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ORIGINAL PAPER

Assessing the water conservation potential of optimized surface irrigation management in Northern Italy

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Abstract

The effects of climate change on water availability affect the performance of surface irrigation, which is the oldest and most common method of water application to row crops worldwide. A paradigm shift towards strategies aimed at increasing flexibility of irrigation scheduling and improving the design and management of field layouts and irrigation practices should be explored to promote water conservation at the farm scale. In this study, we investigate how by adopting a more flexible irrigation scheduling and optimizing irrigation management variables and field layout it is possible to increase the efficiency of border irrigation and thus achieve water conservations and improve quality of crop production. The analysis of the actual performance of border irrigation was carried out on two maize fields located in the Padana Plain (Northern Italy) in 2 years characterized by different rainfall patterns (i.e. 2021 and 2022). Based on this information, continuous monitoring of soil moisture status combined with the AquaCrop-OS agro-hydrological model was used to manage flexible irrigation scheduling over the experimental fields, while the optimization of irrigation management (flowrate per unit width and cutoff time) and field geometries (border width and slope) was studied using WinSRFR 5.1 USDA software, which was properly calibrated by measures of waterfront advance and recession. The results show that with flexible irrigation scheduling and proper irrigation management and field layout, significant water conservation can be achieved. Specifically, in the case study, seasonal water conservation of about 10% was obtained just by scheduling irrigation based on actual crop water needs in a very dry agricultural season, while water conservation reached up to 60% in a wetter season. On average, an additional 7% of water conservation was achieved over the agricultural season when the irrigation duration was correctly applied to each border of the experimental plots, while approximately 20% of water was conserved when the border width was correctly designed based on inflow availability. These results provide useful information for improving the management of border irrigation in practice, both under current conditions and in prospective of increasing freshwater scarcity in the future.

Introduction

The consequences of climate change are being experienced globally (Ison 2010), and one of the main areas affected by changes in temperature and precipitation leading to an increase in drought events is irrigated agriculture (Esteve et al. 2015; Worqlul et al. 2019). Irrigated agriculture is particularly vulnerable in areas historically characterized by an abundance of freshwater, such as the Padana Plain, the largest irrigated plain in Europe (Nikolaou et al. 2020). For example, the 2022 agricultural season was the worst drought in the region in the past 70 years, with about 50% less rainfall than the average of the past two decades, and storage—including mountain hydroelectric reservoirs and natural lakes—was 53% less than the 2006–2020 reference average. As a result, the General Confederation of Italian Agriculture declared a 30% loss in crop production (especially rice and

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fodder crops) in 2022, with hundreds of millions of euros in damages in the agri-food sector (The New York Times—July 12, 2022, The Guardian—July 10, 2022). In addition, the presence in the Padana Plain of large areas cultivated with intensively irrigated crops such as rice and maize, mainly irrigated with surface methods, exacerbates the effects of this water shortage.

The modernization of surface irrigations (e.g., laser levelling systems, automatic water distribution systems in upstream fields) has contributed to improve the efficiency of these irrigation methods, which are considered to be water-intensive. Nevertheless, due to its low investment cost and the possibility of delivering a significant amount of water to a given field in a few times, surface irrigation managed with its traditional operation is still widely practiced worldwide (Playàn et al. 2018). However, since not all farmers can benefit from a substantial amount of water at the same time, a water rotation is usually applied at the irrigation district level. This situation significantly reduces the flexibility of this irrigation system, i.e. the farmer cannot irrigate when he decides to do so. This lack of flexibility is considered one of the main barriers to water savings in surface irrigation (Maihlol and Merot 2008, Mailhol et al. 2004).

Data from the International Commission on Irrigation and Drainage, published on the Food and Agriculture Organization's Aquastat website, show that surface irrigation is used on 97% of the irrigated area in India, 94% in China, 44% in the United States, and 100% in Pakistan (i.e., the 58% of the world's total irrigated area). In general, among the different types of surface irrigation, border irrigation is the most common method for watering row crops worldwide (Fadul et al. 2020), especially in Australia (Kohec and Langat 2018), northern China (Liu et al. 2020), and southern Europe (Masseroni et al. 2017). Despite its low energy costs (compared to pressurized systems), the practice of border irrigation is often accused of high inefficiency due to overwatering and poor application uniformity (Gillies and Smith 2015; Morris et al. 2015; Chari et al. 2019). To address these allegations, EU policies at various levels (from regional to national irrigation authorities) are allocating funds for the modernization of surface irrigation infrastructure, favoring the transition to new irrigation methods rather than increasing the operational efficiency of traditional methods. An example was the case of the Spanish government, which launched the National Irrigation Modernization Plans (MAPAMA and MAPAMA 2002, 2010) to address deficiencies in irrigation projects, water scarcity problems, EU water directives, and changes in social structure. These plans took advantage of new information and communication technologies for a broad transition to pressurized systems (Playan et al. 2018; Zapata et al. 2023). A new plan to improve the efficiency and sustainability of irrigated areas in Spain was implemented as part of the European Union's post-COVID recovery and resilience plan (BOE 2021). Similar experiments aimed at modernizing surface irrigation practices were carried out in southern France, where models were developed to test the impact of a decision rule on hay production at the plot scale and for a given climatic scenario (Mailhol and Merot 2008).

In Italy, a practical example of this transition, which is linked to a preference for switching to new irrigation methods rather than improving the operational efficiency of traditional one, is demonstrated by the recent approval of 149 projects to "maintain the resilience of irrigated agricultural systems to improve the management of water resources", for a total of 1.6 billion euros. Only 10% of these projects funded under Mission 2 of the Italian Recovery Plan have in their title a clear reference to the implementation of systems to improve the irrigation management of existing infrastructures (e.g. monitoring systems, automation and telecontrol) rather than the construction of new ones. Since only a few and often isolated experiences on surface irrigation in the EU have been carried out so far to understand (i) the current irrigation efficiency of these practices and (ii) the expected performance of new management solutions, the above-mentioned policy oriented towards a radical conversion of traditional irrigation pratices really be blamed.

In light of these considerations, there is an urgent need for studies in this context to understand whether alternative solutions to the substitution of traditional, gravitational irrigation methods with pressurized systems are actually feasible and sustainable. New soft-path strategies aimed at improving traditional irrigation techniques and increasing their efficiency are emerging through bottom-up initiatives in the form of "information and pilot project actions" with the aim of assessing the potential of novel approaches to marginal irrigation management (Masseroni et al. 2021). In particular, in this work we go a step further than the results obtained by Masseroni et al. (2022) to develop a comprehensive analysis of the water conservation potential of optimized surface irrigation management. Specifically, this work examines the results of an extensive experimental campaign carried out in the years 2021 and 2022, aimed at (i) analyzing the actual performance of border irrigation in case studies located in the Padana plain, (ii) testing and simulating the effects on water consumption of a more flexible scheduling of irrigation interventions and (iii) exploring to which extent optimizing the intervention management variables (discharge per unit width and cut-off time) and the field layout can contribute to increasing the efficiency of border irrigation. This work focuses on a specific case study, but we believe that its results provide indications for improving border irrigation that are valid in general.

Material and methods

The study domain

The irrigation performances and the new irrigation management were studied and tested on two different fields located in the Padana plain during the agricultural seasons 2021 and 2022. The two fields (fields A and B), each about 1.5 ha in size, are located 2 km from each other in the area south of Lake Garda, within the same 130 ha irrigation district (i.e. the Ponte Trento irrigation district) (Fig. 1). The Padana plain has traditionally been characterized by an abundance of freshwater resources resulting from a favorable system of mountains, natural reservoirs , rivers and canals that, respectively, generate, store, and then distribute water throughout the plain. The study area is characterized by a humid subtropical climate according to the Köppen-Geiger classification system (Kottek et al. 2006) and the characteristics of the irrigation district can be found in Masseroni et al. (2021). Regarding the rainfall pattern, the average value of total rainfall during the agricultural season (from 1st April to 30th September) in the past 27 years (from 1993 to 2020) was about 230 mm. In the 2021 agricultural season, the total rainfall in the study area was about 241 mm (i.e. very close to the historical average between April and September), while in 2022 it was about 144 mm (i.e. 60% less than in

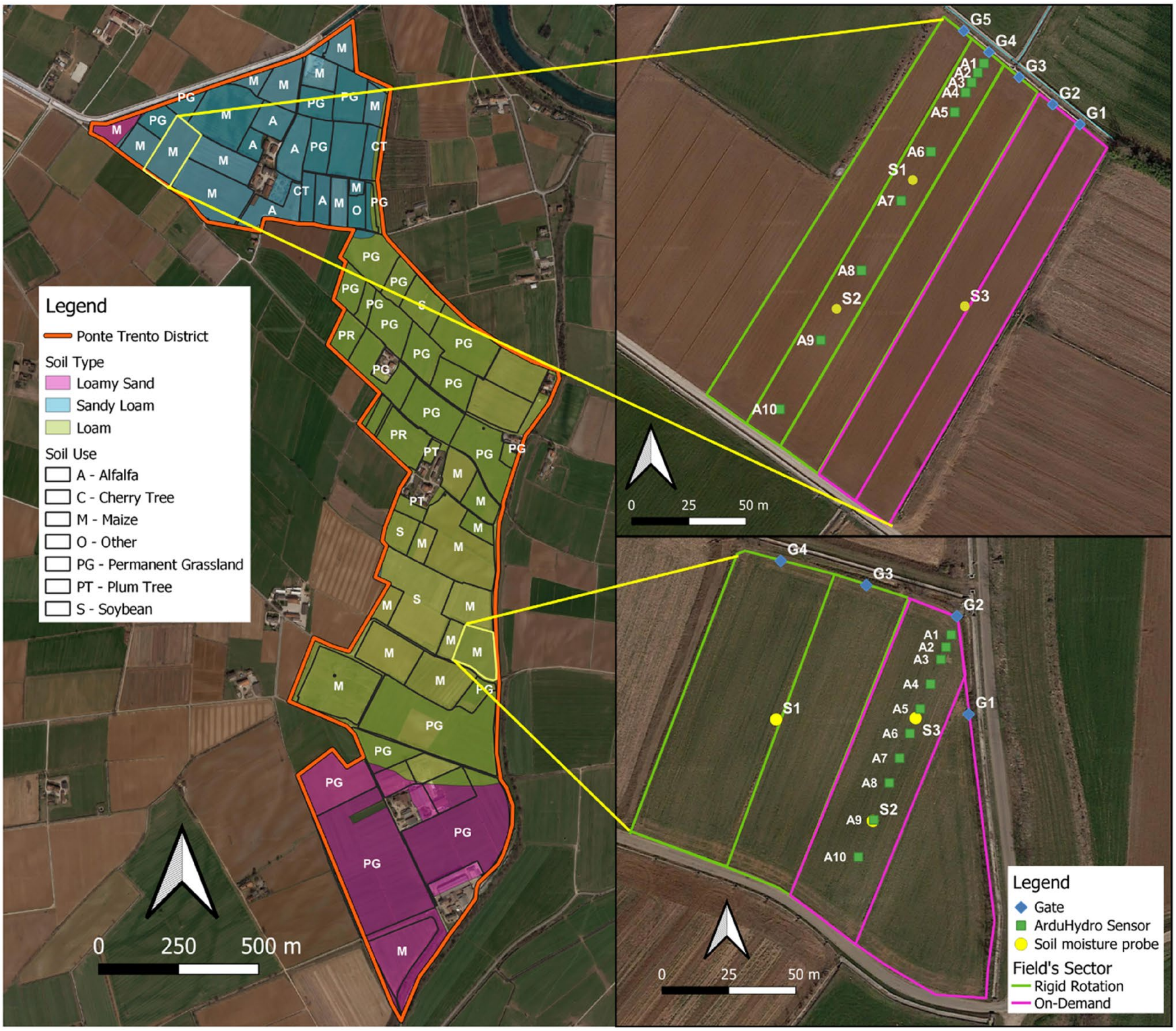


Fig. 1 Ponte Trento irrigation district with focus on the two experimental fields (i.e. Field A at top and Field B at bottom). The image shows the land use and type over the district, while for the two experimental plots, the location of the soil moisture and water level sensors are shown

2021), showing that the year 2022 was very dry compared to the average of past seasons.

