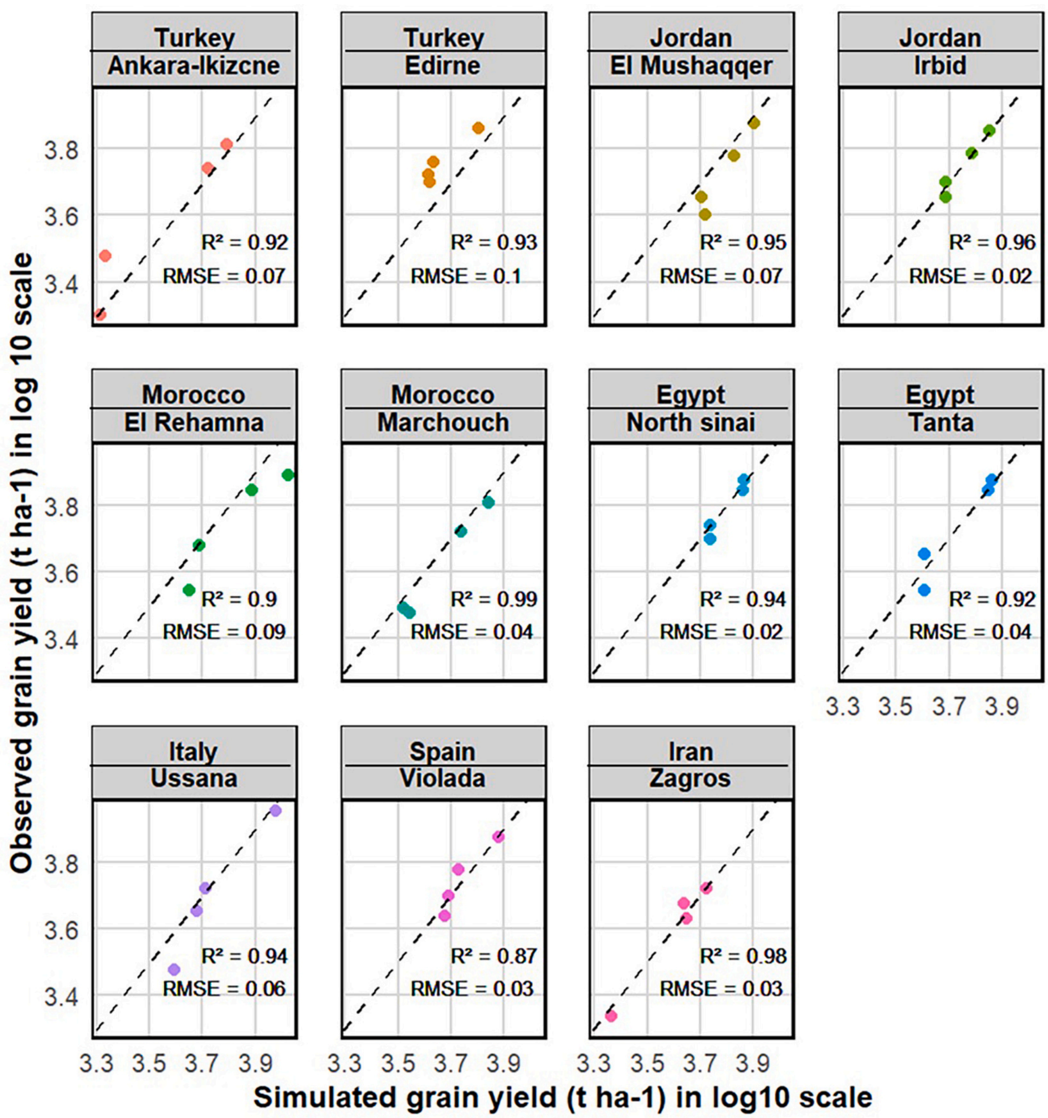

Fig. 3. Calibration and evaluation of the model using baseline log_{10}-transformed grain yield (t ha^{-1}) for 11 sites of 7 Mediterranean countries. Observed vs. simulated grain yields are plotted, values inside the figures are Root Mean Square Error (RMSE) and Pearson coefficient of determination (R^2) for each site.

