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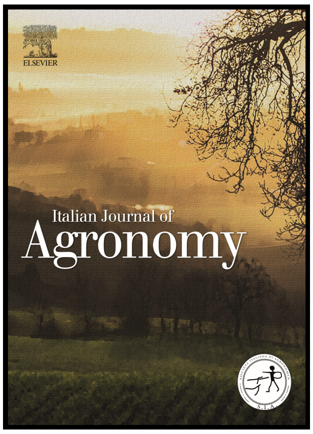

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Assessing the impacts of regulated deficit irrigation on soybean using AquaCrop

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Abstract

Deficit irrigation (DI) is a viable adaptation strategy to reduce agricultural water demand. Field experiments and subsequent data modelling help assess the impacts of DI on crop yield and water productivity (WP_{ET}). This study aims to simulate the potential impacts of climate change on soybean performance under full (FI) and regulated deficit (RDI) irrigation using 30-years (1993–2022) of historical climate data. The field experiment showed no significant difference in yield and actual water productivity (WP_{obs}) between FI and RDI, with average values of 3447 kg ha^{-1} and 6.6 kg ha^{-1} mm^{-1}, respectively. However, RDI saved about 22.5% of irrigation water. Additionally, the AquaCrop model accurately simulated the effects of FI and RDI on soybean performance in the last 30 years of climatic conditions. The 30-year simulations revealed that RDI reduced yield by an average of 4.0%, biomass by 4.8%, and WP_{ET} by 0.9% compared to FI. In contrast, RDI increased irrigation water saving by an average of 17.0% (-55 mm per year) and the irrigation water productivity (WP_{Irr}) by 14.5% (+1.6 kg ha^{-1} mm^{-1}). These results indicate that the AquaCrop model can effectively simulate the impacts of DI on soybean, making it a valuable tool in designing irrigation management plans as adaptation strategies to climate change and water scarcity.

Keywords: climate change; crop water requirement; *Glycine max* L.; irrigation water management; regulated deficit irrigation; water productivity

1. Introduction

Climate change makes different agricultural systems increasingly vulnerable to extreme weather events, such as drought, which directly impacts the sustainability of the agricultural sector, especially regarding irrigation water availability and use. The decrease in soil moisture and groundwater reserves due to reduced rainfall, increased temperature, low air relative humidity, and strong winds over prolonged periods can result in yield loss or even crop failure (Nguyen et al., 2023). Since agricultural production and food security are highly dependent on water, the occurrence of drought, combined with the impacts of land use change, increasing population, and competition for resources, underscores the urgent need to improve the efficiency of water use in agriculture, thus preserving resources for other sectors (Douh et al., 2021; Eshete et al., 2022; García-Vila et al., 2009). Therefore, it is essential to enhance water productivity (WP) (kg ha^{-1} mm^{-1} of water) (Rosegrant et al., 2009).

Deficit irrigation (DI) is viewed as a practical and adaptive strategy in response to the challenges posed by climate change and the increasing demand for environmental water resources (Kiyan et al., 2022; Mushtaq and Moghaddasi, 2011; Wale et al., 2022). Indeed, this irrigation strategy can lead to an increase in WP (de Almeida et al., 2024). DI consists of providing the crop with less irrigation water than what is necessary to fulfill maximum evapotranspiration (ET_{max}) (English and Nuss, 1982). Although this practice may have a negative impact on yield, it can reduce irrigation cost and increase the farm income (English, 1990) and therefore be profitable for farmers (Painagan and Ella, 2022). Indeed, when the cost of water is high, reducing irrigation volumes can lower crop production costs and save water. This conserved water can then be used to expand irrigable land, thereby increasing the opportunity cost of water (Capra et al., 2008; Mushtaq and Moghaddasi, 2011). Some studies have shown that DI is successful in increasing WP for various crops without causing severe yield reductions (Geerts and Raes, 2009; Mushtaq and Moghaddasi, 2011). However, it is essential to understand the crop's behavior at different growth stages to determine the type of water stress that should be applied to maximize WP (García-Vila et al., 2009; Liu and Song, 2020). In this context, the regulated deficit irrigation (RDI) strategy was developed to enhance WP while maintaining high yields by fully meeting the crop's water requirements during water-stress-sensitive growth stages and applying irrigation amounts insufficient to meet ET_{max} during other phenological stages (Geerts and Raes, 2009).

Crop WP functions are extensively used to express the relationships between crop yield and water inputs or crop water consumption during crop growth and development (He et al., 2022; Mahmoudzadeh, 2016). Methods based on this approach are provided by the Food and Agriculture Organization (FAO) in Irrigation & Drainage Paper no. 33, "Yield Response to Water" (Doorenbos and Kassam, 1979), and in CROPWAT (Smith, 1992).

Given the limitations of empirical functions, crop simulation models offer a viable alternative. However, simpler yet robust models are preferred over highly complex ones that demand advanced skills and several input parameters, which may not always be available (Adeboye et al., 2019; García-Vila et al., 2009). To address these challenges, the FAO of the United Nations developed the user-friendly AquaCrop model, which requires only a limited set of inputs (Khoshsirat et al., 2022). AquaCrop is a water-driven model that has proven reliable and robust for assessing irrigation water levels, DI strategies, and farm irrigation management across a variety of crops (Solgi et al., 2022).

In Italy, the period from late spring to the second half of August is typically characterized by a water deficit due to insufficient rainfall to meet the atmospheric evapotranspiration demand. Water management is, therefore, crucial for spring-summer crops, especially when most of the crop evapotranspiration (ET_c) must be supplied by irrigation. This is particularly relevant for soybean [*Glycine max* (L.) Merr.], the fourth most widely cultivated crop globally (FAOSTAT, 2024), grown for livestock feed, the biofuel sector, and human nutrition as a source of protein and fat (Aydinsakir, 2018). In 2022, the global area under soybean cultivation was approximately 134 million ha, with a total seed production of about 349 x 10^6 Mg (FAOSTAT, 2024). Irrigation management is critical for soybean, as it directly impacts final yield (Aydinsakir, 2018). Consequently, DI combined with crop simulation models to explore different scenarios, plays a key role in sustainable water management (Painagan and Ella, 2022).

Several studies have explored the impact of DI on the performance of different soybean cultivars across various locations and field management practices (Morbidini et al., 2024; Pejić et al., 2024). In the context of RDI, research has shown the positive effect of supplemental irrigation during the reproductive stage on soybean performance (Adeboye et al., 2015; Garcia et al., 2010; Karam et al., 2005; Montoya et al., 2017).

Despite these advances, only a limited number of studies have used crop simulation models (CSMs) to simulate the effects of DI on soybean for maximizing WP (Dogan et al., 2007; Giménez et al., 2017; Wei et al., 2015). Notably, the AquaCrop model stands out as a widely used CSM for simulating the performance of various crops. However, its application to soybean under DI has been relatively sparse, with only a few studies addressing this (Abi Saab et al., 2014; Adeboye et al., 2017; Montoya and Otero, 2019; Morales-Santos et al., 2023), some of which have focused on rainfed conditions and water conservation practices (Adeboye et al., 2019). Nonetheless, these studies have demonstrated AquaCrop's ability to accurately simulate soybean development, biomass production, and yield formation (Adeboye et al., 2017; Solgi et al., 2022).

In view of the above considerations, this study aims to: (1) compare the soybean performance in terms of grain yield and actual water productivity (WP_{obs}) under full irrigation (FI) and RDI (70% of FI before and after flowering); (2) parametrize and calibrate AquaCrop model for soybean under FI and RDI using field data; and (3) use the parametrized and calibrated AquaCrop model to estimate the potential impacts of RDI compared to FI over the last 30 years (1993–2022) in terms of potential irrigation water saving, WP_{ET}, WP_{Irr}, and grain yield losses.