In the Ponte Trento district, irrigation water is supplied by the Virgilio canal (the main canal diverting up to 24 m^3 s^{-1} from the Mincio River) and distributed to the fields through a dense and ramified network of irrigation ditches. On average, the irrigation season begins each year on April 1 and ends on September 30. The nominal flow diverted from the Virgilio Canal and delivered to each field in the district is 360 l/s, according to a rigid rotation of 7 days. Therefore, farmers are limited to using water for irrigation once a week.

All fields in the Ponte Trento irrigation district are border irrigated (including Field A and B). Water flows onto the field through a series of steel gates that are manually opened in sequence to supply water to each strip, starting from the main supply canal located at the upper end of the field. During irrigation, water is distributed in the longitudinal direction of the field (i.e., following the field slope) until the strip is fully irrigated. Both fields are well leveled, but not laser leveled. The water is completely gravity driven from the diversion point to the field with zero energy cost for irrigation. No surface runoff is observed during irrigation because both fields are closed-ended. Both fields are planted with maize. First and second harvest maize were sown in Field A and B, respectively. In field A, the maize sowing date corresponded to the literature standards (i.e. around the end of March), while in field B, the maize was sown 20 days in delay than in 2021 (i.e. in mid-June—which is the standard). This was due to the very peculiar dry season that occurred in 2022, which drastically limited the availability of surface freshwater for irrigation in a large part of the Padana plain. As a result of a series of water supply restrictions imposed by irrigation agencies, many farmers decided to abandon the second harvest or to postpone the sowing date so that the moment of maximum water demand of the plant would fall back to the late summer or in autumn, i.e. when rainfall events should be more frequent in the mid-latitudes.

Additional information on the characteristics of Field A and B (e.g. geometries, soil type, crop, sowing and harvesting dates, etc.) is reported in Masseroni et al. (2022) and briefly summarized in Table 1.

Instrumentation and monitoring activity

A weather station (ATMOS 41, Meter Group®, USA) equipped with a rain gauge, a radiometer, an anemometer, and thermo-hygrometer was installed nearby the experimental fields (about 500 m from Field A and 1.5 km from the Field B) at the beginning of the 2021 agrarian season to continuously monitor agro-meteorological variables. In addition, three soil moisture monitoring points were installed within each experimental field for evaluating soil water status during the whole irrigation season (Fig. 1). Each point was equipped with five soil moisture probes (Teros 12, Meter Group®, USA) at a depth of 10, 30, 50 and 70 cm for detecting the water content down to the lower limit of the root zone. Five soil samples were collected at 0–5, 10–15, 30–35, 50–55 and 70–75 cm (i.e., roughly where soil moisture probes were installed) to evaluate soil texture and, indirectly, soil hydrological proprieties—these latter

Table 1 Details on the characteristics of the experimental fields

Description	Year	Field A	Field B
Coordinates (WGS84-Lon,Lat)	2021–2022	(10.6873,45.3025)	(10.6989,45.2882)
Size (ha)	2021–2022	1.7	1.4
Average field length (in the longitudinal direction) (m)	2021–2022	188	113
Average longitudinal slope (‰)	2021–2022	6.9	6.1
Number of strips	2021–2022	5	4
Average strip width (m)	2021–2022	18	30
Average strip area (ha)	2021–2022	0.34	0.34
Crop	2021–2022	Maize	Maize
Cultivar	2021–2022	Pioneer P2088–70 (FAO 300)	Dekalb DKC6795 (FAO 600)
Sowing date	2021	29th March	19th June
	2022	27th March	9th July
Harvesting date	2021	11th August	10th October
	2022	1st August	28th October
Soil texture*	2021–2022	Sandy/sandy-loam (with about 30% of skeleton)	Sandy/sandy-loam (with about 30% of skeleton)
Irrigation rotation (days)	2021–2022	7	7

*According to the United States Department of Agriculture definitions using pedo-transfer functions implemented within the agro-hydrological models used for estimating crop water requirements (see Section "Crop water requirement modelling and settings"). The soil, in the sampling points, resulted to have morainic terrain proprieties: its texture was predominantly sandy, sandy-loam with a skeleton higher than 30%.

For each irrigation event, the real flow rate and duration of irrigation intervention were monitored for determining the average irrigation depth in each strip and onto the field. In all cases, data were collected with an hourly time resolution and were aggregated to a daily scale to be used for modeling (see Section "Crop water requirement modelling and settings").

The monitoring of the border irrigation water depth evolution onto the field (in terms of waterfront advance and recession) was performed during two irrigation events, ion 23 March 2021 for Field A and on 27 July 2021 for Field B. The water depth was detected through ten homemade water level devices (ArduHydro—Galli et al. (2022)), which were installed along the longitudinal direction of the field as shown in Fig. 1. The water depth values over the field during the irrigation event were obtained as the difference between the distance from the ground surface and from the water surface measured by the sensor, respectively, before and during the irrigation event. The sensors were installed just before the beginning of the irrigation intervention and removed right after the water depth across the field was completely depleted. In Field A, the water level sensors were installed at 5, 10, 15, 20, 30, 50, 75, 105, 140 and 175 m from the head of the field; in Field B they were located at 10, 15, 20, 30, 40, 50, 60, 70, 85, 100 m. More information on the instrumentations and monitoring procedures adopted in both experimental fields can be found in Masseroni et al. (2022) and Costabile et al. (2023).

Crop water requirement modelling and settings

Irrigation requirements were estimated by AquaCrop-OS (model version 6.0 of Foster et al. (2017) and Steduto et al. (2012)) and used to make in-season irrigation scheduling decisions in both fields. Specifically, the model was calibrated on the study fields using soil moisture probe measurements, and then used to support irrigation decisions. The model calculates the values of total available water (TAW), readily available water (RAW) and critical soil moisture (CMC) in addition to estimating the temporal evolution of soil water content (SWC). The CMC represents a threshold of soil water content under which the soil moisture deficit could affect crop health.

A detailed description of the features of the model has already been reported in Masseroni et al. (2022) and is presented here in Supplementary Material—Supplement 1.

Modelling parameterization

Daily time series of the relevant meteorological variables (i.e. air temperature, relative humidity, solar radiation, wind speed and precipitation) needed to simulate the gross irrigation demand on Fields A and B were obtained from the weather station included in the study area for both years of the experimental campaign. Regarding AquaCrop, in addition to the rainfall data, the model requires two sets of calibration parameters that include soil and crop characteristics. Regarding the crop characteristics, the model estimates the different stages of canopy cover development according to Raes et al. (2012). In particular, for fields A and B, the canopy cover parameters were calibrated using the leaf area index (LAI) derived from Sentinel-2 images (10 × 10 m resolution) using the Biophysical 10 mOp tool of the Copernicus Snap software. Specifically, the canopy was derived from the LAI information using the method proposed by Hsiao et al. (2009). Figure 2 shows the calibrated canopy cover curve compared to satellite observations for each experimental plots in both years.

Once the canopy cover parameters were obtained, the soil hydrological properties (water retention at saturation, at field capacity, at permanent wilting point and saturated hydraulic conductivity) were also adjusted by fitting the simulated soil moisture patterns from AquaCrop to those observed by the soil moisture probes. For this purpose, the rooted soil layer was divided into two layers as folows: an upper one, 10 cm deep, where most of the evaporative processes take place, and a lower one, of variable depth according to root growth, where most of the root water uptake for plant transpiration takes place. The water content of the first layer was assumed to be equal to the value measured by the most superficial sensor, while that of the lower layer was calculated as the average of the values measured by the sensors located inside the layer itself. Roots were assumed to be able to explore a maximum of 1 m at full plant growth. The model calibration, performed with measurements carried out in the year 2021, resulted in a good fit between simulated and observed soil water content, especially during the peaks following rain or irrigation events (Fig. 3). The goodness of fit was evaluated by the Root Mean Square Error (RMSE), which was found to be very small in both experimental fields and in both layers: specifically, about 0.1 $m^3\ m^{-3}$ in the evaporative layer and approx. 0.04 $m^3\ m^{-3}$ in the transpirative layer.

Good guideline values for the soil physical properties required by AquaCrop (i.e. water retention at field capacity, water retention at permanent wilting point, water retention at saturation, etc.) have been derived from the hydraulic property calculator developed by the USDA Agricultural Research Service in collaboration with Washington State University (and already included in the AquaCrop model). These parameters were then slightly

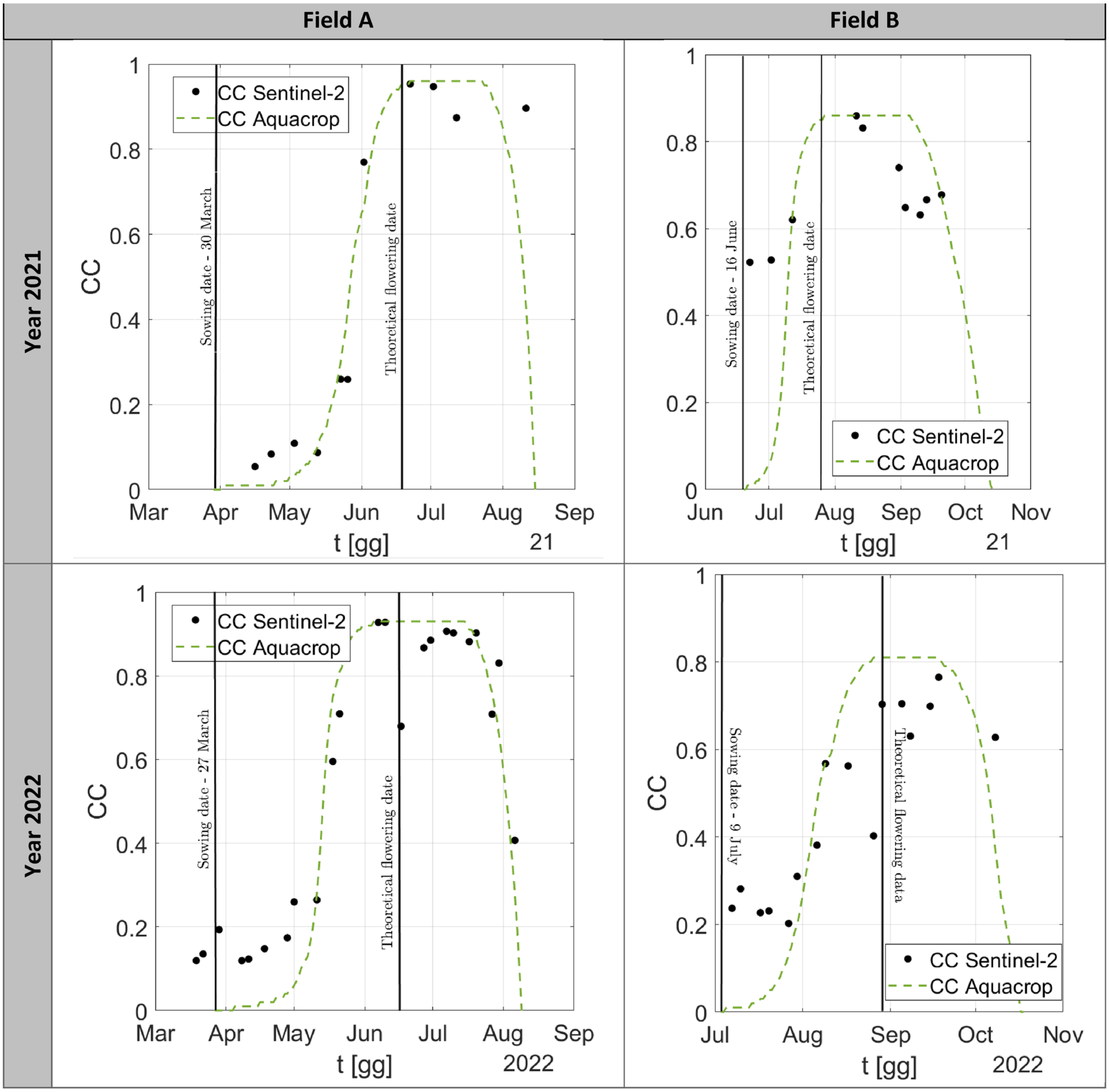


Fig. 2 Observed and simulated canopy cover evolution during the two-year experiment. The observed canopy cover was derived from Sentinel-2 satellite observations. Sowing date and theoretical flowering date (i.e. about 80 days after sowing date for the early harvested maize and about 50 days for the late harvested maize according to Bonhomme et al. 1994) are indicated in the images