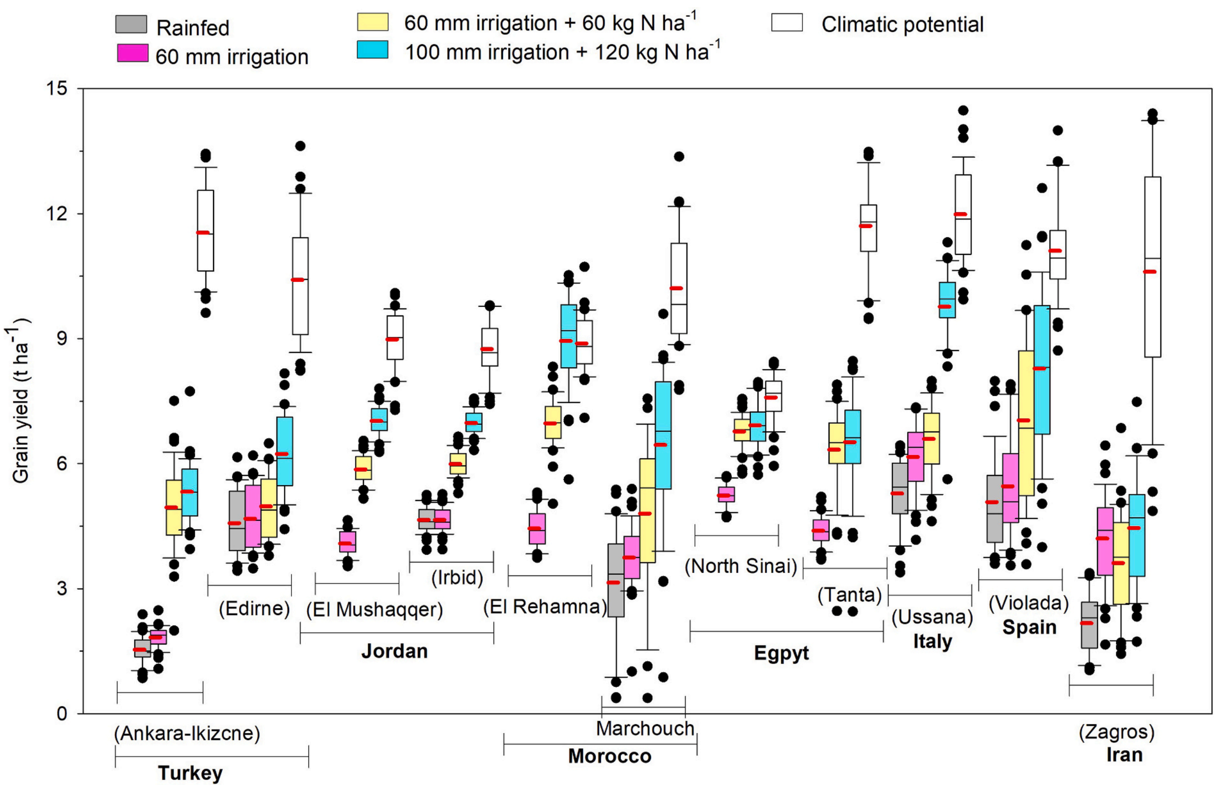

Fig. 4. Long-term simulated grain yield of four treatments from the combination of water and nitrogen across 11 sites in 7 countries compared with climatic potential yield. Black line inside the box median and the red line mean.

ha^{-1} (Italy), and 4.2 t ha^{-1} (Iran). The differences in yield are attributed to the rainfall patterns specific to these locations, soil properties, and climatic conditions. Regions with higher rainfall, such as Italy and Spain, demonstrated superior performance under both rainfed and supplemental irrigation. In contrast, arid regions like Turkey and Iran showed significant yield gains under supplemental irrigation, reflecting its critical role for improving yield.

Further confirmation is derived from the results of irrigation with low fertilization, as well as irrigation with high fertilization. Notably, the results in Iran, Egypt, Turkey, and the comparison between two irrigation amounts in Morocco emphasize the significance of water and fertilizer (nitrogen) management. Examining the variance between treatments reveals that application of nitrogen fertilizer in the range of 60 to 120 kg ha^{-1} leads to stable yields across the Mediterranean and MENA regions.

3.3.2. *Water productivity and nitrogen uptake and loss*

Total water productivity: Total water productivity (Fig. 5A) shows significant variability across regions, ranging from 5–30 kg grain/mm^{-1}. Regions with high climatic potential, such as Italy (Ussana) and Spain (Violada), the highest water productivity was achieved under 100 mm irrigation + 120 kg N ha^{-1}, with median values around 25–30 kg grain mm^{-1}. In contrast, semi-arid regions like Turkey (Ankara-Ikizce) and Morocco (Marchouch) rarely exceed 10–15 kg grain mm^{-1}, reflecting water limitations. Rainfed conditions yield the lowest water productivity (below 10 kg grain mm^{-1}) in all regions, highlighting the insufficiency of rainfall to meet evapotranspiration demands. The addition of 60 mm irrigation combined with N application increased productivity by 25–40% in most regions, and 100 mm irrigation further enhanced productivity by up to 50–70% in high-yielding locations. This aligns with findings by Mateo-Sagasta et al. (2022), who demonstrated that supplemental irrigation maximizes water use efficiency in Mediterranean wheat systems.

Crop water productivity: Crop water productivity (Fig. 5B) follows a similar trend to total water productivity but provides more precise insights into the role of evapotranspiration. High-performing regions such as Spain, Italy, and Egypt (Tanta) exhibit values exceeding 15–25 kg grain mm^{-1}, even under moderate irrigation treatments. Conversely, in arid regions like Turkey and Iran (Zagros), productivity is constrained below 10–12 kg grain mm^{-1}, suggesting that high evapotranspiration rates dilute the efficiency of water use. Comparing rainfed versus irrigated treatments across locations shows statistically significant differences ($p < 0.05$) in crop water productivity, with irrigation improving productivity by up to 50% in regions like Jordan (El Rehamna) and Egypt (North Sinai). This confirms that irrigation not only increases absolute yields but also improves the efficiency of water use in wheat production.