2. Materials and methods

2.1 Study area and experimental layout

The field experiment was conducted in Castelfranco Veneto (Northeastern Italy, 45° 41' 41.14" N, 11° 56' 44.89" E, 12 m a.s.l.). It was laid out in a randomized complete block design during the 2022 soybean growing season. The field was arranged in four plots, each of 1600 m^2 (40 m x 40 m). The RDI treatment involved applying 70% of the FI per event throughout the irrigation season, except during the flowering stage (from BBCH 60 to BBCH 69), when the soybean water requirement was fully satisfied.

Soil samples were collected from 0–20, 20–40, and 40–60 cm depth profiles at the beginning of the experiment, with three sampling points per plot to determine the soil properties. Each sampling point represented the average of three sub-samples (Table 1). The soil exhibited a significant gravel content (average 27.7 %), which reduced its water retention capacity and resulted in a rapid water infiltration rate. Additionally, the water table was very deep and did not contribute to the soil moisture in the root zone of the crop.

The usual farm management practices for soybean cultivation in Italy were implemented as follows: plowing, harrowing, fertilization (75 kg P_2O_5 ha^{-1} and 75 kg K_2O ha^{-1}), seeding (50 cm x 4.4 cm spacing), and post-emergence herbicide application using Tifensulfuron-methyl, Imazamox, and rapeseed oil. The soybean (cv. Avril) was sown on May 20th and harvested on October 4th 2022. At full maturity, pods were harvested from each plot within 3 sub-plots of 4 m^2 each, and dry grain yield was determined by threshing and drying the seeds at 65 °C.

Considering the soil type and the need to apply water according to the wetted strip approach, irrigation water was carried out through a drip system equipped with drip tape featuring the following characteristics: 16 mm outer diameter, 8 mm wall thickness, 30 cm emitter spacing, and a nominal flow rate of 1 L h^{-1} per emitter at 0.7 bar.

The amount of water applied to each treatment was measured using flow meters. Drip lines were placed every two rows, resulting in lateral spacing of 1 m. The wetted strip width at the final basic intake rate (K_i) represented the actual infiltration surface for the applied irrigation water and was approximately 40% of the total field area. The net irrigation dose (NI) for each event was determined using the FAO procedure to calculate ET_c, accounting for rainfall during the period and and the system distribution uniformity (DUlq) to obtain the gross irrigation dose (GI). The objective was to refill the soil profile within the wetted strip to field capacity, matching the root zone depth, in the FI treatment (100% ET_c) and applying 70% of ET_c in the RDI treatment, except during the flowering period, as previously described. Each irrigation event was monitored using volumetric soil moisture data provided by sensors (TEROS 10 and TEROS 12, METER Group, Inc., Pullman, WA, USA) installed at depths of 20, 40, and 60 cm in each plot, as well as soil water potential readings at 40 cm (TEROS 21, METER Group, Inc., Pullman, WA, USA). Meteorological data were obtained from an agrometeorological station managed by the Veneto Region Agency for Environmental Protection (ARPAV) near the study site. Table 2 presents the number of irrigation events and the amount water applied per event. At the end of the experiment, the WP_{obs} was calculated using Eq. 1.

$$WP_{obs} = \frac{Y}{IRR + R} \text{ (Eq. 1)}$$

where WP_{obs} (kg ha^{-1} mm^{-1}) is the actual WP, Y is the actual soybean dry grain yield (kg ha^{-1}), IRR is the total irrigation volume (mm) applied during the growing period, and R is the total rainfall received by the crop throughout the growing period

2.2 Model description

AquaCrop version 7.0 was used for simulations, with input parameters provided in Table 3. The AquaCrop model simulates canopy development, transpiration, dry above-ground biomass production, and yield formation on a daily basis (Raes et al., 2022). In the model, canopy cover (CC) replaced the concept of leaf area index (LAI) because it is simpler and can be used to partition soil evaporation and crop transpiration. The amount of transpiration (Tr), mm day^{-1} is then translated into a proportional amount of above-ground crop biomass (B), kg m^{-2} produced by multiplying it by water productivity (WP), kg m^{-2} mm^{-1} (Eq. 2). Once the biomass value is obtained, it is multiplied by the harvest index (HI) and the yield (Y) (Eq. 3) is obtained (Steduto et al., 2009).

$$\text{Crop biomass (B)} = \text{WP} * \sum \text{Tr} \text{ (Eq. 2)}$$

$$\text{Yield (Y)} = \text{B} * \text{HI} \text{ (Eq. 3)}$$

Moreover, biomass WP and ET water productivity can be distinguished in the AquaCrop model. Biomass WP refers to the amount of biomass that can be obtained with a certain quantity of water transpired. On the other hand, ET water productivity is the relationship between crop yield and ET_c which is expressed as kg ha^{-1} (yield) per mm of water (evapotranspired). In this study, the WP is reported as soybean dry grain yield over crop evapotranspiration (ET_c) which was calculated using Eq. 4.

$$WP_{ET} = \frac{\text{grain yield (kg ha}^{-1}\text{)}}{ET_c \text{ (mm)}} \text{ (Eq. 4)}$$

2.3 Model parametrization and calibration

2.3.1 Meteorological data

The model was first parametrized using the indicative values reported in the AquaCrop user guide (Raes et al., 2022) and then calibrated using the meteorological and experimental data collected during the 2022 growing season (Figure 1). The meteorological data were used as climate input parameters in the model and to calculate the reference evapotranspiration (ET_o) (mm). ET_o was calculated on a daily basis using the Hargreaves equation (Eq. 5), calibrated against the Penman–Monteith equation by Berti et al. (2014) for the experimental region:

$$ET_{0,Har} = H_A \times R_e(T + 17.8) \times \Delta T^{H_E} \text{ (Eq. 5)}$$

where $H_A = 0.0020$ (Berti et al., 2014) and $H_E = 0.5$, R_e is the water equivalent of the radiation measured on the ground (mm d^{-1}), T is the mean temperature ($(T_{max} + T_{min})/2$ °C) and ΔT is the difference between maximum (T_{max}) and minimum (T_{min}) temperature. The calculated ET_o was then directly imported into the model

2.3.2 Soil characteristics

A soil profile file was created using the soil characteristics of the site (Table 1). The soil type at 0 to 60 cm depth was loam, with field capacity ranging from 27.8% to 28.9% and permanent wilting point ranging from 14.8% to 15.3%. The simulations were performed considering only the contribution of fine soil texture to the water balance.

2.3.3 Crop characteristics

In the model, crop characteristics are distinguished as conservative or non-conservative. The cultivar-specific and non-conservative crop parameters were adjusted, as they vary with the selected cultivar and might be affected by field management, soil profile conditions, or climate. Phenology is critical for accurately simulating crop development during the calibration process. Therefore, it was fine-tuned by specifying the actual dates of emergence, flowering, yield formation, and ripening in the model. Several important parameters, such as crop type, sowing method, canopy development, root deepening, and soil water stress were adjusted using the trial-and-error method within the value ranges provided in the user manual (Raes et al., 2022) and the fine-tuning procedure outlined by Vanuytrecht et al. (2014). Some default parameters from the manual were adopted directly, especially those that are conservative and generally applicable for soybean (Table 3). Once the values were set, the crop file was converted into Growing Degree Days (GDD) mode (Raes et al., 2022).

2.3.4 Management practices

Field management practices were not considered in this study, as the experiment did not include treatments related to soil fertility, mulching, or field surface practices. Furthermore, herbicide treatment is a common practice in soybean production at the study site, so the effects of weeds on crop development was assumed to be negligible. For irrigation, the existing strategy in Castelfranco Veneto was assessed by creating an irrigation file for the FI and RDI treatments and specifying the irrigation events and amounts (Table 2). The drip irrigation method was specified in the model, using 40% of soil surface wetted.