adjusted to match the simulated soil moisture measurements. The calibrated soil and crop model parameters are presented in Table 2, while additional information on model parameterization for this specific case study can be found in Masseroni et al. (2022).

Dynamics of the border irrigation event

Dynamics of the irrigation events were investigated using WinSRFR 5.1 model (Bautista et al. 2009) developed by the United State Department of Agriculture (USDA). It

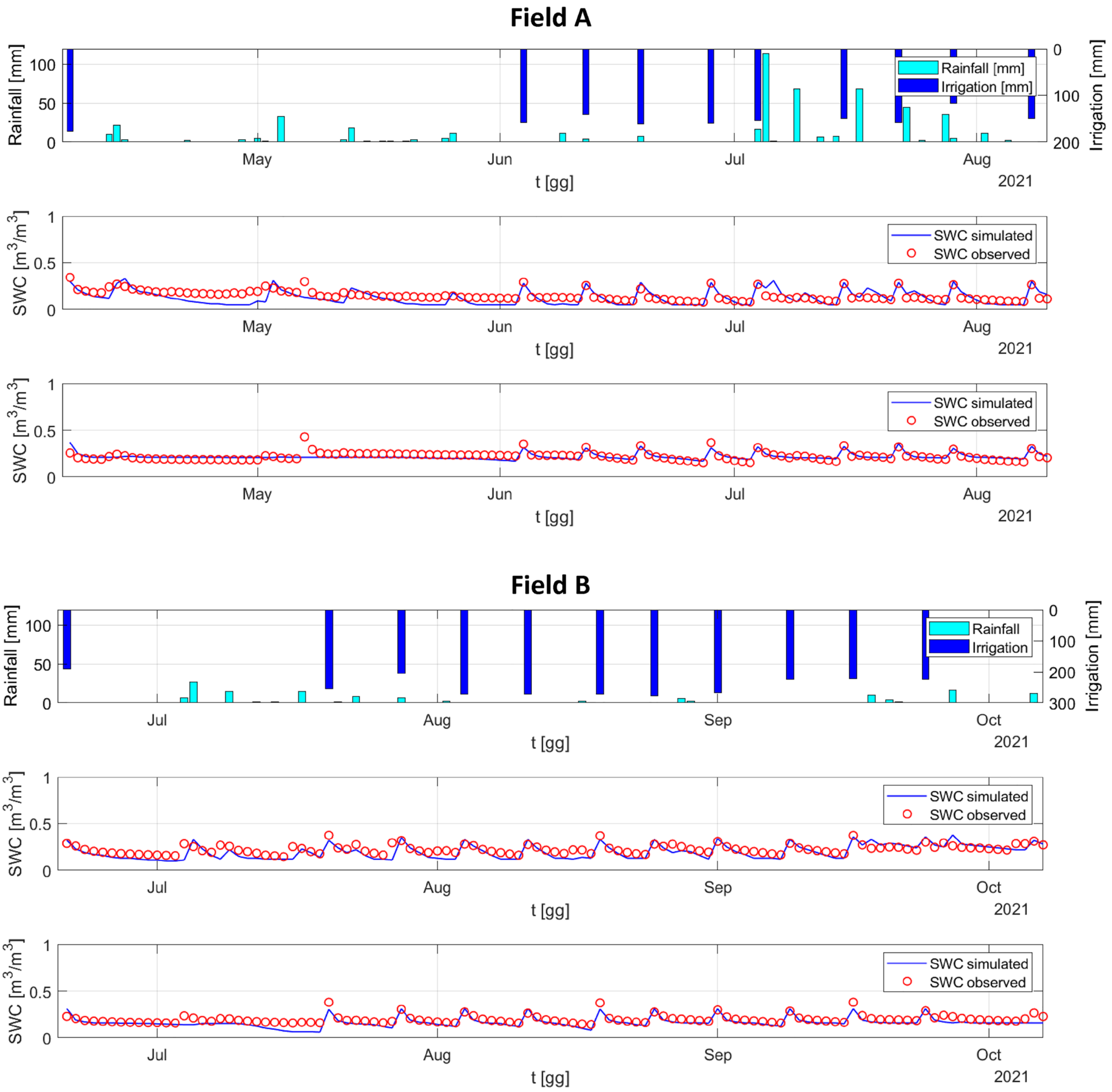


Fig. 3 Comparison between simulated and observed soil water content (SWC) in the evaporative and transpirative layer of the Field A and B. Agricultural season 2021

represents a new generation of software for analyzing surface irrigation systems. Founded on an unsteady one-dimensional flow hydraulic model, the software integrates event analysis, design, and operational analysis functionalities, in addition to simulation. The software has a user-friendly interface, from which the user can edit data, run the analysis, and view outputs. Performance indicators generated by the software include the application efficiency (AE), low-quarter irrigation adequacy (AD_{lq}), minimum irrigation adequacy (AD_{min}), low-quarter distribution uniformity (DU_{lq}), minimum distribution uniformity (DU_{min}), runoff (RO) and deep percolation (DP) fractions (Burt et al. 1997).

In both experimental fields (i.e., Field A and Field B), the model was applied in the simulation mode, operation, and design analysis. These simulation environments can simulate unsteady surface–subsurface flow for individual strips. Flow rate, irrigation duration, strip geometries, and downstream conditions (i.e., blocked borders) were introduced into the model prior to simulation. Contrary to the other irrigation systems, the irrigation operation in the border irrigation

Table 2 AquaCrop soil and crop calibrated parameters on the case studies

Model parameter	Field	Layer (m)	θ_S (m^3/m^3)	θ_{FC} (m^3/m^3)	θ_{WP} (m^3/m^3)	K_{sat} (mm/day)
Soil	A	0.1	0.33	0.22	0.07	2132
		0.9	0.37	0.20	0.09	466
	B	0.1	0.38	0.32	0.11	2532
		0.9	0.37	0.32	0.11	566
			CC_0	CC_x	CGC	CDC
Crop	A		6.5	0.927	0.0169	0.007
	B		6.5	0.86	0.015	0.0064

θ_{FC} water retention at field capacity, θ_{WP} water retention at permanent wilting point, θ_s water retention at saturation, K_{sat} saturated hydraulic conductivity, *CC0* green canopy cover when 90% emergence has occurred, *CCx* canopy cover maximum, *CGC* canopy growth coefficient, *CDC* canopy decline coefficient. (Table based on Masseroni et al. (2022))

methods is strongly influenced by the waterfront advance process. The latter is itself influenced by the soil water status (soil water deficit) just before the start of irrigation. Consequently, the irrigation decision should not only be based on the soil water deficit, but also take into account the impact of this water deficit on the advance process. Therefore, infiltration process was described by the Green-Ampt equation (Green and Ampt 1911), where saturated water content, wetting front pressure head, and saturated hydraulic conductivity were derived from soil texture characteristics using literature information and then adjusted as appropriate after the calibration step. Instead, the initial volumetric water content was determined from the soil moisture probes installed in the fields. Manning resistance was also calibrated, while the average longitudinal slope of the strip was used to describe the soil.

Model calibration consisted of finding a unique set of infiltration and roughness parameters that provided a good description of the waterfront advance and recession curves. This was achieved by comparing the model predictions of the waterfront evolution with the ArduHydro measurements along the longitudinal direction of the field. The best fit obtained between the observed and simulated advance and recession curves in the two monitored irrigation events of May 23, 2021 (in Field A) and July 27, 2021 (in Field B) is presented in Fig. 4, while the best infiltration and roughness parameters obtained through a manual trial-and-error calibration are presented in Table 3.

Experimental design and simulations

The experimental campaign at field scale was organized in two successive moments: the first year was mainly dedicated to the field observations and the second year was dedicated to the implementation of new border irrigation management strategies. The field observations consisted in studying the

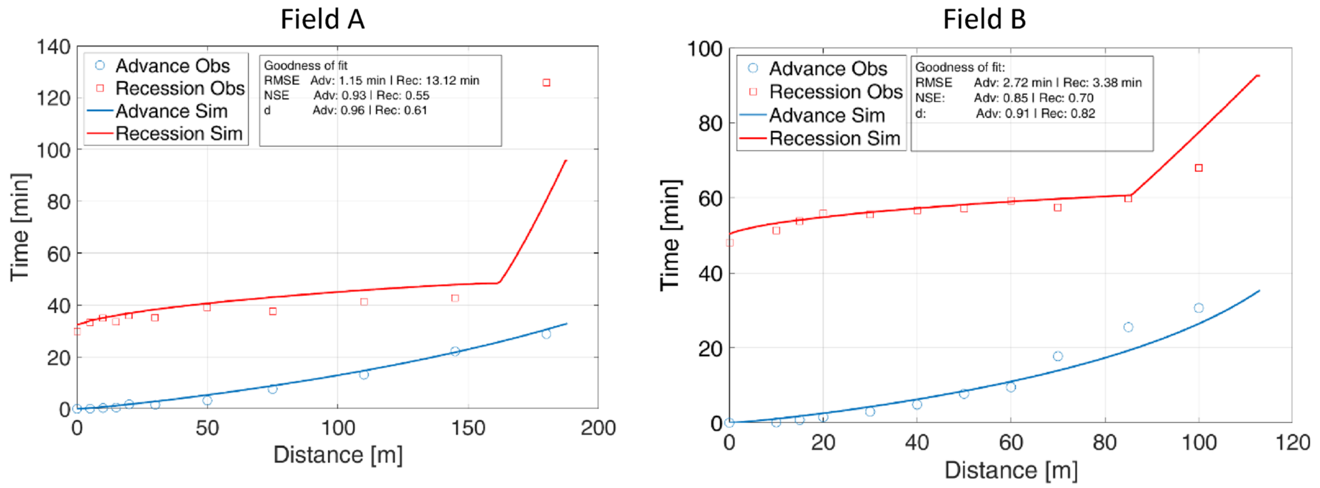


Fig. 4 Comparison between observed and simulated advance (Adv) (blue) and recession (Rec) (red) curves in Field A and B during the events of May 23, 2021 (in Field A) and July 27, 2021 (in Field B). Goodness of fit statistics are also reported in the graphs (*RMSE* Root Square Mean Error, *NSE* Nash-Sutcliff coefficient by Nash and Suchliff (1970), *d* index of agreement by Willmot (1981) (colour figure online)