Nitrogen uptake: Nitrogen uptake (Fig. 5C) demonstrates clear variability among regions, with high-yielding regions such as Italy (Ussana) and Spain (Violada) achieving uptake values of 200–300 kg N ha^{-1} under the most intensive management (100 mm irrigation + 120 kg N ha^{-1}). In contrast, semi-arid regions like Morocco (Marchouch) and Turkey (Ankara-Ikizce) show limited uptake, generally below 150 kg N ha^{-1}, even under optimal treatments. Rainfed conditions result in the lowest N uptake across all regions, with median values below 100 kg N ha^{-1}. Supplemental irrigation improved N uptake by 20–40%, and further increases were observed with 120 kg N ha^{-1} fertilization. These results are consistent with findings by Sadras and Angus (2006), which reported that irrigation enhances soil moisture availability and improves N absorption and translocation in wheat crops.

Nitrogen losses: Nitrogen losses (Fig. 5D) are minimal under rainfed conditions, remaining below 20–30 kg N ha^{-1} in all regions. However, losses increase significantly with irrigation and high N inputs. Regions like Italy and Spain, which achieve the highest yields, also exhibit the greatest N losses, often exceeding 60 kg N ha^{-1} under 100 mm irrigation + 120 kg N ha^{-1}. This highlights the trade-off between high productivity and environmental sustainability. Semi-arid regions like Morocco (Marchouch) and Turkey (Ankara-Ikizce) had lowest N losses across all