2.4 Data analysis and model performance evaluation

The soybean yield and WP_{obs} during the 2022 growing season under FI and RDI were analyzed statistically using an independent samples t-test. Furthermore, statistical indices were used to evaluate the performance of the AquaCrop model during the calibration by comparing actual and simulated yield and WP. The root mean squared error (RMSE) is expressed in Eq. 6. Values close to 0 indicate optimal performance, and for agricultural models, a 15% is considered good, while 20% is satisfactory. For biomass and yield, Hanson et al. (1999) recommended a 15% error. The normalized root mean square error (NRMSE) (Eq. 7) was used as the error index. The NRMSE values were classified as <10% - excellent, 10–20% - good, 20–30% - fair, and >30% - poor (Jamieson et al., 1991).

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \quad (\mathrm{Eq.\,6})$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\bar{O}} \times 100 \quad (\mathrm{Eq.\,7})$$

where O_i is the measured data, $\bar{O}$ is the mean of measured data, S_i is the simulated data, $\bar{S}$ is the average of simulated data, and n is the number of observations

2.5 30-year simulations of FI and RDI impacts

The parametrized and calibrated crop model was used to evaluate the impacts FI and RDI on soybean performance over the past 30 years (1993–2022). Historical meteorological data of the study site were obtained from ARPAV and used as climate input parameters. The daily ET_o was calculated using the Hargreaves equation (Eq. 5). The same soil file used for calibration applied to all simulations. On the other hand, the irrigation files for both FI and RDI were defined based on the total available water (TAW) in the soil profile (Table 1) at a maximum effective rooting depth of 0.5 m. In the root zone, TAW is defined by the model as 200% of the readily available water (RAW).

Considering the inter-annual meteorological variability, two irrigation schedules were developed based on RAW percentage thresholds. For RDI, the threshold to start irrigation was 100% RAW depletion before and after flowering stages, while it was 50% during flowering. In contrast, for FI, the threshold was 50% RAW depletion throughout all phenological stages. Based on this information, the allowable depletion (mm) and irrigation depth (mm) were calculated by ratio and proportion. Thus, the crop under RDI was purposely exposed to canopy expansion stress before and after flowering whereas no stress was applied under FI.

To compare the irrigation strategies and assess their advantages, a simulation under rainfed conditions was also conducted.

The simulation period spanned from May 1 to September 15, with the initial soil water profile set to field capacity. A fixed sowing date was chosen to avoid confounding effects, in contrast to using a variable sowing date based on annual onset criteria like cumulative rainfall or temperature thresholds. By setting the initial soil condition to field capacity, the simulations provided optimal conditions for crop germination and establishment. Additionally, the conditions at the end of each simulation were reinitialized at the start of each new simulation year to further minimize confounding effects. Since the crop file was in GDD mode, the growing period for each year of simulation was automatically calculated by the model (Raes et al., 2022). The GDD was calculated by subtracting the base temperature (T_{base}) from the average air temperature (T_{ave}).

In the 30 year simulations, the following variables were analyzed for each of the three water regimes (FI, RDI, rainfed):

- Soybean dry grain yield and above-ground biomass production
- Crop evapotranspiration
- Seasonal irrigation volume
- Water productivity, WP_{ET} (Eq. 4)
- Irrigation water productivity, calculated as:

$$WP_{Irr} = \frac{Y_i - Y_r}{IRR} \quad (Eq. 8)$$

where Y_i is the simulated yield of the irrigated treatment (FI or RDI) (kg ha^{-1}), Y_r is the simulated grain yield under rainfed condition (kg ha^{-1}), and IRR is the total volume of irrigation (mm) throughout the growing period

2.6 Statistical analysis

The dynamics of the meteorological variables and the simulations across the years were analyzed using analysis of variance (ANOVA). Mean differences between FI and RDI strategies were compared using post-hoc analysis. The relationship of yield, biomass, and WP_{ET} with meteorological variables were analyzed using quadratic regression analysis, following the general linear model with irrigation strategy set as a factor. All the statistical tests were performed at α = 0.05 using open-source statistical software jamovi©, while the results were presented graphically using RStudio (R Core Team, 2021).

3. Results and discussion

3.1 Field experiment

The meteorological data and the results of the field experiment during the 2022 growing period are presented in Figure 1. A total of 278 mm of rain was recorded throughout the growing period, which was 38.9 % lower than the 30-year average seasonal rainfall, particularly in June (31 mm) and July (19 mm), which received on average 104 mm and 90 mm of rain, respectively, in the 1993–2022 period. Most of the rainfall occurred during the yield formation and ripening stages of soybean while the least during the emergence. The cumulative ET_o was 585 mm, with the highest daily values during the flowering stage (on average 5.1 mm day^{-1}). Although fluctuating, the T_{min} and T_{max} gradually increased across the growing season and then decreased, with averages of 16.6 °C and 30.2 °C, respectively. During the soybean growing season, a total of 244 mm and 189 mm of irrigation was applied under FI and RDI, respectively.

Independent samples t-test showed that the yield [$t(10) = 0.46$, $p = 0.66$] and WP_{obs} [$t(10) = -0.62$, $p = 0.55$] for FI were not statistically different with RDI, with average values of 3447 kg ha^{-1} for yield and 6.6 kg ha^{-1} mm^{-1} for WP_{obs}. However, RDI saved about 22.5% of irrigation water. Considering that yield was not significantly reduced, these results suggest that RDI is a viable water-saving option in the context of water scarcity and climate change. Our findings align with previous studies that show minimal yield differences in soybean under RDI. Specifically, soybean yield remains relatively unaffected when no irrigation is applied at the beginning of pod formation, followed by FI until maturity (Irmak et al., 2014). Other studies (Abi Saab et al., 2014; Karam et al., 2005) have also found higher yield with FI compared to when irrigation was withheld for two weeks during full bloom or stopped entirely during seed enlargement. Babazadeh et al. (2022) reported significant yield reductions compared to FI when RDI was implemented during flowering and grain filling, while Adeboye et al. (2015) observed the lower yield compared to FI when irrigation was skipped every other week during seed filling. In terms of WP_{ET}, our results were consistent with Karam et al. (2005), who recorded the highest average WP_{ET} at full bloom stage under RDI, in contrast with Adeboye et al. (2015), who showed the highest W_{PET} under FI.

3.2 AquaCrop calibration

Despite the AquaCrop model has been already extensively calibrated for soybean (Morales-Santos et al., 2023; Moroozeh et al., 2023; Rosa et al., 2023), we used the experimental data acquired in 2022 growing season for further adjustment to local conditions. The performance indicators were calculated after calibration. During calibration, the simulated yield was 3737 kg ha^{-1} under FI and 3071 kg ha^{-1} under RDI. On the other hand, the simulated WP_{ET} was 9.5 kg ha^{-1} mm^{-1} under FI and 8.3 kg ha^{-1} mm^{-1} under RDI. Except for the RDI yield, these values slightly exceeded the observed values in the 2022 growing season, indicating a slight and negligible overestimation. However, performance evaluation of the model indicates that AquaCrop successfully simulated the impacts of FI and RDI on the yield and WP_{obs} of soybean. The RMSE ranged from 0.7 to 256.0, and NRMSE from 6.8 to 18.8% (Table 4).

3.3 Simulation of soybean performance in the last 30 years

3.3.1 Temporal dynamics of meteorological variables

The temporal dynamics of meteorological variables from 1993 to 2022 are presented in Figure 2. In general, seasonal rainfall, ET_o, T_{min} and T_{max} across the soybean growing season fluctuated and showed significant ($p<0.01$) differences over the 30-year period. Notably, linear regression showed that T_{min} has been increasing during the period by about 0.1 °C per year, explaining 54.1% of the total variation. This indicates that from 1993 to 2022, T_{min} has increased by approximately 3.0 °C.