Table 3 Calibrated infiltration and roughness parameters derived from observations of the waterfront evolution during the irrigation event of May 23, 2021 (in Field A) and of (July 27, 2021) in the Field B

Parameter	Description	Field A	Field B
Infiltration	Saturated water content (cm/cm)	0.35	0.317
	Initial soil water content* (cm/cm)	0.156	0.164
	Wetting front pressure head (cm)	12.9	24.3
	Saturated hydraulic conductivity (cm/hr)	18.9	26.6
Roughness	Manning coefficient (−)	0.12	0.11

*Derived from the soil moisture probe observations

farmers' attitudes during irrigation, i.e. monitoring the number of irrigation interventions, water consumption and the dynamics of waterfront evolution on the field. In the second year, flexible irrigation scheduling was tested on both experimental plots. Specifically, each experimental field was divided into two different sectors as follows: the first one (including the first and second strips of Field A and B) was managed with "on-demand" irrigation (i.e., irrigation was triggered when the observed soil water content—SWC—reached a critical soil moisture condition—CMC—corresponding approximately to about 70% of the readily available water—RAW), while the second (including the third, fourth and fifth strips of field A and the third and fourth strips of field B) was irrigated according to the experience of the farmers and following the 7-day rigid rotation (hereafter "rigid rotation") imposed by the irrigation agency. In the "on demand" sectors, the calibrated AquaCrop model was used to decide on the triggering of the irrigation intervention. Specifically, each day the weather information registered by the weather station was sent to a dedicated personal computer where the Matlab version of the AquaCrop model (the latter customized for Field A and B) was launched. Daily SWC (simulated by the model) was compared with CMC threshold to decide whether or not to irrigate. The decision was additionally supported by rainfall forecasts of a few days beyond that provided by free weather services, but in this work rainfall forecasts were not included in the AquaCrop model. In both sectors, the duration of each irrigation event (and thus the applied irrigation depth) was decided by the farmers according to their experience, without any intervention by the researchers.

In the agricultural season 2021 (i.e. when the irrigation is triggered according to the "rigid-rotation" scheduling), potential scenarios of "on-demand" irrigation were studied using the AquaCrop model with daily weather data recorded by the agro-meterological station in the study area, with the aim of investigating their impact on the soil–water balance, reduction of the number of irrigation interventions and water conservation. In this case, the gross irrigation depth at each irrigation intervention was considered equal to the mean of the irrigation depths applied by the farmers in the 2021 irrigation season.

Finally, two modelling exercises to evaluate how different irrigation durations (cut-off times) and boundary geometric layouts can affect irrigation performance and water consumption were carried out on Field A and B using the WinSRFR model. In Field A, the model was used in the "operational analysis" mode to optimize irrigation durations as a function of the observed range of inflow rates provided by the irrigation agency during the 2021 and 2022 agricultural seasons. The analysis was performed using performance contours, which show the variation of irrigation performance indices as a function of inflow rate and irrigation duration. In Field B, instead, WinSRFR was used in the "design analysis" mode to find optimal values of strip width and field slope for given infiltration and hydraulic roughness characteristics, target infiltration depth, and available inflow rate (the latter occurring during the July 27, 2022 calibration event).

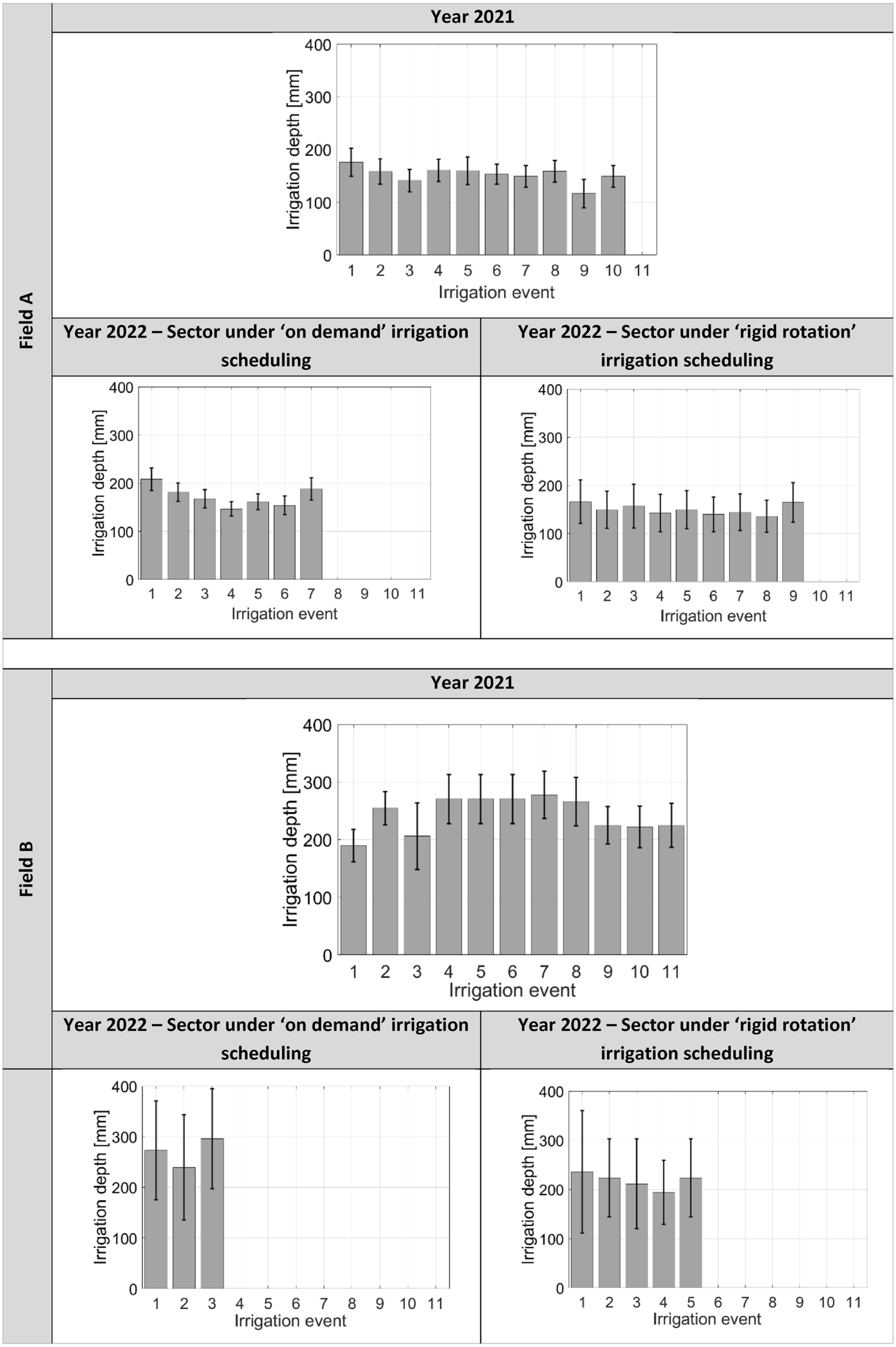
In Table 4 summarizes the list of experiments conducted on Fields A, B.

Performance indicators

The performance of flexible irrigation scheduling was evaluated through different parameters such as number of

Table 4 List of tests and simulations carried out on the experimental fields

Place	Tool	Objective
Field A	On-field	Test "on-demand" irrigation scheduling and its effect on water use and number of watering events
	AquaCrop	Estimation of crop water requirements, soil–water balance, and water consumption for the 2021 and 2022 agricultural seasons
	WinSRFR	Evaluate the performance of irrigation operations derived from the application of different irrigation durations
Field B	On-field	Test "on-demand" irrigation scheduling and its effect on water use and number of watering events
	AquaCrop	Estimation of crop water requirements, soil water balance, and water consumption for the 2021 and 2022 agricultural seasons
	WinSRFR	Evaluate the performance of irrigation operations resulting from the application of different border geometric layouts


Field A
Year 2021
Irrigation depth [mm]
0
100
200
300
400
1
2
3
4
5
6
7
8
9
10
11
Irrigation event
Year 2022 – Sector under 'on demand' irrigation scheduling
Year 2022 – Sector under 'rigid rotation' irrigation scheduling
Field B
Year 2021
Year 2022 – Sector under 'on demand' irrigation scheduling
Year 2022 – Sector under 'rigid rotation' irrigation scheduling

◂**Fig. 5** Observed number of irrigation interventions and amounts of water delivered during the 2021 and 2022 agricultural seasons in Field A and B. In 2022, the number of irrigation interventions and irrigation depths are divided between the sector served by an "on-demand" irrigation scheduling and the sector served by a "rigid-rotation" irrigation scheduling

irrigation interventions, water consumption, quantity and quality of crop production.

Regarding the performance of the irrigation operation, they were evaluated through the minimum irrigation adequacy (ADmin) indicator as follows:

$$AD_{\min} = \frac{\textit{Minimum infiltrated depth}}{\textit{Water required in the root zone}} = \frac{D_{\min}}{D_{req}}, \quad (1)$$

where Dmin is the minimum infiltrated depth (i.e. minimum infiltration value along the final infiltration profile in accordance with WinSRFR 5.1 Manual). AD provides an estimate of irrigation adequacy (under-irrigation, adequate irrigation, over-irrigation), i.e. it indicates the ability of an irrigation intervention to deliver the right amount of water in the effective root zone to meet the irrigation demand (Dreq). In general, the required depth of application is chosen based on the expert judgment of the user, and in our study, we found it reasonable to assume that it is equal to the readily available water.

Returning to AD characteristics, Burt et al. (1997) reported that a field is under-irrigated if ADmin < 1, adequately irrigated if ADmin = 1, and over-irrigated if ADmin > 1. In our work, the ADmin indicator was preferred to application efficiency (AE) (which is considered the linchpin indicator for evaluating the performance of irrigation operations—Zerihun et al. 2005) because the latter has recently been criticized as being highly dependent on the choice of Dreq (Anwar et al. 2016), and the possibility of achieving high AE but inadequate irrigation performance by applying less water than the irrigation requirement to minimize losses to deep percolation (Irmak et al. 2011). Similarly, ADmin was preferred to the distribution uniformity indicator because the latter could reach high values, but at the cost of excessive irrigation. Nevertheless, in our work, application efficiency (AE) and distribution uniformity (DU) were considered as additional indicators to discuss the performance of irrigation operations.

Analysis of crop production

Laboratory analyses were carried out to understand whether the two irrigation management practices tested in Field A and B in 2022 (i.e., "on-demand" and "rigid-rotation") had affected the quantity and quality of crop production. First, maize was harvested separately for the two sectors and then weighed. Second, three silage samples from each sector were randomly collected and analyzed separately in the laboratory to determine the level of nutrients, fiber and digestibility of the crop production. The differences in silage quality between the two irrigation practices were evaluated using a significance test with a p-value threshold of 0.05. Aflatoxins were also analyzed as they are the major family of toxins produced when the crop is under potential water stress (Chauhan et al. 2008). Details of the forage quality variables measured, and the methodology used for laboratory analysis are reported in the Supplementary Material—Supplement 2.