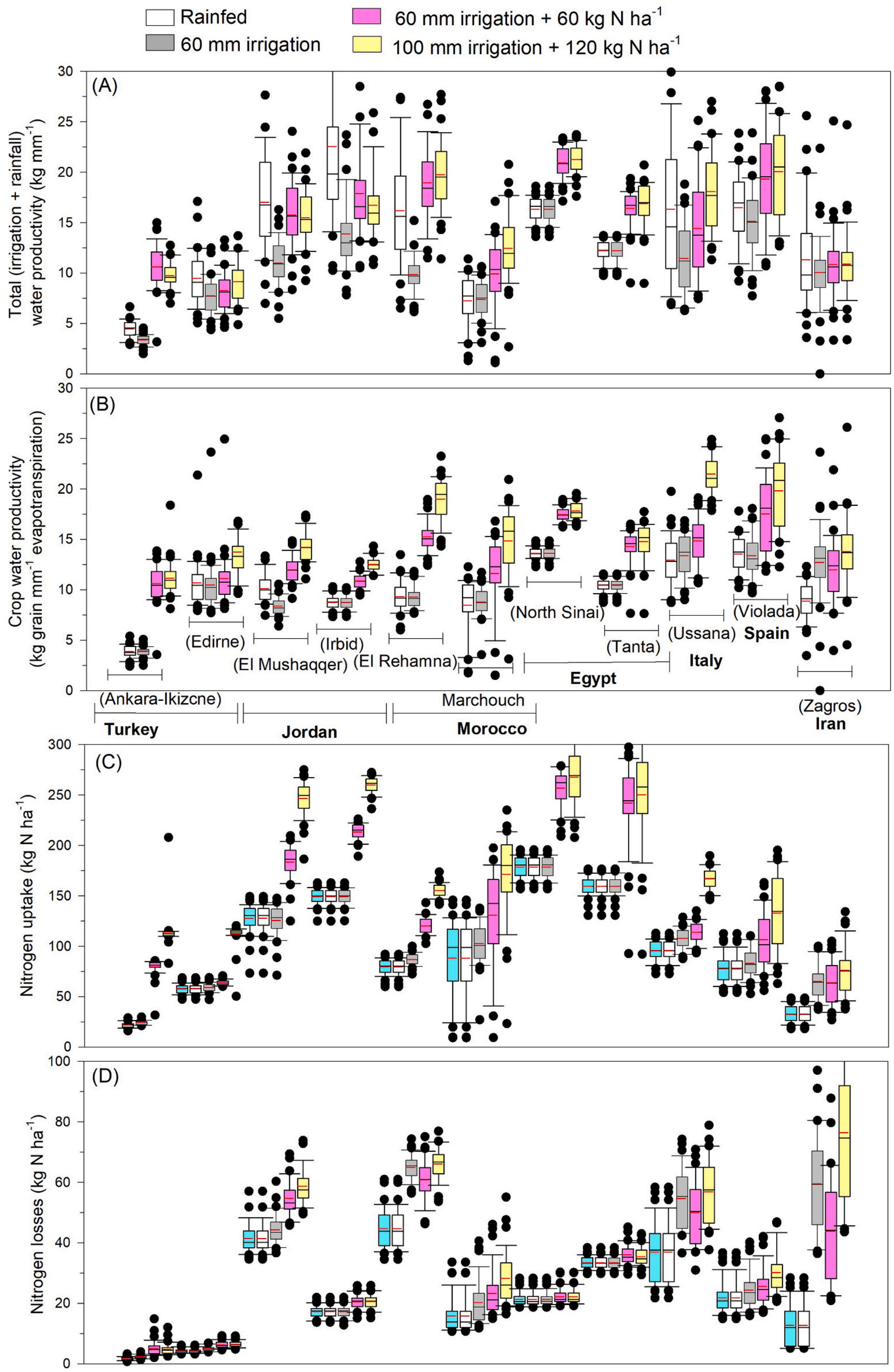

Fig. 5. Total water productivity (A), crop water productivity (B), nitrogen uptake (C) and nitrogen losses (D) from wheat planted under different irrigation and nitrogen management treatments across seven Mediterranean countries and 11 sites. Simulation results from 1986–2023. Black line inside the box median and the red line mean.

treatments, likely due to limited water availability restricting N leaching. However, this comes at the cost of reduced productivity and nutrient efficiency as highlighted by Elrys et al. (2019) and Segurado et al. (2018). Precise estimates of nutrient leaching and other losses is challenging due to the scarcity of national or localized data (Malagó and Bouraoui, 2023).

3.3.3. *Simulated yield under different seeding date*

Figure 6 highlights the effect of seeding dates on wheat yield across diverse agro-ecological regions in the Mediterranean and adjacent areas, revealing significant regional and temporal variability. First and foremost, the ideal period for planting wheat varieties in Turkey, based on a yield of 4.26 t ha^{-1} and a variance of 40 %, is the 15th of November (SI

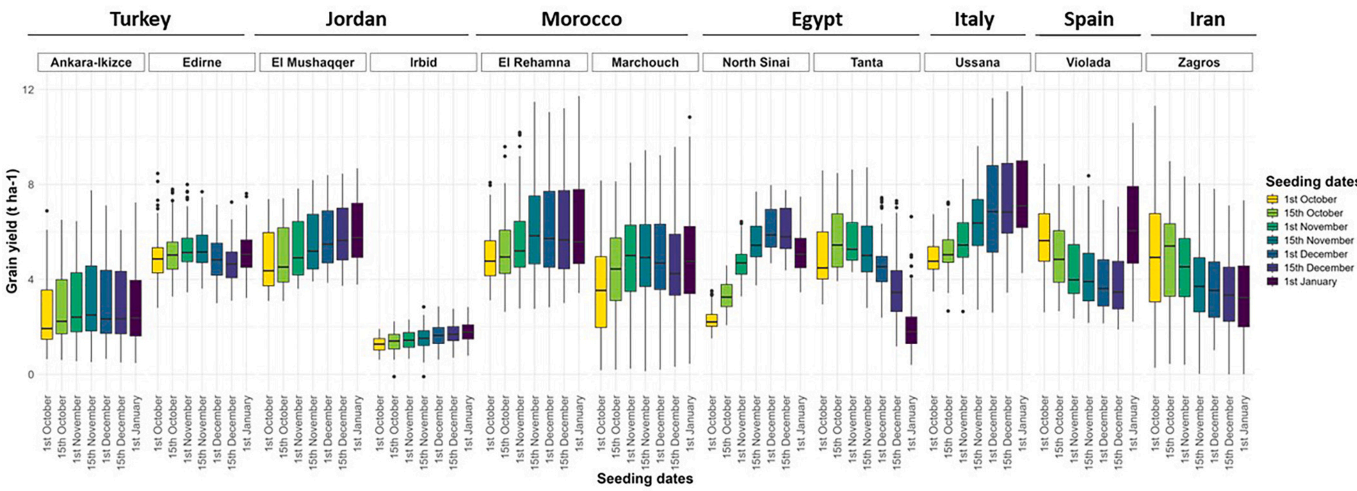

Fig. 6. Simulated wheat grain yield (kg ha^{-1}) across seven seeding dates starting from 1st October to 1st January across 11 different sites in seven Mediterranean region countries. Simulations were performed using historical climate data (1986–2023).

Table 4). Applying a similar approach, we determined that in Jordan, wheat can be seeded between the 1st and 15th of December, resulting in a corresponding yield of 5.9 t ha^{-1} and a variability of 19 %. Furthermore, in Spain, considering a 25 % variability across different seeding periods, wheat can be planted from the 1st of October to the 15th, guaranteeing yields ranging from 5 t ha^{-1} up to 5.6 t ha^{-1}, particularly for the 1st of October (SI Table 4).