The cumulative rainfall during the soybean growing season was the lowest in 2003 (198 mm) and the highest in 2002 (773 mm), with an average of 461 mm. Annual cumulative rainfall during the growing season showed significant variability from the historical average, except for the years 2005–2007 and 2016. In most years, there was a notable reduction in rainfall, ranging from 24 to 158 mm below the historical average. Additionally, the distribution of rainfall across soybean phenological stages was uneven, with the majority of rainfall occurring during the vegetative stage, and the least during the flowering stage. This pattern highlights the potential risk to yield during critical stages of soybean development when water availability is lower.

The average ET_o was 614 mm, with the highest value (689 mm) recorded in 2003 and the lowest (555 mm) in 2014. Considering growth stages, the ET_o was significantly (t = -7.3–11.1, $p < 0.01$) higher during flowering (Figure 2) compared to other growth stages. The average seasonal T_{min} ranged from 13.2 to 16.9 °C, with an overall average of 15.1 °C. The highest T_{min} (18.7 °C) was recorded in August 2018, while the lowest

(9.6 °C) was recorded in September 1996. The highest T_{max} (31.4 °C) was recorded in 2003, and the lowest (26.4 °C) in 2014 with an average of 28.4 °C. Temperature varied across phenological stages, except for T_{max}, which, over the 30 years, did not not show significant differences comparing the flowering, yield formation, and ripening stages (t = 2.5, p = 0.06). In AquaCrop, temperature data are used to calculate the GDD, which determines crop development and phenology, including adjustments in crop transpiration during warm periods (Raes et al., 2022). In this study, a significant increase of about 2.8 °C in the average temperature was observed over the 30-year period. Furthermore, although T_{max} exceeded 30.0 °C, the average temperature across growth stages remained within the optimal range for soybean (Figure 2). Hatfield et al. (2011) identified an optimal seasonal average temperature of 22°C, while Grimm et al. (1994) reported that the optimum average temperature for the reproductive period varies between 25.0 and 29.0 °C. Some studies have emphasized that agricultural crops will require increased water supply to maintain productivity and yield in the future, due to the projected increase in air temperature and ET_o (Edao et al., 2023). In Europe, soybean is one of the main crops that is heavily impacted by water and heat stress. Therefore, the high temperature variability and the increasing trend of T_{min} over the 30-year period, along with occasional T_{max} exceeding the threshold during the reproductive stage, could compromise soybean production in the future by affecting pollination and ET_c, as well as triggering higher water demand. Furthermore, this may substantially contribute to the worsening of drought conditions (Toreti et al., 2022). On the other hand, some studies have projected that higher accumulated temperatures improve soybean yield due to CO_2 fertilization effects (Araji et al., 2018; Durodola and Mourad, 2020).

3.3.2 Soybean performance under rainfed, FI, and RDI

Crop evapotranspiration

Once calibrated, the AquaCrop model was applied to the historical climate data series from 1993 to 2022 (Figure 3). Over the 30-year period, soybean under rainfed conditions showed significantly ($p<0.01$) lower ET_c than both FI and RDI, with no significant differences between the two irrigation strategies (Table 5). Specifically: (i) under rainfed conditions, the ET_c ranged from 179 mm (2003) to 475 mm (2014); (ii) under FI, the ET_c ranged from 502 mm to 605 mm; and (iii) with RDI, ET_c ranged from 487 mm to 578 mm. In both FI and RDI, the highest and lowest ET_c values were recorded in 2001 and 2015, respectively. The ET_c reduction (-3.11%) for RDI compared to FI aligns with findings from previous studies. Similar reductions in ET_c have been reported when irrigation is reduced or delayed during critical growth stages, such as pod initiation (-8.2%), seed filling (-7.6%), and maturity (-5.0 to -5.4%) (Abi Saab et al., 2014; Adeboye et al., 2015). Irmak et al. (2014) also reported reductions of -3.1% and -6.0% with partial irrigation resumption at the beginning pod formation stage. Meanwhile, Candoğan and Yazagan (2016) observed ET_c reductions of -5.7 to -9.5% with 50-75% soil water depletion at various stages, including seed enlargement, pod formation, and flowering.

Rain and irrigation volume

The amount of rainfall ranged from 228 mm in 2003 to 699 mm in 2002, with an average of 455 mm. The irrigation volumes under both FI and RDI fluctuated over the 30 years, following similar trends (Figure 3). As expected, FI required higher irrigation volumes, ranging from 182 mm to 416 mm. In contrast, RDI ranged from 119 mm to 352 mm. In both irrigation strategies, the highest volume was simulated in 2003 and the lowest in 2014. These results align with the expectation that years with higher rainfall correspond to lower irrigation volumes, and vice versa. Compared to FI, RDI saved between 30 to 82 mm of irrigation water per year, with an average saving of 55 mm (Figure 4). This indicates that 1 ha managed with RDI saved 1650 mm of water over the 30 years, equivalent to the amount supplied in five average years under FI. In general, the highest and lowest irrigation water savings correlated with the driest and wettest years, respectively.

Grain and biomass yield

Simulation results indicate a significant decline in soybean yield and biomass production under rainfed conditions ($p<0.01$) compared to FI and RDI, which showed no significant differences between them (Figure 3, Table 5). Under rainfed conditions, no yield was simulated in 2009 due to reduced seasonal rainfall (276 mm), which contributed to increased canopy expansion stress (46.8%) and stomatal stress (63.7%) during the vegetative and reproductive stages, respectively. In the other years, the yield ranged from 202 kg ha^{-1} (2012) to 4491 kg ha^{-1} (2014) with an average of 1728 kg ha^{-1} whereas biomass varied from 930 kg ha^{-1} (2013) to 8457 kg ha^{-1} (2014), with an average of 4321 kg ha^{-1}. Under FI, the yield ranged from 4907 kg ha^{-1} to 5894 kg ha^{-1}, with an average of 5490 kg ha^{-1}. The highest yield was simulated in 2014 while the lowest in 2003, the year with the lowest seasonal rainfall and the highest T_{max}. Similarly, the lowest yield in RDI (4320 kg ha^{-1}) was simulated in 2003, while the highest (5954 kg ha^{-1}) occurred in 2014, when the seasonal rainfall was the highest and T_{max} was the lowest. Over the 30 years, the RDI average grain yield was on average 5272 kg ha^{-1}. The biomass followed a similar trend in both irrigation strategies. In FI, biomass ranged from 9228 kg ha^{-1} (2003) to 10948 kg ha^{-1} (1996), with an average of 10257 kg ha^{-1} . In RDI, it ranged from 8151 kg ha^{-1} (2003) to 10704 kg ha^{-1} (2014), in RDI with an average of 9767 kg ha^{-1}.

The most significant reduction in yield was recorded in 2009, while the least impact was observed in 2008. The tendency of lower yield in RDI to FI aligns with other experimental and simulation studies (Morales-Santos et al., 2023; Zeleke and Nendel, 2024). The difference in biomass follows the same trend as yield, ranging from 55 kg ha^{-1} in 2006 to 1178 kg ha^{-1} in 2009. One of the main benefits of irrigation is the reduction of production variability over time. This effect was observed in this study, where both FI and RDI contributed to stabilizing yield (Figure 3), reducing the coefficient of variation for yield to 3.5% for FI and 6.1% for RDI, compared to 61.7% under rainfed conditions (Table 4). Furthermore, when comparing the two irrigation strategies, FI slightly outperformed RDI in terms of stability effects on yield (Table 4). To achieve optimum yield, lower rainfall amounts are compensated by higher irrigation volumes. As expected, simulations showed that years with abundant rainfall throughout the growing season tend to result in higher yields, while drier years lead to lower yields. Although FI allows yield maximization, the impacts of RDI on economic sustainability and territorial scale effects must be assessed. Considering an average price of grain equal to 0.40 € kg^{-1}, the annual yield reduction of 218 kg results in a decreased revenue of 87.2 €. Additionally, if we considered the average irrigation volume reduction estimated in this study with RDI compared to FI (-55 mm year^{-1}), the cost of water savings is estimated at 0.16 € m^{-3}. Therefore, at a first glance, only irrigation costs exceeding this threshold would warrant the adoption of RDI. However, it is important to consider that: 1) the potential disadvantage for individual farmers may represent a broader advantage at the territorial level for water management authorities (i.e., reduced water use per unit area leading to lower withdrawals from the sources or an increased area served); 2) the economic assessment is influenced by the specific conditions of the year and the site, with the possibility of changing scenarios that could alter the economic framework. For example, geopolitical scenario can change the grain value and/or production costs, environmental regulations can originate withdrawal limitations aimed at maintaining minimum ecological flow in the rivers, the climate change can reduce the water availability for irrigation. In conclusion, our technical result is an orientation that cannot have immediate application, but might be a reference in a modified scenario.