Results

Irrigation performance under the flexible watering management

The observed number of irrigation events and the amount of water applied (i.e., the average depth of water applied to the fields) are shown in Fig. 5 for both irrigation seasons (i.e., 2021 under rigid rotation only and 2022 under rigid rotation and on demand). Details of the monitored flow rate, duration of each irrigation intervention, and irrigation depths for each strip and irrigation event are reported in the Supplementary Material—Supplement 3.

During the 2021 agricultural season, the farmers carried out 10 irrigation interventions in Field A and 11 in Field B. In Field A, the average irrigation depth for each intervention was between 150 and 200 mm, while in Field B, the irrigation depth ranged between 200 and 300 mm.

In the year 2022, when the "on demand" irrigation scheduling was tested, the irrigation interventions in the "on demand" sector of Field A were 7 compared to the 9 in the "rigid rotation" sector, while in Field B, 3 irrigation interventions were made in the "on demand" sector compared to 5 interventions in the "rigid rotation" sector. On average, the irrigation depth for each irrigation intervention in both sectors was within the same range of the year 2021 (i.e. about 150 and 200 mm for the Field A and 200 and 300 mm for the Field B, although with peaks of 400 mm in some Field B borders). Comparing the number of irrigation events in Field B between the years 2021 and 2022, the farmer's decision to postpone the sowing date was found to be successful, since the late summer and autumn rainfall events well supported the satisfaction of the crop water requirements, as shown in the water balance described in Section "Soil water balance".

Soil water balance

The effect of input fluxes (irrigation and rainfall) on the daily soil water content (SWC) in the root zone is shown in Fig. 6. The SWC was compared with both the Total Available Water

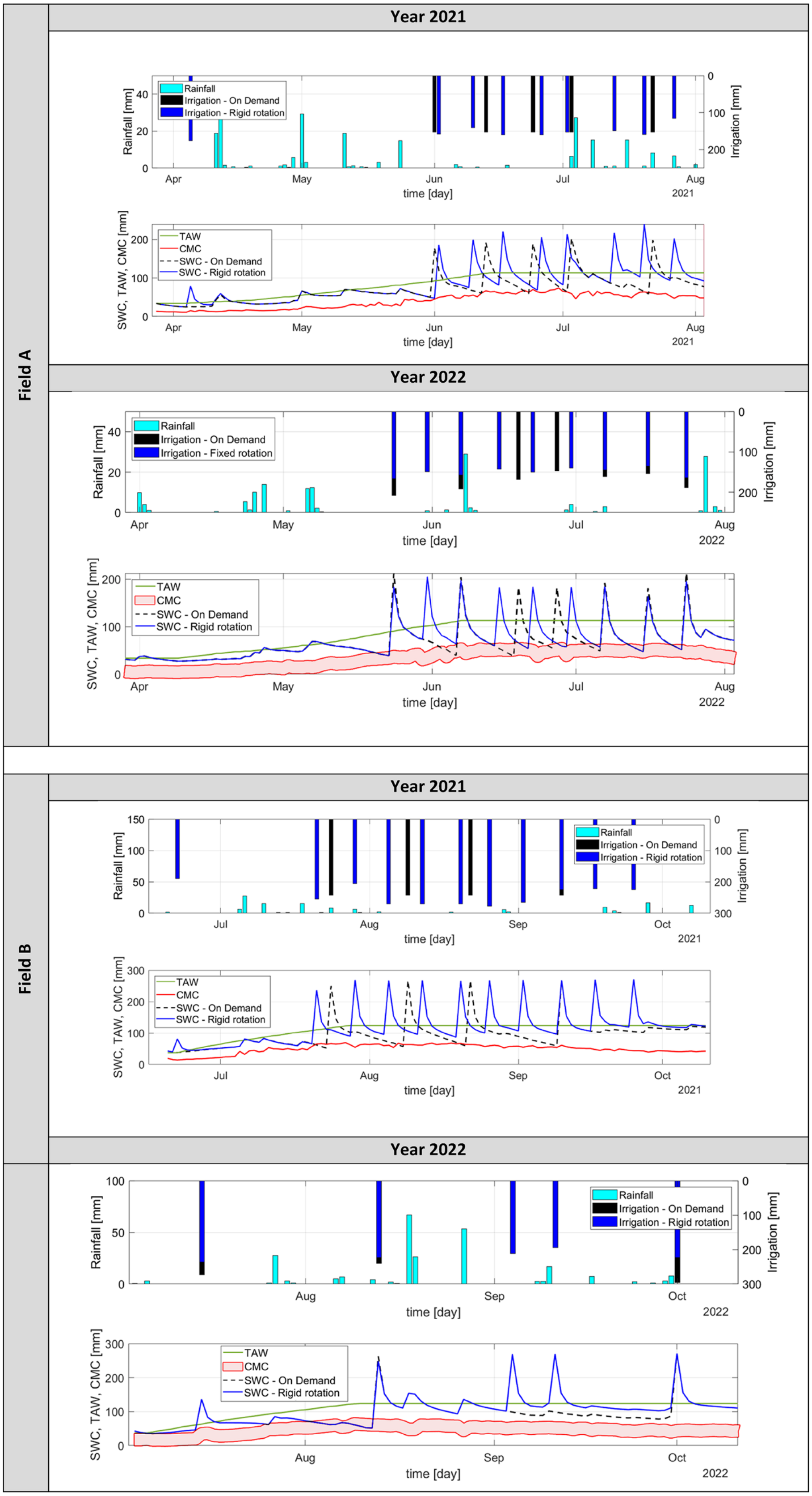


Fig. 6 Seasonal variation of Soil Water Content (SWC) for Field A, Field B in the years 2021 and 2022 associated with rainfall and irrigation water applied. In the year 2021, the irrigation depths under the “on demand” simulation were evaluated as being equal to the average of the irrigation depths applied under the “rigid rotation” in the same year. The SWC is also compared to the patterns of Total Available Water (TAW) and Critical Soil Moisture Content (CMC)

(TAW) and the Critical Soil Moisture Content (CMC) and analyzed in the two experimental fields during the agricultural seasons of 2021 and 2022. Specifically, in 2021 (as already mentioned in Section "Experimental design and simulations"), the irrigation depth of each simulated "on demand" irrigation event was considered equal to the average of the irrigation depths applied under "rigid rotation" in the same year. In 2022, instead, irrigation depths in both sectors were those really observed during each intervention.

In general, irrigation was triggered at both sites before total available water was depleted in both 2021 and 2022. On average, the threshold below which irrigation was triggered was about 85% of TAW in both fields A and B in 2021 (i.e., when the deficit to field capacity was only about 25 mm in field A, 18 mm in B). This shows that farmers have an extremely risk-averse attitude when operating under a "rigid-rotation" irrigation schedule, preferring to irrigate even when soil water content is still much higher than the CMC. This was particularly evident in both fields in 2021 and during two irrigations in field B in the first week of September 2022, when the deficit to field capacity was only a few millimeters. In these cases, a significant portion of the water supplied for irrigation is lost through percolation, which exceeds 900 mm on average over the seasons. It is interesting to note that the loss of water from the soil by this process was faster than that achieved by root uptake (as shown by the change in the slope of the SWC depletion curve when it is found above or below the TAW level).

The "on demand" irrigation scenario provided for the year 2021 showed that 5 and 6 irrigation interventions could be saved in Field A and B, respectively, if the triggering of the irrigation interventions occurred when the soil moisture reached the CMC. The benefits of "on-demand" irrigation scheduling are also reflected in the reduction of percolation fluxes. Specifically, the reduction in percolation fluxes for each irrigation intervention was proportional to the difference between the soil water content at the time of irrigation and the CMC. Over the course of a season, simulations show that cumulative water losses due to percolation can be reduced by up to 70% by adopting "on-demand" irrigation scheduling.

In 2022, the farmers' irrigation management was very different from that in 2021, as a direct consequence of the drought situation that occurred in the first part of the 2022 agricultural season. This was particularly evident in Field A, where a large part of the maize growing season (especially the development and maturity stages—i.e. between mid-May and August) was characterized by very limited rainfall (about 60 mm of rainfall compared to crop evapotranspiration of about 450 mm). This led the farmer of Field A to irrigate the sector under "rigid rotation", using any intervention allowed by the rigid irrigation schedule (i.e. once a week). In terms of water balance, the SWC at the time of each irrigation intervention was almost always included in the CMC confidence interval (which was defined as ± 5% of the CMC value to allow a margin of flexibility—i.e. about 1–2 days—in the application of the irrigation intervention). Therefore, the differences in the number of irrigation interventions between the sector under "rigid rotation" and that under "on-demand" irrigation scheduling were very limited, showing that under these circumstances (i.e., dry seasons), the rigid irrigation scheduling provided by the irrigation agency (i.e., 7-day rotation) was well calibrated. Differences in irrigation interventions between "on demand" and "rigid rotation" sectors were found only in the first part of the agricultural season (i.e. between April and May), where two fewer irrigation interventions were made in the "on demand" sector than in the "rigid rotation" one. In Field B, the water balance was influenced by the delay of the maize sowing by about twenty days compared to the one applied in the year 2021, which allowed to take advantage of the late summer/autumn rainfall of about 200 mm in the maize maturity stage (i.e. between mid-August to October), compared to the crop evapotranspiration of about 300 mm. During this period, the soil was well hydrated, with a deficit from the field capacity of a few millimeters. Only three irrigation interventions were carried out in the "on-demand" sector, two less than in the "rigid-rotation" one.

The seasonal volumes of cumulative irrigation, rainfall and crop evapotranspiration are reported in Table 5. The values refer to the period from seeding to harvest for all experimental fields. Since the cropping periods are different, the total amounts of rainfall (R) and evapotranspiration (ET_c) also differ between the two fields for the same years.

In both years, evapotranspiration ranged between 400 and 500 mm, while rainfall was only able to satisfy a part of the potential crop evapotranspiration ETc, ranging between 30 and 50%. The remaining part was supplied by irrigation, which ranged between 1000 and 2700 mm. These values are about three times higher than those obtained using sprinkler systems (e.g. traveling rain gun system), a device widely used for watering maize in alternative to the border method (Mayer et al. 2022).

Most of the water applied during irrigation is lost to percolation, mainly due to the drainage characteristics of the sandy soil. It can reach up to 2000 mm over the season. The seasonal irrigation volume decreased significantly with the "on-demand" irrigation scheduling. The simulations showed that in an average wet year (like 2021), the irrigation volume can be reduced by up to 60% if the on-demand irrigation scheduling is implemented (see field B in 2021). The reduction in irrigation volume under "on-demand" scheduling is most evident in 2021, but is still significant in the dry year 2022, where observations revealed that the reduction in irrigation volume between "on-demand" and "rigid-rotation" sectors is between 10 and 25%. It follows that the farmer's

Table 5 Seasonal cumulative water balance fluxes (irrigation, rainfall, crop evapotranspiration, percolation) for Field A, Field B and in the years 2021 and 2022

Field	Year	Sector	Management	Observed/Simulated	ET_c (mm)	Rain (mm)	Irrigation (mm)	Percolation (mm)
A	2021	Unique	Rigid rotation	Observed	528	237	1522	1045
			On-demand	Simulated	528	237	918	506
	2022	1–2	On-demand	Observed	540	147	1218	793
		3–4–5	Rigid rotation	Observed	540	147	1350	873
B	2021	Unique	Rigid rotation	Observed	437	142	2677	2107
			On-demand	Simulated	437	142	972	599
	2022	1–2	On-demand	Observed	400	244	808	590
		3–4	Rigid rotation	Observed	400	244	1089	840

Irrigation and rainfall fluxes were derived from direct observations, while crop evapotranspiration and percolation fluxes were derived from AquaCrop

decision to postpone the sowing date in Field B allowed him to take advantage of a significant amount of rainfall during the growing season (about 240 mm), which limited the use of irrigation interventions (and therefore the amount of irrigation water) to meet crop needs. This behavior was also reflected in the percolation fluxes (i.e., the transition to flexible irrigation scheduling allows a better control of hydrological losses). In fact, the water balance components show that there is a strong relationship between the irrigation and percolation depths (as shown in Table 5). On average, the percolation in both fields (characterized by a very draining sandy soil) exceeded the 500 mm during the season with a peak of about 2000 mm in Field B (year 2021) under "rigid rotation". In this case, an irrigation depth of about 2600 mm (the maximum registered in both experimental years) was provided over the season. On the contrary, the minimum irrigation depth recorded in 2022 in Field B (i.e. about 800 mm) resulted in minimum percolation (i.e. 590 mm).