For Morocco, the optimal seeding times vary among different locations: the 1st of November for El Rehamna and the 15th of November for Marchouch. These timings ensure an average yield of at least 5.2 up to almost 5.6 t ha^{-1}, with respective variances of 35 % and 38 % (SI Table 4). In Egypt, wheat varieties can be seeded from the 15th of November to the 1st of December, resulting in yields of 5.4 and 5.3 t ha^{-1}, with a variability of 20–23 % (SI Table 4). Considering Italy, especially the unique situation and microclimate pattern in Sardinia Island, optimal planting can commence from the 15th of November, with a variability of 23 % and an estimated yield of 6.4 t ha^{-1}(SI Table 4). Nevertheless, the 1st of January also exhibits a positive average trend in yield, albeit with higher variability at 27 %, owing to rainfall patterns.

The analysis of Iran has identified the optimal planting dates to be between the 15th of October and the 1st of November, considering a variability of 44 %, resulting in average yields of 5 t ha^{-1} and 4.4 t ha^{-1}(SI Table 4), respectively. In the MENA and Mediterranean region, the overall trend indicates that the optimal seeding date is 1st of November, with a variability of 41 % and an average yield of 4.8 t ha^{-1}(SI Table 4). Semi-arid Mediterranean region exihibited sharp yield declines with delayed sowing (15th December to 1st January), often losing over 30–50% of yield potential, emphasize the importance of early sowing in maximizing yields. These declines are attributed to reduced soil moisture availability, shortened vegetative growth, and exposure to late-season heat stress, conditions exacerbated in water-scarce regions.

3.3.4. *Wheat yield under different climate change scenarios*

This study provides a comprehensive assessment of the projected impacts of climate change on wheat yields across the Mediterranean and MENA regions, highlighting region-specific vulnerabilities and potential resilience strategies. A climate change scenario analysis was conducted based on three distinct climate horizons: 2010–2040, 2040–2070, and 2075–2099, as documented in various studies in the region Al-Bakri et al. (2021), Deihimfard et al. (2018) and Vanli et al. (2019). Climate change decreased crop yields across most locations in the next two decades and towards the end of the century, where yield reduced by -18 % and -20% during 2010-2040 and by -30% and -28% during 2075-2099 under RCP 4.5 and RCP 8.5, respectively. This reduction is attributed to rising temperatures, despite an overall increase in rainfall, and increased climatic variability. Notably, the most significant yield reduction, 75 % on average, was projected in Zagros, Iran, while Marchouch in Morocco and Violada District in Spain emerged as the least affected, with 8 % and 6 % yield increases, respectively, under both RCP 4.5 and RCP 8.5 (Fig. 7a).

Except in Morocco, where supplementary irrigation of 100 mm and conservation agriculture were implemented with climate change scenarios, in all other locations, there was yield reduction under RCP 8.5 by mid- and end-century (Figs. 7b and c). The MIROC5 model showed a greater reduction in yield under RCP 4.5 compared to RCP 8.5 for mid and end-century periods. In the MENA and Mediterranean regions, an average yield reduction of 27 % (RCP 4.5) and 28 % (RCP 8.5) was recorded for mid-century, while end-century projections indicated reductions of 30 % (RCP 4.5) and 28 % (RCP 8.5). In the case of Iran, mid-century yield reductions were alarming at 80 % (RCP 4.5) and 86 % (RCP 8.5), with end-century projections showing 88 % (RCP 4.5) and 82 % (RCP 8.5) reductions (Fig. 7b and c). As an adaptation strategy, implementing conservation agriculture, as practiced in Morocco, could mitigate the average mean yield reduction. Conservation practices, particularly residue retention, no-tillage and minimum tillage, could be crucial in maintaining yield stability under changing climatic conditions (Devkota et al., 2022a). In these regions, a slightly positive trend was maintained under both RCP 4.5 and RCP 8.5, ranging from −1 % to 6 % in mid-century and 1 % to 20 % by the end of the century, particularly in Marchouch (Morocco) and Violada District (Spain) (Fig. 7b and c). Notably, Violada District showcased an upper quartile range of yield around 6.4 t ha^{-1} by the end of the century, while Iran displayed a lower quartile of 0.5 t ha^{-1}. Conversely, Mediterranean countries like Egypt and Turkey experienced around a 40 % reduction (RCP 4.5) in Ankara and 30 % in Edirne by the end of the century (Fig. 7c). In Egypt, substantial reductions of 68 % (RCP 4.5) and 62 % (RCP 8.5) were estimated in North Sinai, and 61 % (RCP 4.5) and 63 % (RCP 8.5) in Tanta by the end of the century.