Harvest index

The HI was significantly ($p<0.01$) lower under rainfed conditions compared to FI and RDI, with values fluctuating over the 30 years (from 0 % in 2009 to 53.1% in 2014), and an average value of 38.3% (Table 5). In contrast, the HI was not significantly different between FI and RDI, ranging from 53.0% to 55.6%.

Water productivity

The WP_{ET} was significantly ($p<0.01$) lower under rainfed conditions compared to FI and RDI, which were not significantly different from each other (Figure 3, Table 5). Under rainfed conditions, WP_{ET} ranged from 0.8 kg ha^{-1} mm^{-1} (2012) to 9.5 kg ha^{-1} mm^{-1} (2014), with an average of 4.9 kg ha^{-1} mm^{-1} and zero WP_{ET} in the year 2009 due to zero simulated yield. In FI treatment, the WP_{ET} values ranged from 9.1 kg ha^{-1} mm^{-1} to 11.2 kg ha^{-1} mm^{-1} whereas in RDI, the lowest WP_{ET} was 8.7 kg ha^{-1} mm^{-1} while the highest was 11.7 kg ha^{-1} mm^{-1}. For both irrigation strategies, the lowest WP_{ET} was reached in 2003 and the highest in 2014. Over the 30 years, the average WP_{ET} of FI and RDI was 10.0 kg ha^{-1} mm^{-1}. There is conflicting evidence in the scientific literature regarding the impact of DI in water productivity. Some studies demonstrated higher water productivity for soybean under DI in sub-humid climates (Candogan et al.; 2013; Marković et al., 2016), while others reported higher water productivity for irrigated soybean compared to rainfed soybean cultivation (Suyker and Verma, 2009).

Considering the WP_{Irr}, the values in FI ranged from 6.1 kg ha^{-1} mm^{-1} to 15.6 kg ha^{-1} mm^{-1} with an average of 11.5 kg ha^{-1} mm^{-1}. In RDI, the WP_{Irr} ranged from 8.2 kg ha^{-1} mm^{-1} to 18.9 kg ha^{-1} mm^{-1}, with an average of 13.1 kg ha^{-1} mm^{-1}. In both irrigation strategies, the lowest WP_{Irr} was recorded in 2002, when the seasonal rainfall was highest, while the highest WP_{Irr} occurred in 2020. Although some years showed similar or higher WP_{Irr} in FI compared to RDI, the general trend was an increase, ranging from 0.3 to 4.6 kg ha^{-1} mm^{-1}, with an average value of 1.7 kg ha^{-1} mm^{-1} (Figure 4). The highest and lowest increases in WP_{Irr} followed trends similar to those of yield and biomass.

3.3.3 Meteorological variables and soybean performance

In field conditions, various meteorological factors and field management practices significantly impact crop performance. Therefore, we examined the relationship between soybean performance and meteorological variables. Notably, the soybean response to rainfall followed a quadratic relationship, while it showed a linear relationship with ET_o, T_{max}, and ET_c (Figure 5). Regression analysis further revealed that rainfall positively influenced soybean yield, biomass production, and WP_{ET}, explaining approximately 32.5 to 50.5% of the total variation. In contrast, ET_o and T_{max} negatively impacted these parameters, explaining about 46.9 to 59.1% of the total variation, while ET_c negatively affected WP_{ET} explaining 27.0% of the total variation. These results align with previous studies (Ahumada and Cornejo, 2021; Hatfield and Prueger, 2015; Toffanin et al., 2023; Toreti et al., 2022), which found that soybean performance was particularly sensitive during periods of reduced rainfall and elevated T_{max}. Our findings are consistent with Thomasz et al. (2024), who demonstrated a strong relationship between rainfall and T_{max} with soybean yield, explaining on average 91.2% of the variation. Similarly, irrigation volume showed a significant linear relationship with rainfall, accounting for about 75.5% of the observed variation. Irrigation volume also displayed a significant quadratic relationship with ET_o, explaining 75.9% of its variation and a significant linear relationships with T_{max} and ET_c, explaining 62.2% and 31.9% of the variation, respectively.

These results confirm that increased temperature, evaporative demand, and reduced rainfall contribute to higher irrigation requirements for soybean. Overall, years with reduced rainfall and increased temperature and ET_o, significantly reduced yield and increased irrigation demand.

4. Conclusions

Exploring adaptation strategies like DI is crucial for improving future water productivity. The field experiment demonstrated that RDI on soybean reduced irrigation volume by 22.5% without significantly impacting yield. The parametrized and calibrated AquaCrop model successfully simulated the effects of FI and RDI on soybean yield, biomass, irrigation volume, WP_{ET}, and WP_{Irr} in the last 30 years. Simulation results indicated that if the RDI had been applied in the last 30 years, an average of 17.0% of the irrigation volume (-55 mm year^{-1}) would have been saved, with a slight yield reduction of 4.0% (-218 kg ha^{-1} year^{-1}). Given these considerations, RDI represents a promising irrigation management strategy in water-scarce contexts.