Quantity and quality of crop production

The results of the weighing operations show that the different irrigation management did not significantly ($p < 0.05$) affect the quantity of crop production. Specifically, in Field A, 58 t/ha of silage were obtained in the sector under “on-demand” irrigation scheduling, while 55 t/ha were obtained in the sector under “rigid-rotation”. They are in good agreement with the world average yield of 57 t/ha (FAO 2022). In Field B, 29.5 t/ha were obtained in the on-demand irrigation sector, while 33 t/ha were obtained in the rigid rotation sector. The ratio between silage production and irrigation amount revealed a water productivity of about 2.5 kg/m^3 in both fields in good agreement with the results of Salamati and Abbasi (2022) on surface irrigated maize.

The results point out significant differences in crop production between field A and B. In particular, the crop production in field B was about 40% lower than that obtained in field A. This was probably due to the different cultivars and also to the excessive delay in the planting date (about 20 days later than in the previous year), which hindered the crop development and led to a lower biomass production, as shown by the reduced canopy cover in Fig. 2.

Regarding the quality of the production, the chemical composition and digestibility of the silages obtained in the two sectors of field A and B are presented in Table 6. In general, the quality composition of the silage in both fields was within the standards registered in 2022 in the geographical area of the case study (Gallo et al. 2022). In addition, no evidence of Aflatoxin B1 contamination was found in both fields and sectors under the different irrigation management (i.e. Aflatoxin B1 < 0.5 ppb). A noteworthy observation can be made by analysing the indices that are significantly different between the sectors, in particular NDF, NDFD, ADL and starch, which are parameters closely related to the digestibility of silage. In general, a good silage product should have more starch and less NDF, so that it is more energetic and less fibrous for the same dry matter at harvest. In addition, the NDFD, which represents the digestibility of NDF, should be high. In field A, these proportions are respected and, in particular, in the “on-demand” sector, starch and NDFD are higher than those observed in the “rid-rotation” sector. On the contrary, ADL and NDF are lower in the ‘on demand’ sector than in the ‘rigid rotation’ sector. In area B, significant differences were also found in terms of NDFD, with a 6% lower NDFD in the ‘rigid-rotation’ than in the ‘on-demand’ one. These results, although based on a single experimental campaign, show that the adoption of on-demand irrigation management, based on triggering

Table 6 Comparison between the forage quality of silage in the two irrigation management sectors of Field A and B

	u.m	Average		Standard deviation		*P*-value
		'On-demand'	'Rigid rotation'	'On-demand'	'Rigid rotation'	
Field A						
Dry Matter 65°	%	37.50	37.38	0.97	1.33	0.903
NDF	*%DM*	*36.09*	*42.67*	*2.79*	*2.24*	*0.033*
ADF	%DM	24.94	27.44	0.83	1.44	0.059
ADL	*%DM*	*2.82*	*3.15*	*0.08*	*0.11*	*0.012*
NDFD	%NDF	64.52	57.43	1.80	4.18	0.054
uNDF	%DM	6.95	7.72	0.96	0.30	0.256
Ash	%DM	3.57	3.88	0.11	0.19	0.068
Protein	%DM	6.75	6.65	0.25	0.67	0.826
Soluble protein	%DM	2.99	3.02	0.18	0.32	0.895
Etehr extract	%DM	2.34	2.23	0.19	0.18	0.505
Starch	*%DM*	*34.58*	*28.63*	*2.47*	*1.12*	*0.019*
Glucose	*% DM*	*1.67*	*1.72*	*0.08*	*0.04*	*0.345*
Field B						
Dry Matter 65°	%	33.38	34.76	0.86	1.21	0.182
NDF	%DM	35.08	34.89	0.92	0.06	0.740
ADF	%DM	20.86	21.33	0.61	0.27	0.296
ADL	%DM	2.49	2.43	0.19	0.03	0.614
NDFD	*%NDF*	*60.53*	*56.05*	*2.09*	*1.39*	*0.036*
uNDF	%DM	5.57	5.44	0.59	0.68	0.808
Ash	%DM	4.03	4.05	0.13	0.20	0.919
Protein	%DM	7.19	7.07	0.23	0.17	0.507
Soluble Protein	%DM	3.09	3.17	0.08	0.25	0.627
Etehr Extract	%DM	2.14	2.20	0.10	0.12	0.509
Starch	%DM	36.03	37.11	0.91	0.48	0.143
Glucose	*%DM*	*1.88*	*1.68*	*0.09*	*0.05*	*0.026*

The parameters with a significant difference between the sectors ($p < 0.05$) are shown in italics

The acronyms represent *NDF* neutral detergent fiber, *ADF* acid detergent fiber, *ADL* acid detergent lignin, *NDFD* NDF digested after 48 h of rumen incubation, expressed on NDF basis, *uNDF* undigested NDF after 240 h of rumen incubation

irrigation events at the right level of soil water content, has a positive effect on crop production quality.

Irrigation performances under different irrigation durations

Figure 7a, b show the contour plots of two irrigation performance indicators (application efficiency and minimum distribution uniformity) in the case of Field A, obtained by simulating the irrigation applications with the WinSRFR software under different values of inflow rate and irrigation duration. The red area represents the range of variation of inflow rate and irrigation duration registered during all the irrigation events that occurred in the years 2021 and 2022. Specifically, the observed inflow rate ranged between 318 and 350 ls^{-1}, while the irrigation duration ranged between 18 and 35 min (0.3–0.58 h) for each strip. The former depends on the water supply provided by the irrigation agency and is strictly limited, while the latter depends on the farmer's choice and can be optimized. The dotted line represents combinations of inflow rate and irrigation duration that satisfy the irrigation requirement everywhere in the irrigated strip (i.e. Dmin = Dreq). In general, as expected, AE is maximized in the lower left corner of the graph (Fig. 7a) and decreases with increasing inflow rate and irrigation duration. Inflow rate-irrigation duration combinations to the right and above the dotted line produce Dmin > Dreq and represent excessive irrigation of the field. Proper irrigation (for an inflow rate between 318 and 350 l/s) can be achieved if the irrigation duration is between 26 and 29 min (0.42–0.48 h) (i.e., solution along the Dmin = Dreq line). In this case, AE is equal to minimum distribution uniformity (DUmin) (since the field has no runoff) and AE is between 70 and 77%. The increase of the AE can be obtained only at the expense of a decrease of the DUmin (Fig. 7b) and under severe irrigation conditions (especially suffered at the end of the field).

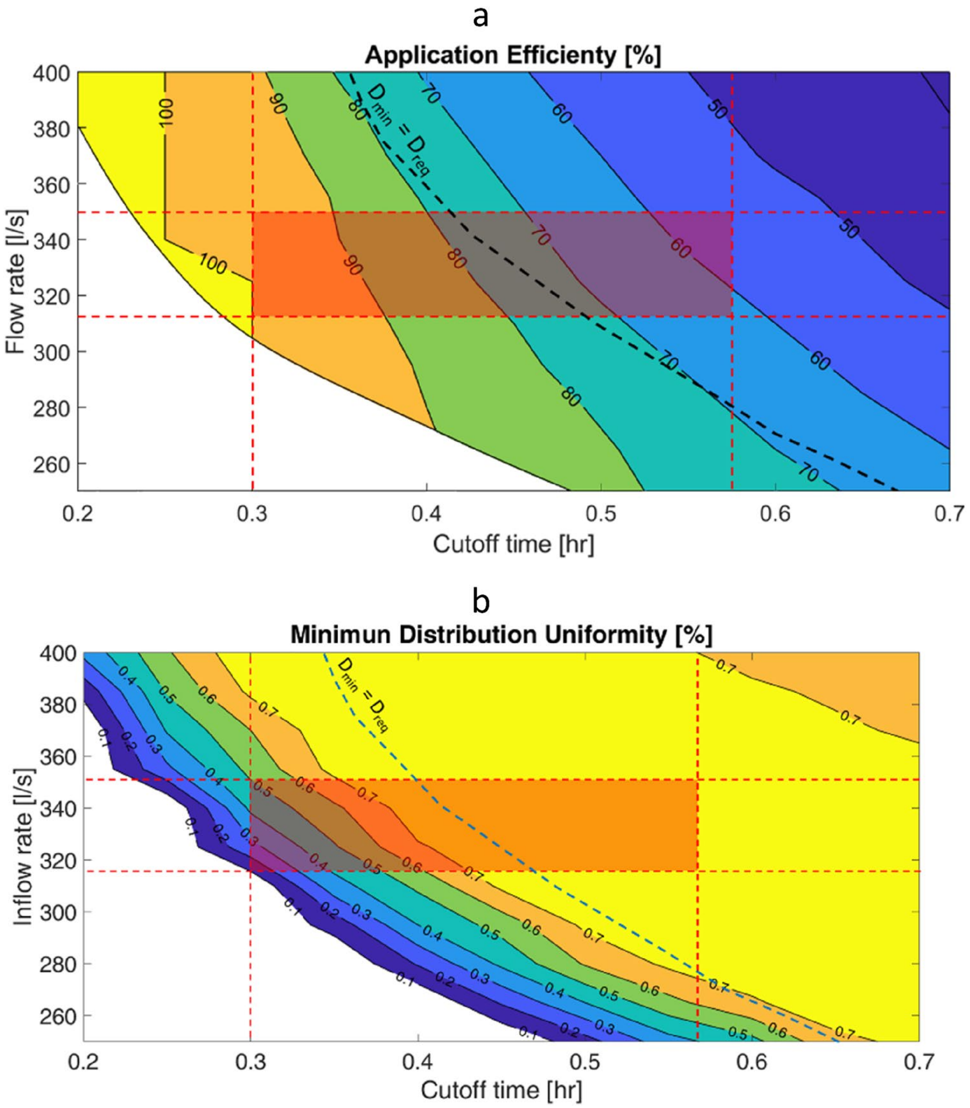


Fig. 7 Contour plots of application efficiency (**a**) and minimum distribution uniformity (**b**) as a function of inflow rate and cut-off time. The rectangle superimposed on the contours represents the range of inflow rates and cut-off times observed in 2021 and 2022. The dotted line represents the Dmin = Dreq solutions

In fact, uniformity decreases rapidly at irrigation durations lower than 25 min (0.4 h). In this region of the contour plot, small changes in irrigation duration can cause large differences in distribution uniformity (i.e., from 0 to 50%), making irrigation operations very delicate. In contrast, on the right side of the dotted line, distribution uniformity is less sensitive to changes in irrigation duration because the field is overwatered and irrigation demand is more than met.