The study concludes that future temperature increases are likely to decrease wheat yield by approximately 28 % in mid-century and around 30 % at the end of the century. This reduction is attributed to a shortened growth cycle due to increased temperatures, impacting grain size and weight. The differences between RCP 4.5 and RCP 8.5 scenarios highlight the significance of global mitigation efforts and climate actions. These findings underscore the need for adoption of region-specific climate-smart agricultural practices and development of adaptive breeding strategies that focus on developing heat-resistant, water-stress

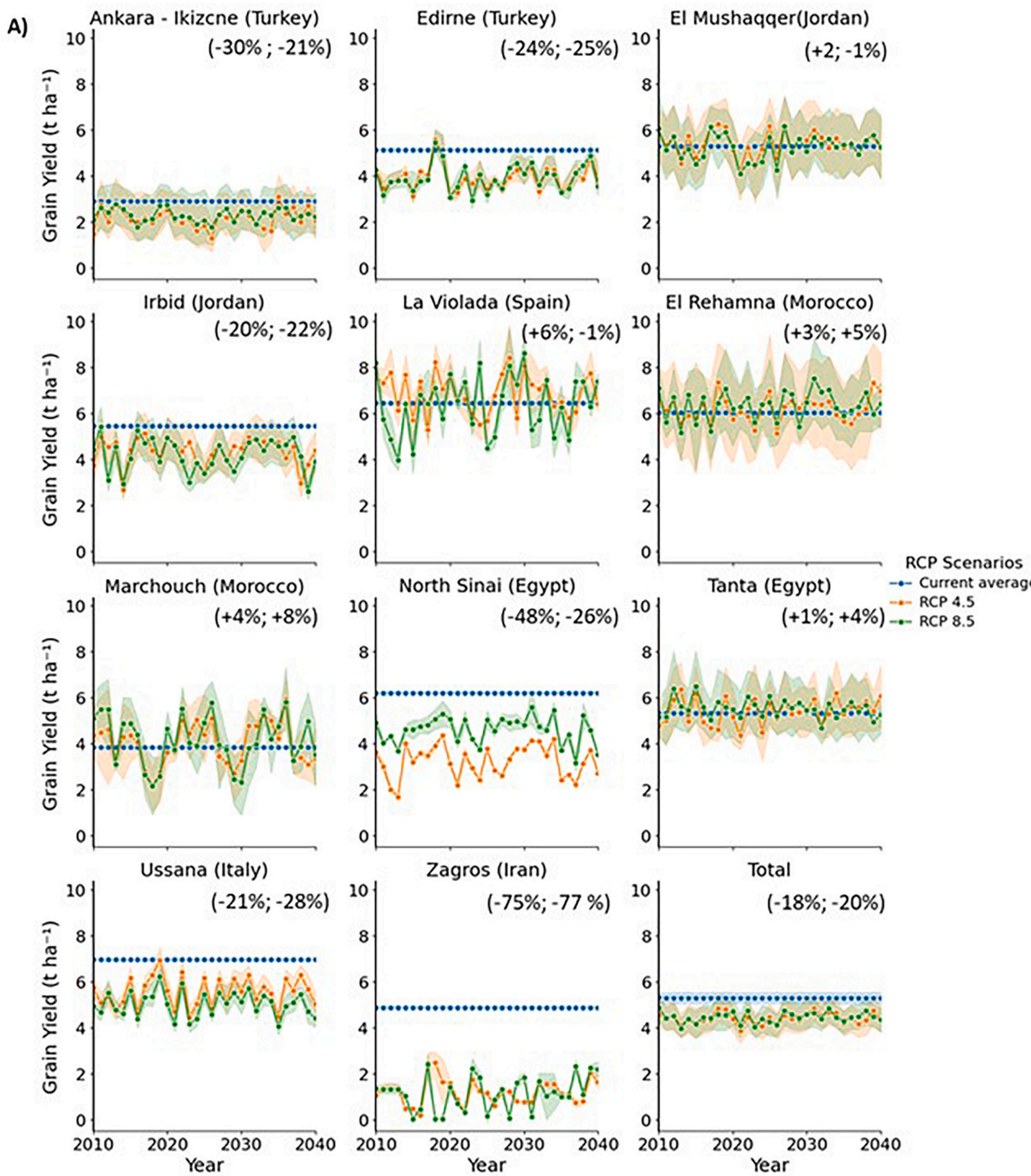

Fig. 7. Yield response of wheat under different climate change scenarios, RCP 4.5 and RCP 8.5 compared with current yield averaged (between 1986 and 2023). Simulation under three-time steps: present 2010–2040 (A), mid-century 2040–2070 (B), far-future 2075–2099 (C).

tolerant, and short duration wheat varieties capable of maintaining productivity under accelerated growth cycles or switch towards more resilient crops such as barley or quinoa. Further assessments involving different GCMs and the accuracy of various crop models, such as APSIM and AQUACROP, are required, especially in regions like Jordan and Egypt, which are getting affected due to soil salinity (Deihimfard et al., 2018; Halima et al., 2021). Expanding the scope of future research to include a broader range of GCMs and integrating multi-model approaches could provide more robust predictions and inform targeted interventions to mitigate the combined effects of heat stress and salinity on sustainably closing wheat yield gaps in these vulnerable regions.