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Figures

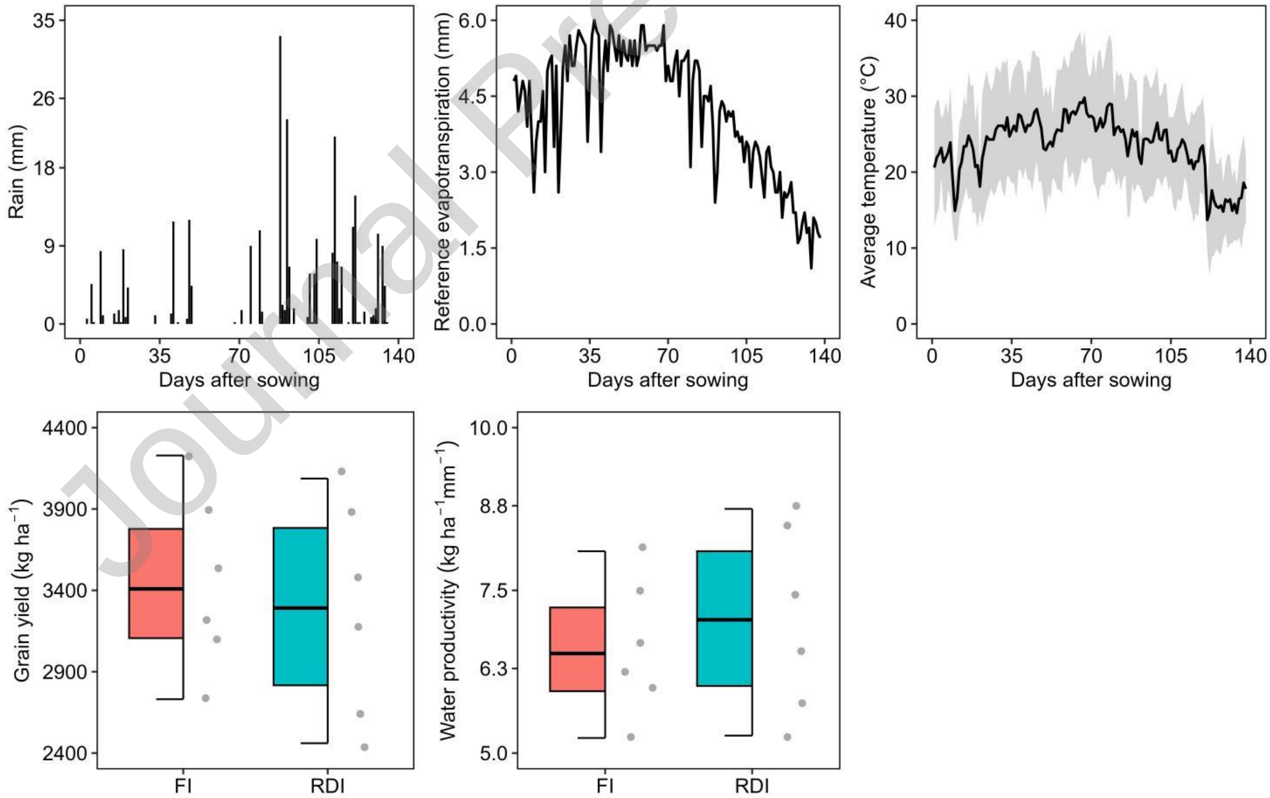

Figure 1. Observed meteorological conditions, grain yield, and water productivity of soybean under full (FI) and regulated deficit irrigation (RDI) during the 2022 growing season (May 20th to October 4th). For the temperature, the shaded grey areas are the minimum (T_{min}) and maximum (T_{max}) temperatures whereas the black solid line is the

average (T_{ave}). For grain yield and water productivity (WP_{obs}), the distribution of data is represented by jitters (grey circles) on the side of the boxplots.

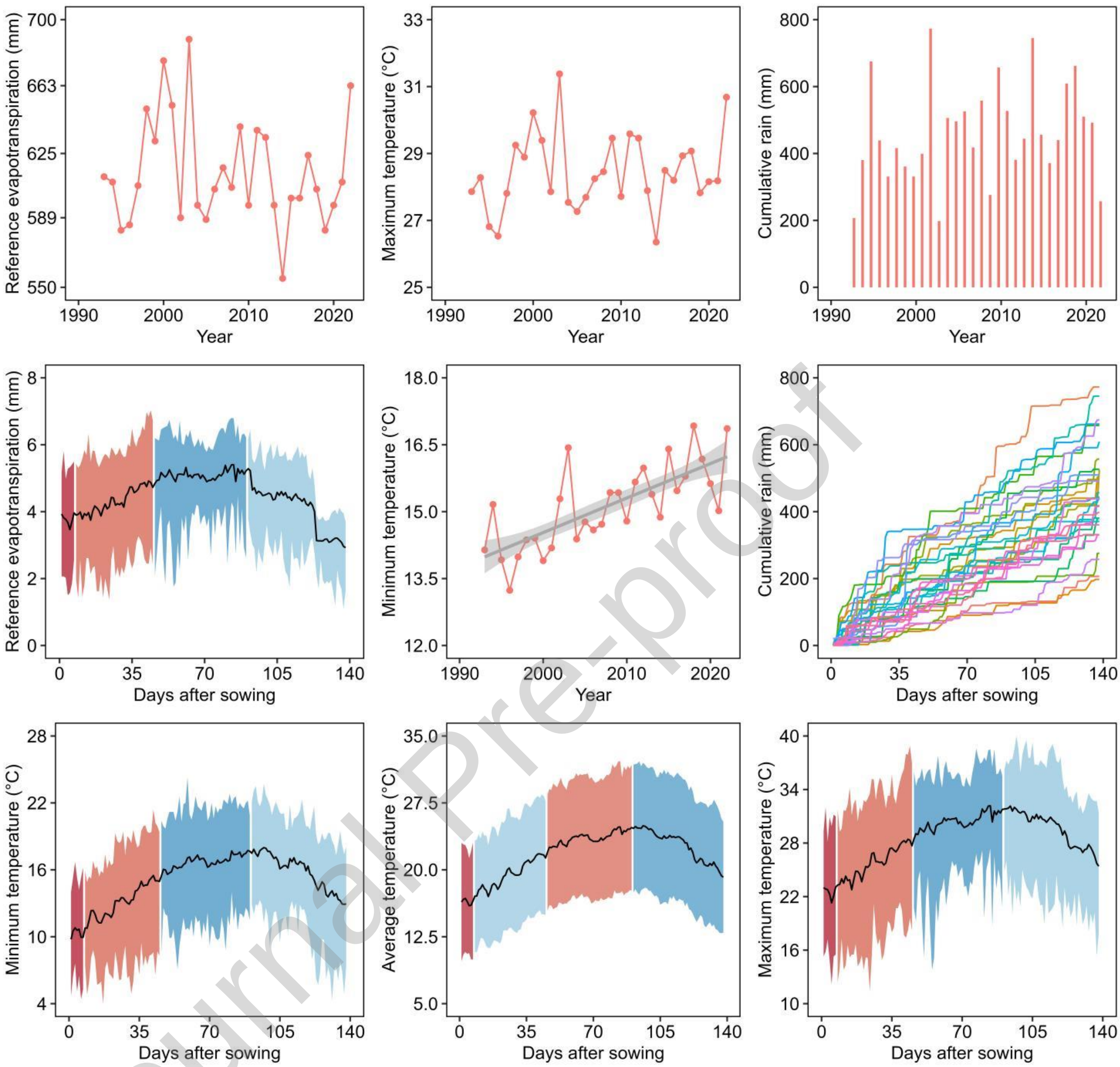

Figure 2. Meteorological variables of Castelfranco during the soybean growing season (May 1 to September 15) over the 30-year period (1993–2022). Upper panel: yearly seasonal reference evapotranspiration (ET_o) (mm), maximum temperature (T_{max}) (°C), and cumulative rain (mm). Middle panel: average daily ET_o (mm), yearly minimum temperature (T_{min}) (°C), and cumulative rain (mm) across growing period. Lower panel: average daily T_{min} (°C), T_{ave} (°C), and T_{max} (°C). For the temperature and ET_o, the solid black line is the average while the shaded areas correspond to minimum and maximum values colored according to phenological stages.