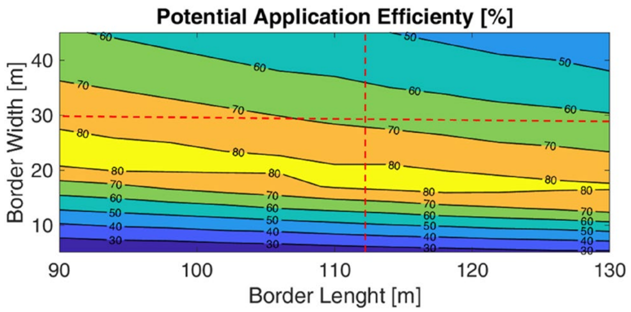


Fig. 8 Contour plot of application efficiency as a function of border width and length. The intersection of dotted lines represents the application efficiency and cut-off ration of the actual configuration

Irrigation performances under different border geometries

Figure 8 shows the contour plots of application efficiency in the case of Field B, obtained by simulating the irrigation applications with the WinSRFR software under different values of border width and length. In this simulation, the inflow rate was fixed and equal to the one that occurred during the July 27, 2021 irrigation event (i.e., 355 ls^{-1}), while the slope is equal to the average slope of the field (i.e., 6.1 ‰). The graph shows only solutions that satisfy the condition Dmin = Dreq (i.e., where the application efficiency values match those of the distribution uniformity), and for this reason the contours of the minimum distribution uniformity are similar to those shown in the application efficiency graph and are not shown here. The red dotted lines represent the actual border width and length (30 and 113 m, respectively). Figure 8 suggests that high application efficiency and distribution uniformity (~80%) can be obtained in a range of border widths between 16 and 20 m (i.e. discharge per unit field width of 18–22 ls^{-1} m^{-1}), while both indicators appear less sensitive to variation in border length.

The analysis of the influence of the longitudinal slope on the irrigation performance indices (in terms of application efficiency and cut-off time) is presented in Fig. 9. The graph was obtained by successive simulations with WinSRFR from a range of allowable slopes between 1‰ and 10‰, as proposed by Gonzales et al. (2011). The inflow rate and boundary width were kept constant and equal to the experimental values (355 l/s and 33 m). The results show that the maximum AE is obtained in a range of slopes between 3‰ and 6‰, associated with a minimum irrigation duration of about 33 min (0.55 h) (very close to that applied during the event of July 27, 2021). The trend of AE decreases both before and after this range, due to the excess of percolation water found in the first part of the field (when the slope is close to zero) and in the last part of the field (when the slopes exceed 6‰). Conversely, at the extremes of the slope range (i.e., below 3‰ and above 6‰), irrigation durations increase up to 36 min. Therefore, the actual longitudinal slope (i.e. slope 6.1‰) seems to provide a good balance between application efficiency and cut-off time.

Discussion

Effect of flexible irrigation scheduling on water conservation

The differences in the number of irrigation interventions and seasonal irrigation volumes between rigid and flexible irrigation management on Field A, B and at the irrigation

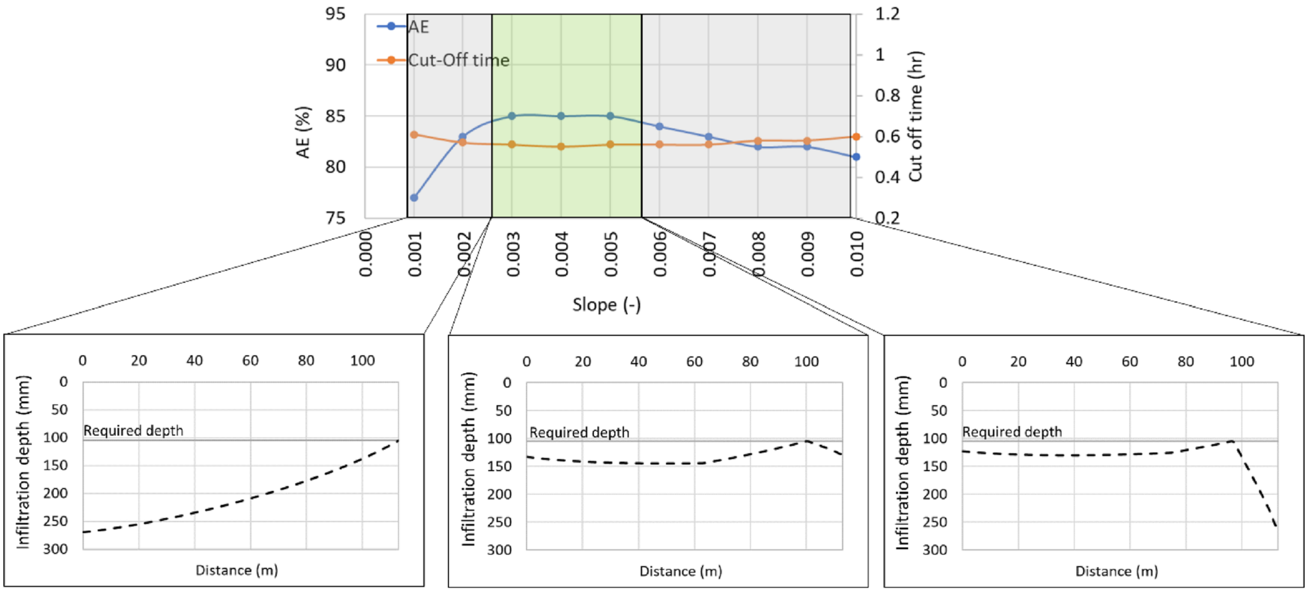


Fig. 9 Influence of the longitudinal slope on application efficiency, irrigation duration and profile of infiltration depth in the Field B

Table 7 Differences between rigid and flexible/on-demand irrigation management reported in terms of number of irrigation interventions and seasonal irrigation volumes

Place	Year	Transition	Difference in number of irrigation events (%)	Difference in irrigation volume (%)
Field A	2021	From 'rigid-rotation' to 'on-demand'*	– 50	– 40
	2022	From 'rigid-rotation' to 'on-demand'	– 22	– 10
Field B	2021	From 'rigid-rotation' to 'on-demand'*	– 55	– 64
	2022	From 'rigid-rotation' to 'on-demand'	– 40	– 26

*Obtained by considering in the AquaCrop simulation that the irrigation depth of each irrigation event is equal to the average of the irrigation depths observed in the year under "rigid rotation" scheduling district scale are summarized in Table 7. The results show that the application of a flexible irrigation management, following the real crop water needs, can significantly reduce the number of irrigation interventions and irrigation volumes, especially when significant rainfall occurs during the agricultural season, such as in 2021 on Field A and B and in 2022 on field B only. These results are in good agreement with the findings of Therani et al. (2023), Grant et al. (2009), and Gu et al. (2020), which show how, for different crops and soils, effective irrigation scheduling can help increase water conservation and profits while minimizing over-irrigation, percolation, and potential negative environmental impacts. However, the observations in our case study clearly show that farmers tend to avoid irrigation when they consider the amount of rainfall to be adequate to meet crop water needs, even under a rigid irrigation schedule. This is evident in the graph of SWB of Field B in the year 2022 (Fig. 6), where a well-distributed series of rainfall events with a depth greater than the critical soil water deficit (about 20 mm, which is on average the difference between TAW and CMC in the full development stage of the crop) occurred from about 20 days after sowing until harvest. In this case, the farmer decided to avoid some irrigation interventions with a significant reduction in water consumption compared to the previous year. In addition, the delay in the sowing date (20 days with later than in 2021), played favourably for the rainfall satisfaction of the water needs of the crop (i.e. allowing to take advantage of the autumn rainfalls that are typical of the mid-latitude where the study area is located).

Examining the differences in irrigation volumes shown in Table 7, between 10 and 60% of water conservation could be obtained if a transition to flexible irrigation scheduling is implemented. These values are very interesting when compared with the reduction of freshwater deliveries imposed by the irrigation districts agencies of the Padana plain area in the 2022 dry season. In some parts of the plain, the restriction of water deliveries reached up to 70%, while in the area where the study domain is located, the restrictions were around 10%. This confirms the assumption that by working on the scheduling of surface irrigation interventions it is possible to achieve the objectives of savings that could be required during dry seasons.

An additional multi-year scenario was run to confirm the water saving results obtained in the experimental plots and presented in Table 7. 30 years of data (from 1992 to 2022) registered by an official agro-meterological station 5 km away from the study area (managed by the Lombardy Environmental Protection Agency) were used in the AquaCrop model (properly calibrated) to simulate the irrigation scheduling of Field A (but very similar results were also obtained for Field B and therefore they are not reported) under a rigid and flexible water supply. Specifically, in the 'rigid rotation' scenario, watering was performed every 7 days after the sowing dates, the latter assumed equal for each year and in both scenarios, as confirmed by the experimental evidence. On the contrary, in the "on demand" scenario, irrigation was only applied when the soil deficit was between 75 and 85% of the TAW (as observed in both experimental fields). The irrigation depth for each irrigation event in both scenarios was randomly varied between 150 and 200 mm (as duly observed in the experimental fields). Figure 10 shows the daily cumulative irrigation depths over the multiple agricultural seasons, as well as the total sum of irrigation volumes over 30 years. The daily pattern of irrigation events reflects expectations, i.e., in the "rigid rotation" scenario, irrigation demand is approximately constant throughout the season as a result of a rigid calendar of irrigation interventions, whereas in the "on demand" scenario, the irrigation pattern more closely follows the actual crop water demand, which is mainly concentrated in the early and mid growing season.

If the cumulative irrigation volumes of the two scenarios are considered, the implementation of a flexible irrigation scheduling allows to conserve about 45% of water in respect to the rigid-rotation one. These results are in good agreement

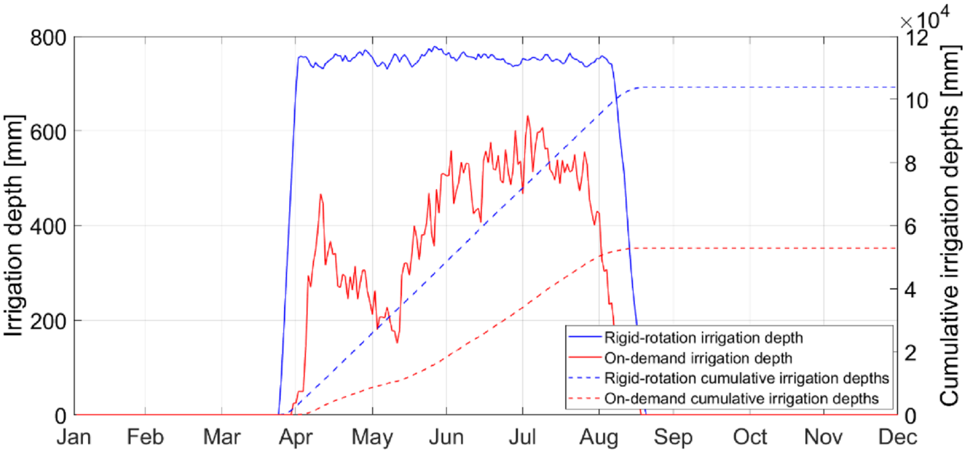


Fig. 10 Cumulative daily pattern of irrigation depths over 30 agricultural seasons (from 1992 to 2022) in the Field A. 'Irrigation depth' represents the cumulative daily irrigation depth for that day over 30 years. 'Cumulative irrigation depths' represents the sum of 'irrigation depth' over 30 years

with those observed in the two experimental years (2021 and 2022) and presented in Table 7. Logically, in this simulation, the 45% should be considered as the upper limit of water conservation, since the rigid-rotation scenario does not take into account some dynamics that the farmer implements for deciding whether or not to irrigate (e.g., the possible presence of rainfall in the days close to the irrigation event scheduled in the calendar, or the presence of favourable antecedent soil moisture condition before the irrigation intervention).