4. Conclusions

This study highlights the critical challenges and opportunities for sustainable intensification of wheat production in the Mediterranean and MENA regions under current and future climate scenarios.The current assessment of yield gaps reveals a significant unexploited potential, ranging from 19 % to 62 % of attainable yield across the Mediterranean and MENA countries. Simulation results under climate change scenarios revealed yield reductions were most pronounced in regions like North Sinai (Egypt) and Zagros (Iran), where yields are projected to decline by 60–88% by the century's end under RCP 4.5 and RCP 8.5. These declines are largely attributed to increased temperatures,

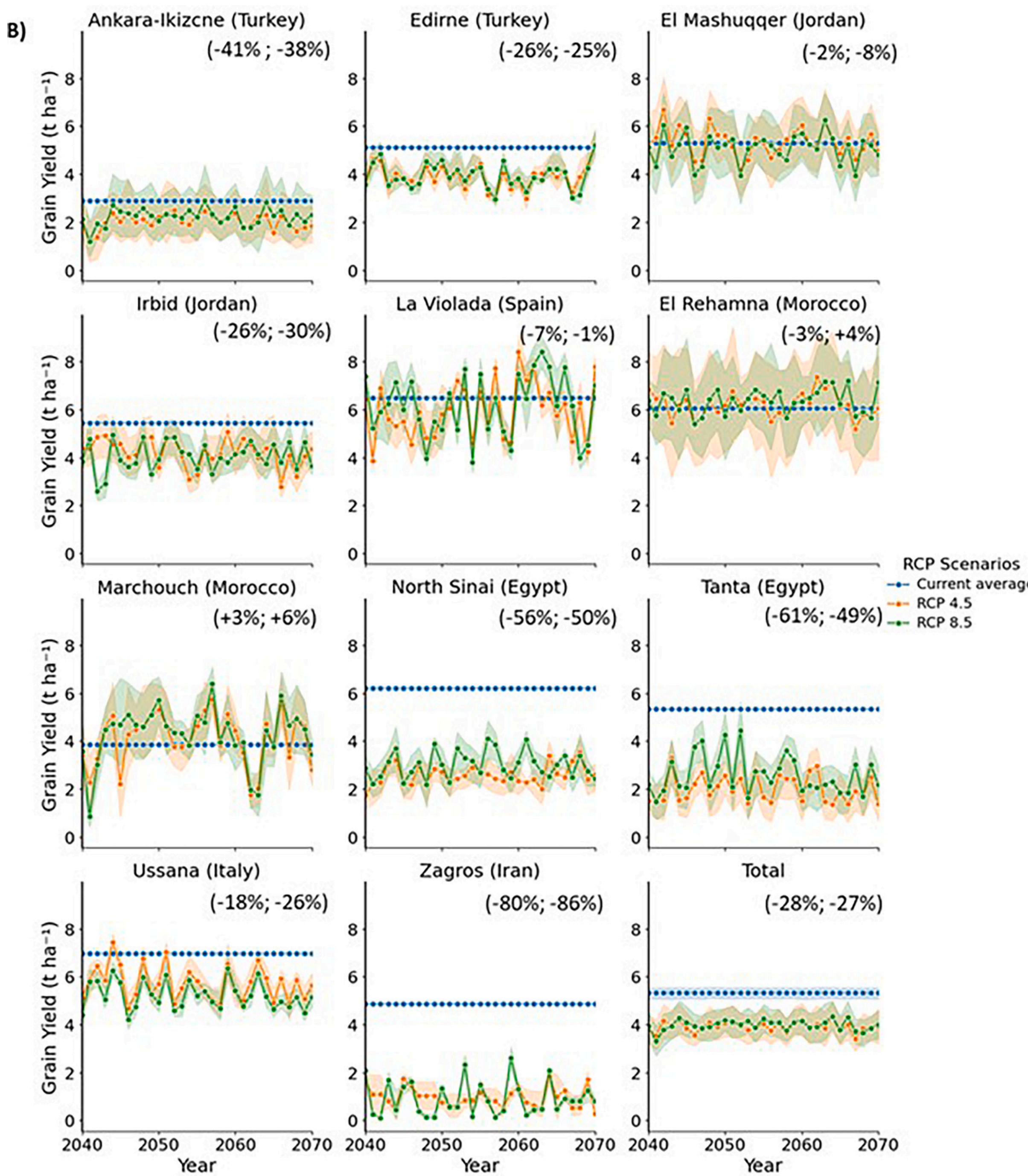

Fig. 7. (*continued*).

reduced rainfall, and reduced crop growth cycles, which limit grain filling and productivity. Supplemental irrigation (60–100 mm) combined with nitrogen application (60–120 kg ha^{-1}) significantly improved yields across all locations, narrowing the yield gap by 30–50% and enhancing water productivity by 25–70%. This study also warns of the environmental risks associated with high nitrogen application and irrigation, including increased nitrogen losses (up to 80 kg N ha^{-1}) and water inefficiencies in regions like Egypt and Jordan. These findings indicated the importance of balancing yield optimization with environmental sustainability, highlighting the need for climate-smart precision agriculture practices that tailor inputs to local conditions. Optimal seeding dates between November 1st and 30th were identified as pivotal for maximizing yields, with delayed sowing resulting in a 30–50% reduction in yield potential. This result not only validates existing agronomic recommendations but also suggests the potential for fine-tuning seeding dates in response to future climate projections, ensuring continued yield stability in a changing environment (SI Fig. 8). The current findings, however, are consistent with existing literature on the subject, and are enriching the subject by the improvement of water and fertilization program currently used in the area of the Mediterranean basin.