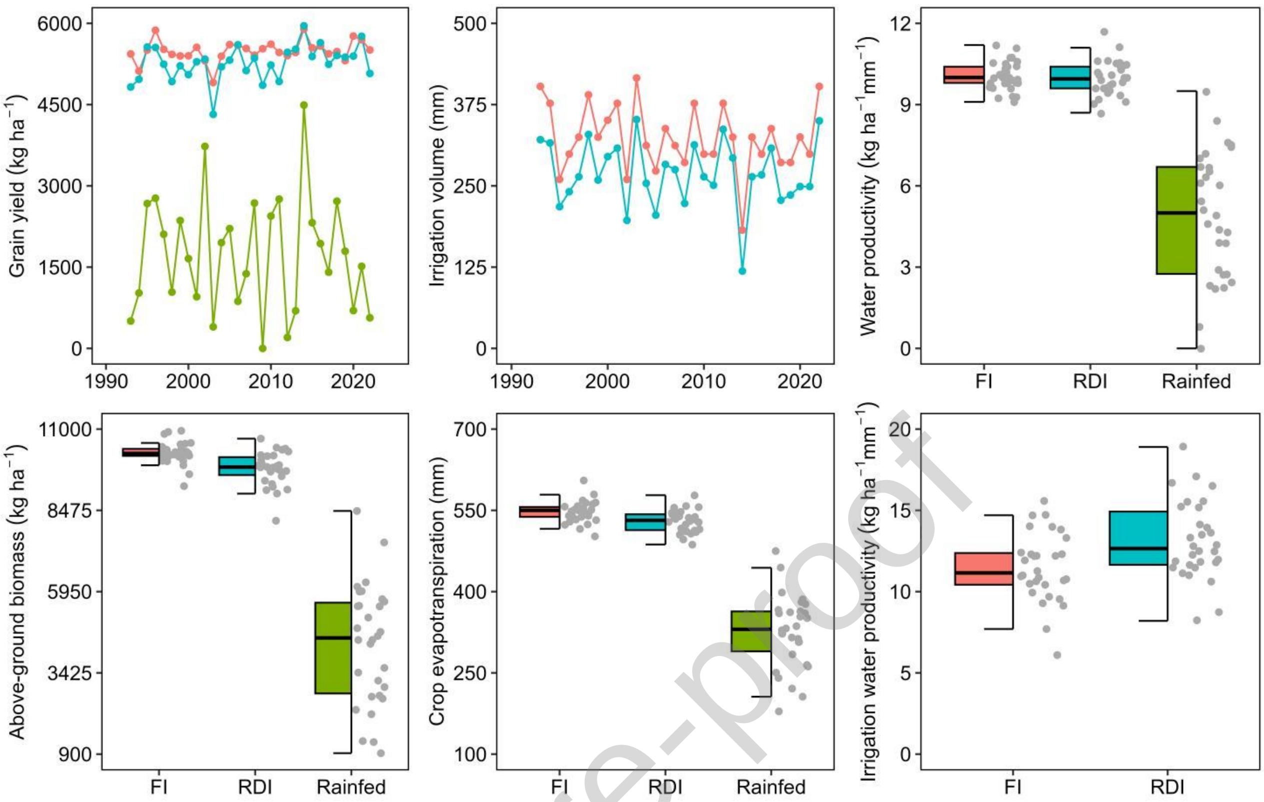

Figure 3. Soybean performance under full (FI) and regulated deficit (RDI) irrigation and rainfed conditions in terms of simulated grain yield (kg ha^{-1}), irrigation volume (mm), water productivity (WP_{ET}) (kg ha^{-1} mm^{-1}), above-ground biomass (kg ha^{-1}), crop evapotranspiration (ET_c) (mm), and irrigation water productivity (WP_{Irr}) (kg ha^{-1} mm^{-1}) over the 30-year period from 1993 to 2022. The color of the line graphs corresponds to irrigation strategies which is red for FI, cyan for RDI, and green for rainfed. The distribution of data is represented by jitters (grey circles) on the side of the boxplots.

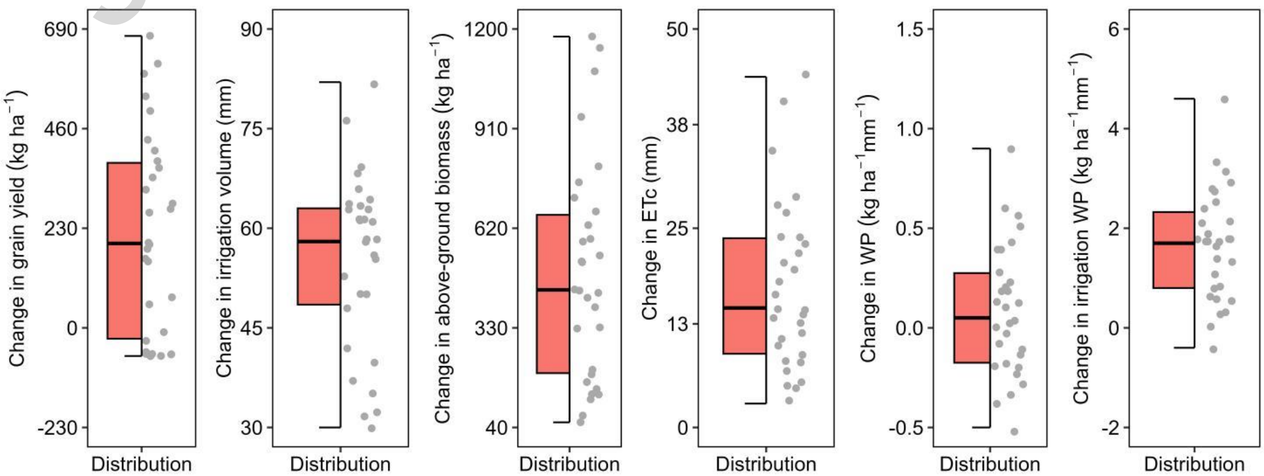

Figure 4. Changes (reductions) in grain yield (kg ha^{-1}), irrigation volume (mm), above-ground biomass (kg ha^{-1}), crop evapotranspiration (ET_c) (mm), water productivity (WP_{ET}) (kg ha^{-1} mm^{-1}), and irrigation water productivity (WP_{Irr}) (kg ha^{-1} mm^{-1}) of regulated deficit irrigation (RDI) relative to full irrigation (FI) simulated over the 30-year period from 1993 to 2022. The distribution of data is represented by jitters (grey circles) on the side of the boxplots.