Although the results strongly confirm that the transition to flexible irrigation scheduling can provide significant benefits in terms of water conservation and crop quality, the implementation of flexible irrigation scheduling could have a significant impact on water distribution planning at the irrigation district level. Assuming that changes to the water distribution infrastructure network should be minimized to limit costs, the transition will require irrigation district agencies to adopt computerized software and algorithms to manage concurrent demands, especially in monoculture irrigation districts. The use of telemetry, remotely controlled (and coordinated) systems of gates within the canal network could facilitate coordination operations and reduce the inertia of moving water masses from one point to another in the irrigation network. At the field level, different planting dates between fields should be encouraged to differentiate irrigation needs in the early stages of crop growth. In addition, the use of early or late developing maize varieties should be promoted to take advantage of the spring and fall rains typical of the mid-latitudes.

Effect of irrigation duration on water conservation

The potential water conservation expected from optimizing irrigation duration are shown in Fig. 11a, b for each strip and irrigation event of the years 2021 and 2022. In addition, Fig. 11c, d shows the percentage of water conservation of all irrigation interventions averaged over each strip. Positive percentages represent a margin of reduction in water consumption, while negative percentages indicate insufficient irrigation duration and therefore under-irrigation by the farmer.

The results of the WinSRFR simulations show that, on average, an additional 7% of water conservation could be expected if the irrigation duration is correctly applied on each strip of Field A. However, this percentage, although reasonable, could be affected by a series of hardly quantifiable uncertainties related to the structure of the WinSRFR hydrodynamic model used to simulate the waterfront advance during each irrigation intervention. In particular, the model is one-dimensional and does not take into account the 2D microtopography, which has a relevant influence on the accuracy with which both water advance times and water depths on the field can be reproduced (Costabile et al. 2022). Moreover, specific variations in soil hydraulic properties within the sector, not detected in the three soil sampling points, could affect local infiltration processes and thus the duration of each irrigation intervention. In addition, the real inflow rate is distributed across the entire strip width by the model, while in the case study the inflow is applied through a narrow gate at the head of the strip, approximately in the middle of the strip width. Finally, the model calibration was performed considering measurements of waterfront advance and recession in a single strip and during a single irrigation intervention, while it can be expected that hydrological properties may vary slightly during the agricultural season (Mazarei et al. 2021) and between strips.

The analysis of the potential water conservation between irrigation interventions shows that in the first irrigation interventions (approximately from the first to the fourth event), the water conservation are more evident than in the following interventions, which are associated with the last part of the agricultural season. This was confirmed by the farmers, since at the beginning of each irrigation season they use the first irrigation interventions to roughly calibrate the irrigation duration in each strip, which would then be kept approximately constant during the irrigation season. The results show that within the field, the first three strips are generally over-irrigated, while the last two are under-irrigated. The third strip is the most over-irrigated in both years, with a potential water saving of about 25%, while the fifth strip was largely under-irrigated in 2022, probably due to the inability of the model to simulate potential water exchange between the ridges (especially lower towards the end of the strips) and thus the potential backflow from the adjacent over-irrigated strips. Nevertheless, in general, the water supply between the strips seems to be quite balanced, showing that on average the farmer has good control over the irrigation of the fields during each intervention.

Effect of border layout on water conservation

The potential water consumption expected by changing the strip width of field B is shown in Fig. 12. Eighteen different values of strip width between 6 and 40 m were tested and for each of them the WinSRFR model was applied to find the optimal irrigation duration (i.e. the irrigation duration that allows to obtain $AD = 1$). The flow rate (assumed constant in time and equal to that monitored during the irrigation intervention of July 27, 2021) was multiplied by the optimal irrigation duration to obtain the irrigation volume of the single strip. Then, the volume of the single strip was multiplied by the new potential number of strips (obtained by dividing the field width—about 120 m—by the new strip width) to determine the total irrigation volume of the field.

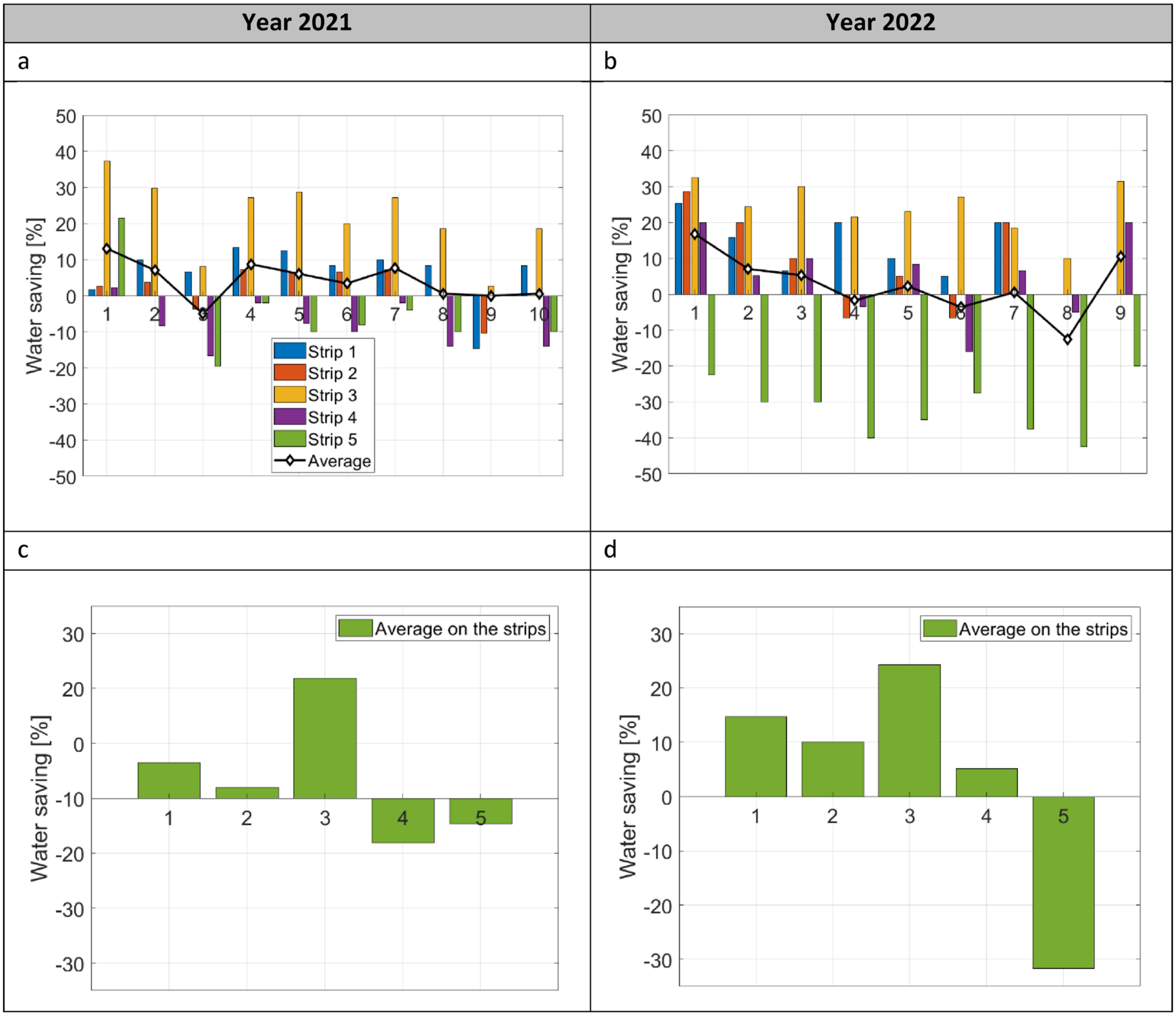


Fig. 11 Potential water conservation calculated for each strip and irrigation intervention that occurred in Field A during the 2021 and 2022 agricultural seasons

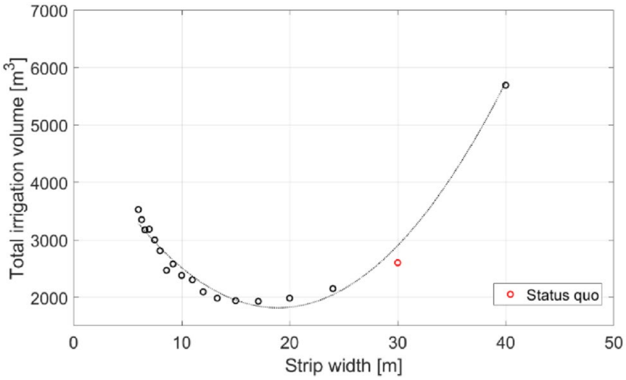


Fig. 12 Evolution of the total irrigation volume of field B by varying the strip width while optimizing the cut-off time (i.e. AD = 1)

Considering the current strip width (about 30 m), the total irrigation volume was 2600 m^3, while a reduction of about 25% (i.e. about 1900 m^3) was obtained with a strip width of 17 m. These results reflect the nature of the speed with which the waterfront propagates along the strip in the current situation and in the modified one. Calculating the mean flow velocity as the ratio between the field length and the time elapsed from the start of irrigation to the instant when the waterfront reaches the end of the strip (equal to the irrigation duration), resulted in approximately 4 m min^{-1} with a strip width of 30 m, while it increased to 9 m min^{-1} with a strip width of 17 m.

Reducing the strip widths of field B to 17 m, the flow rate per unit field width during the irrigation interventions becomes very close to that found in field A (about 20 l s^{-1} m^{-1}) and the irrigation depth is also similar (about 150 mm).

Conclusion

In this study, an experimental campaign was designed and implemented in the agricultural seasons 2021 and 2022 to understand what margin water conservation that could be achieved by transitioning from a rigid to a flexible irrigation schedule and by customizing the application management variables and the field layouts.

The results obtained on two maize fields in northern Italy show that there is a relevant potential to improve the irrigation performance of traditional border irrigation maintaining the same crop yield and possibly increasing its quality. Using AquaCrop model for supporting irrigation scheduling and WinSRFR for reproducing border irrigation operations, our analysis confirms the evidence that border irrigation performance is strongly related both to the water management strategy adopted by farmers during irrigation events and to the field layout. Despite that the models were subject of some simplifications, significant percentages of water conservation were found in both wet and dry years when irrigations were triggered when the soil water content was properly depleted, while a well-designed field layout (border width and slope) with respect to the available flow rate could significantly increase application efficiency and distribution uniformity. The duration of irrigation applications can also be optimized as a function of border size and available flowrate.

We believe that these results provide useful insights to help implement new water management strategies aimed at improving the efficiency of border irrigation. In addition, the results show that the water conservation achieved through the management of irrigation strategies could match the reductions in water deliveries potentially imposed by irrigation agencies in dry seasons (such as those that occurred in 2022). This confirms the priority of the actions that should be implemented in the programs of modernization of the irrigation systems, i.e. put first the improvement of the irrigation management strategies and then the modification of the irrigation methods and infrastructures.

In conclusion, this study can help farmers in adapting to changes in water availability as a result of policy decisions and/or changing climate patterns. A key challenge will be to translate these findings into operational guidelines and best practices that will allow the tradition of border irrigation to be maintained, while increasing its efficiency.

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Declarations

Conflict of interest The authors declare no competing interests.

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