In light of climate projections, regions implementing conservation or minimum disturbance practices, such as minimum or no tillage and supplementary irrigation using drip, furrow, or sprinkler demonstrate superior adaptability and performance. This underscores the need for integrated soil health and water management strategies that combine

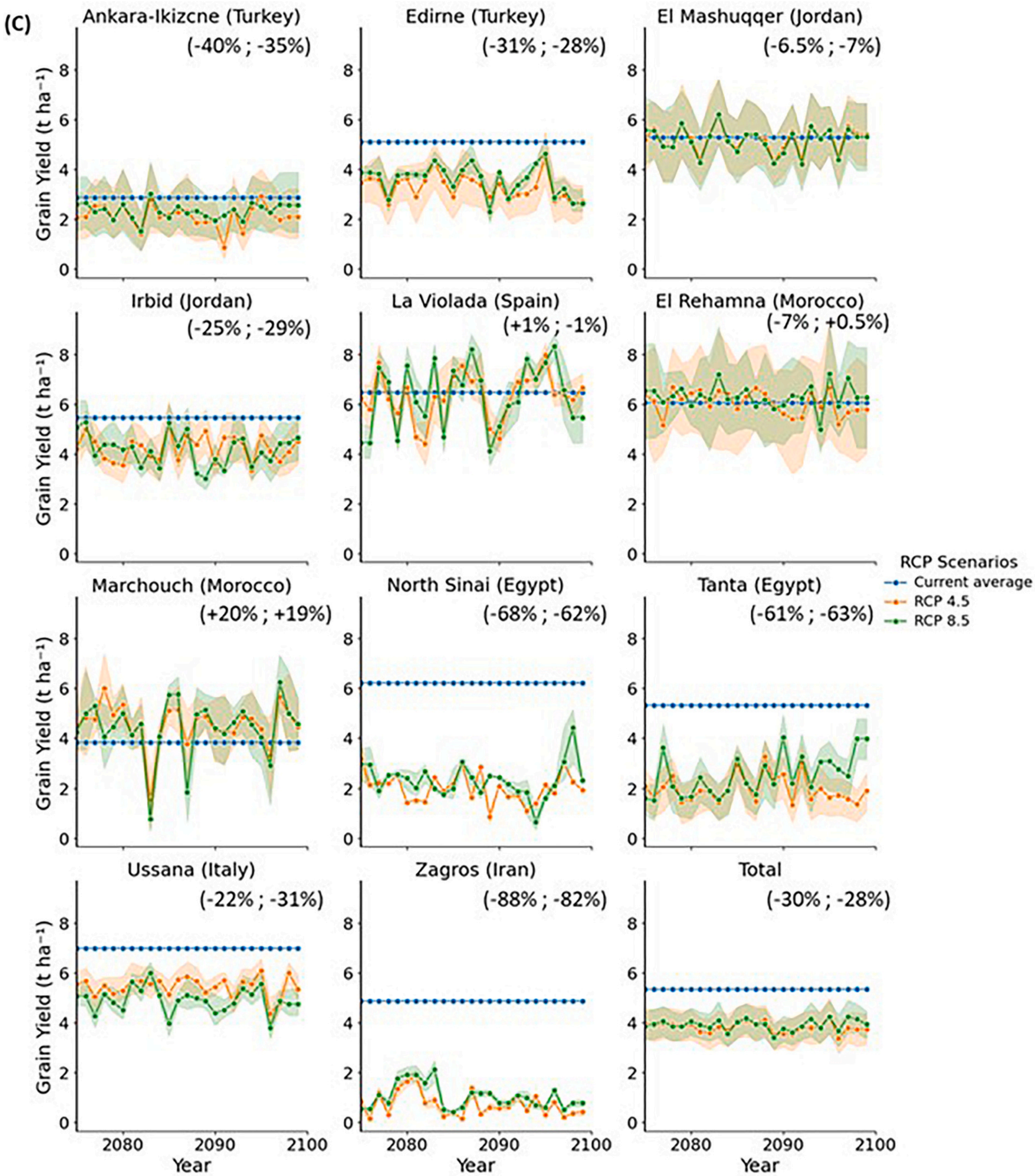

Fig. 7. (*continued*).

precise irrigation with crop demand based nutrient management to mitigate environmental impacts. Policymakers must support the transition to data-driven decision-making by providing farmers with access to decision support 'climate action' tools, enabling tailored interventions that address local challenges. These efforts are crucial for safeguarding food security and agricultural sustainability in one of the world's most climate-vulnerable regions.

CRediT authorship contribution statement

Davide Tita: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Karrar Mahdi:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Krishna Prasad Devkota:** Writing – review & editing, Validation, Supervision, Software, Data curation, Methodology, Conceptualization. **Mina Devkota:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization.

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.2024.104242.

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