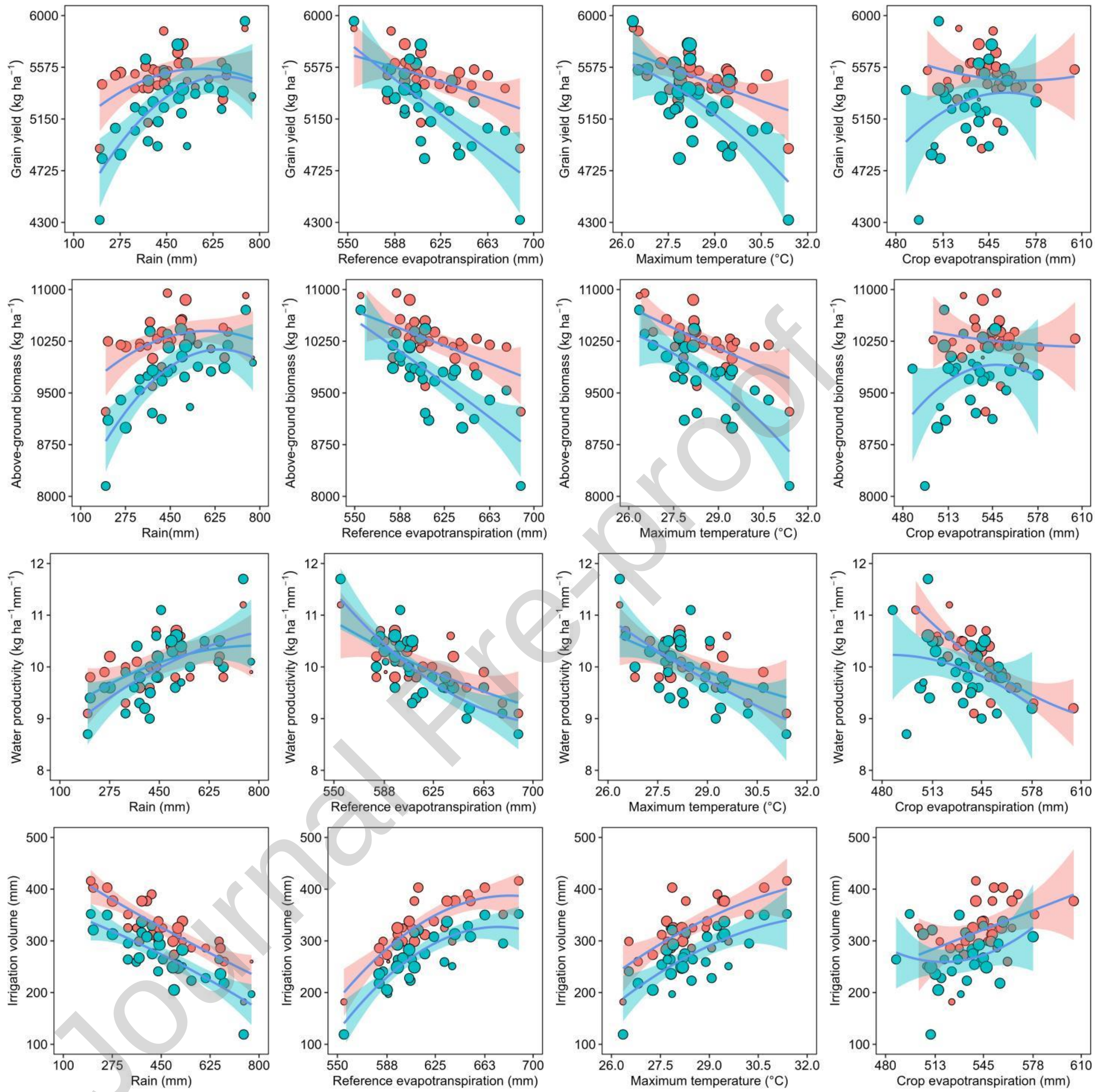

Figure 5. Regression analysis of the relationship of grain yield (kg ha^{-1}), above-ground biomass (kg ha^{-1}), water productivity (WP_{ET}) (kg ha^{-1} mm^{-1}), and irrigation volume (mm) with rain (mm), reference evapotranspiration (ET_o) (mm), maximum temperature (T_{max}) (°C), and crop evapotranspiration (ET_c) (mm) over the 30-year period from 1993 to 2022. The color of the bubble and confidence intervals corresponds to irrigation strategies which is red for FI and cyan for RDI. The size of the bubble is proportional to irrigation water productivity (WP_{Irr}).

Tables

Table 1. Physical and hydrological properties of soil samples in Castelfranco (PD) experimental field. Values were obtained from the analysis of fine soil texture.

Depth	Texture	Field capacity (%)	Permanent wilting point (%)	Hydraulic conductivity (mm/day)	Total available water (mm/m)	Saturation (%)
0–20 cm	Loam	28.1	15.1	229.7	102	45.5
20–40 cm	Loam	28.9	15.3	212.8	107	45.7
40–60 cm	Loam	27.8	14.8	240.5	102	45.4

Table 2. Rainfall and irrigation water supplied in the experimental field of Castelfranco during the growing season (May–October 2022).

Month	Wetting events (n°)	Irrigation volume (mm)		Rain (mm)	Irrigation + Rain (mm)	
		FI	RDI		FI	RDI
May	0	0	0	14.8	14.8	14.8
June	4	31	24	30.8	61.8	54.8
July	7	108	92	19	127	111
August	3	78	54	112.6	190.6	166.6
September	1	27	19	100.8	127.8	119.8
October	0	0	0	0	0	0
Total	15	244	189	278	522	467

Table 3. AquaCrop input parameters used to simulate soybean responses.

Parameter	*Default value	Value	Unit	Remarks
Crop characteristics				
Base temperature (T_{base})	5	5	°C	Default value
Upper temperature (T_{upper})	30	30	°C	Default value
Soil surface covered by an individual seedling at 90% emergence	5.00	5.00	cm^2 $plant^{-1}$	Default value

Number of plants per hectare	250,000 – 450,000	262,500	–	Measured value
Time from sowing to emergence	150 – 300	105	GDD	Measured value
Canopy growth coefficient (CGC)	0.015	Fast expansion (0.844)	% GDD^{-1}	Calibrated value
Maximum canopy cover (%)	Almost entirely covered to Entirely covered	Almost entirely covered (98)	%	Measured value
Time from sowing to start senescence	Time to emergence + 1600 – 2400	1425	GDD	Measured value
Canopy decline coefficient (CDC)	0.015	Very slow decline (0.192)	% GDD^{-1}	Calibrated value
Time from sowing to maturity	Time to emergence + 2000 – 3000	2070	GDD	Measured value
Time from sowing to flowering	Time to emergence + 1000 – 1500	675	GDD	Measured value
Length of the flowering stage	400 – 800	675	GDD	Measured value
Crop determinacy linked with flowering	Yes	Yes	–	Default value
Minimum effective rooting depth (Z_n)	0.30	0.30	m	Default value
Maximum effective rooting depth (Z_x)	Up to 2.40	Shallow rooted crop (0.50)	m	Calibrated value
Shape factor describing root zone expansion	1.5	1.5	–	Default value
Crop coefficient when canopy is complete but prior to senescence	1.10	1.10	–	Default value
Decline of crop coefficient as a result of ageing, nitrogen deficiency, etc.	0.300	0.300	% day^{-1}	Default value
Effect of canopy cover on reducing soil evaporation in late season stage	25	25	%	Default value
Water productivity normalized for ETo and CO_2	15.0	15.0	$g\ m^{-2}$	Default value

Water productivity normalized for ETo and CO2 during yield formation (as percent WP* before yield formation)	60	60	%	Default value
Reference harvest index (HI)	45	55	%	Calibrated value
Possible increase (%) of HI due to water stress before flowering	Small	Small	–	Default value
Coefficient describing positive impact of restricted vegetative growth during yield formation on HI	None	None	–	Default value
Coefficient describing negative impact of stomatal closure during yield formation on HI	Strong	Strong	–	Default value
Allowable maximum increase of specified HI	10	10	%	Default value
Soil water stress				
Soil water depletion threshold in the soil for canopy expansion p_{exp} (upper)	0.15	0.15	–	Default value
Soil water depletion threshold in the soil for canopy expansion p_{exp} (lower)	0.65	0.65	–	Default value
Shape factor for water stress coefficient for canopy expansion	3.0	3.0	–	Default value
Soil water depletion threshold for stomatal control p_{sto} (upper)	0.60	0.60	–	Default value
Shape factor for Water stress coefficient for stomatal control	3.0	3.0	–	Default value
Soil water depletion threshold for canopy senescence p_{sen} (upper)	0.70	0.70	–	Default value
Shape factor for water stress coefficient for canopy senescence	3.0	3.0	–	Default value

*Source: Raes et al. (2022)

Table 4. Performance indicators of AquaCrop model calibration for full (FI) and regulated deficit irrigation (RDI). RMSE = root mean square error; NRMSE = normalized root mean square error.

	Yield		**Water productivity**	
	FI	*RDI*	*FI*	*RDI*
RMSE	235.2	256.0	1.2	0.7
NRMSE	6.8	7.8	18.8	10.3
Coefficient of variation (%)	3.5	6.1	5.2	6.5

Table 5. Average crop evapotranspiration (ET_c), irrigation volume, grain yield, above-ground biomass, harvest index (HI), water productivity (WP_{ET}), and irrigation water productivity (WP_{Irr}) of soybean under full (FI) and deficit (RDI) irrigation over the past 30 years from 1993 to 2022.

Irrigation strategy	**Crop evapotranspiration (mm)**	**Irrigation volume (mm)**	**Yield (kg ha^{-1})**	**Biomass (kg ha^{-1})**	**Harvest index (%)**	**Water productivity (kg ha^{-1} mm^{-1})**	**Irrigation water productivity (kg ha^{-1} mm^{-1})**
Full irrigation	547^{ad}	324^{a}	5490^{ad}	10257^{ad}	53.5^{ad}	10^{ad}	11.5^{a}
Deficit irrigation	530^{bd}	269^{b}	5272^{bd}	9767^{bd}	54.0^{bd}	10^{bd}	13.1^{b}
Rainfed	326^{c}	–	1728^{c}	4321^{c}	38.3^{c}	4.9^{c}	–

values with the same letter are not significantly different ($p<0.05$)

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

1. Regulated deficit irrigation (RDI) reduced dry grain yield by 4.6% and increased water productivity by 6.1% in the field.
2. AquaCrop simulated well the impacts of full and regulated deficit irrigation from 1993 to 2022.
3. According to simulations RDI reduced irrigation volume by 17% (-55 mm per year) respect FI, with yield loss of 4.0%
4. Regulated deficit irrigation is a viable option to maximize soybean water productivity.