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Assessing the precision irrigation potential for increasing crop yield and water savings through simulation

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Abstract

In regions such as the Brazilian Cerrado where water availability is low and disputes for water resources are increasing, it is important to evaluate technologies that can increase the efficiency of irrigation. In this scenario, precision irrigation has great potential. However, studies that evaluate the real benefits of precision irrigation are necessary. The present work aimed to assess the precision irrigation potential for increasing crop yield and water savings. To evaluate the possible precision irrigation benefits, two center pivots, acting over soils that had different hydro-physical characteristics, were studied. The available water in the soil (AWC) was used as a reference for irrigation management in two conditions, one considering and one disregarding soil spatial variability. In the management under homogeneous soil conditions, the lowest, the average and the highest AWC values were considered. Management under variable conditions was carried out individually for each pixel with a dimension of 25 m^2 (5 × 5 m), considering its real AWC value. Also, four soybean crop sowing dates were considered in a rainy and a dry year. A specific precision irrigation module was developed in Python language to carry out the simulations. The results obtained indicated an average water savings potential of 4.5% in a rainy year and 4.3% in a dry year. The average increased yield potential was 6.4% in the rainy year and 4.0% in the dry year.

Keywords Irrigation efficiency · Variable rate irrigation · Center pivot · Spatial variability

Abbreviations

BHBV	Buriti Vermelho river basin
BHALPA	Alto Paranapanema river basin

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(es–ea)	Vapor saturation deficit, kPa
AWC	Soil available water capacity, mm cm^{-1}
BD	Bulk density, g cm^{-3}
CM	Conventional management
CM1	Conventional management using as a reference the lowest soil available water capacity value found in the irrigated area
CM2	Conventional management using as a reference the average soil available water capacity value found in the irrigated area
CM3	Conventional management using as a reference the highest soil available water capacity value found in the irrigated area
DAS	Days after sowing
DEM	Digital elevation model, m
DP	Total deep percolation, mm
DPRP	Deep percolation reduction potential
DY	Dry year
ea	Partial vapor pressure, kPa
ECa	Soil apparent electrical conductivity, mS m^{-1}
es	Vapor saturation pressure, kPa
ETai	Current daily crop evapotranspiration, mm day^{-1}
ETm	Maximum total evapotranspiration, mm
ETo	Reference evapotranspiration, mm day^{-1}
FC	Field capacity, %
G	Soil heat flux, MJ m^{-2} d^{-1}
IAI	Current irrigation adequacy index
Ieq	Pixels that received equal irrigation depths than the management deficit, %
Igr	Pixels that received greater irrigation depths than the management deficit, %
I_{ri}	Applied irrigation depth, mm
Ism	Pixels that received smaller irrigation depths than the management deficit, %
ISSM	Irrigation strategy simulation model
IWPP	Increased water productivity potential from irrigation, kg m^{-3}
IYP	Increased yield potential
JD	Julian days
Kc	Average crop coefficient
Ke	Crop evapotranspiration correction coefficient
Ks	Soil evaporation reduction coefficient
Ky	Crop response factor to water stress
PI	Precision irrigation
PivoBHALPA	Pivot located in the Alto Paranapanema river basin
PivoBHBV	Pivot located in the Buriti Vermelho River Basin
PWP	Permanent wilting point, %
R_i	Effective rainfall, mm
Rn	Surface radiation balance, MJ m^{-2} d^{-1}
RY	Rainy year
SD	Sowing dates
SD1	Sowing on September 10th
SD2	Sowing on October 10th

SD3	Sowing on November 10th
SD4	Sowing on December 10th
SDI	Spatial dependence index
SWD_i	Soil moisture deficit on day i, mm
SWD_{i-1}	Soil moisture deficit on day i^{-1}, mm
T	Average air temperature, °C
Tmax	Average maximum temperature, °C
Tmin	Average minimum temperature, °C
U_2	Wind speed measured at a height of 2 m, m s^{-1}
WP	Water productivity, kg m^{-3}
WSP	Water savings potential
Y_a	Current crop yield, kg ha^{-1}
Y_m	Maximum crop yield, kg ha^{-1}
γ^*	Psychrometric constant = 0.063 kPa $°C^{-1}$
Δ	Slope of the saturation vapor pressure curve, kPa $°C^{-1}$

Introduction

The Brazilian savannah (Cerrado) occupies nearly 24% of the country and is responsible for about 70% of the national production of grains and beef (Klink, 2014; Pereira et al., 2012; Silva et al., 2015). The Cerrado can effectively help to supply part of the projected increase in the food demand of a population that by 2050 will be around 10 billion people (FAO, 2017). On the other hand, regions under water conflict are increasing in the region, which may worsen with a continuous growth of irrigated agriculture, which already represents about 64% of the irrigation practiced in Brazil (FEALQ, 2014). Studies carried out by Althoff & Rodrigues (2019) indicated that 80% of the country's center pivots are located in the Cerrado. Also, the irrigated area is expected to expand 56 000 ha $years^{-1}$ on average and may reach up to 3 Mha in 2050, which might impact the dynamics of water use in the region.

Irrigated agriculture brings important benefits to the region's agriculture since it provides yield gains, production stability and agriculture viability throughout the year. However, irrigated agriculture uses water resources intensively, especially during the dry season (April to September). Thus, if not properly planned and managed, its expansion could aggravate disputes over the use of water in the region.

Improving irrigation efficiency is a strategy that can increase the economic viability and environmental sustainability of irrigated agriculture (Bastiaanssen & Steduto, 2017; Levidow et al., 2014). Considering Cerrado's current scenario of water use and the tendency of increasing conflicts over this resource, it is paramount to produce more using less water. Hence, assessing and improving tools that contribute to using water efficiently is essential.

Although it is known that there are different types of soil within irrigated area, historically irrigation has been managed considering the irrigated area as a homogeneous unit. This means that the water is usually applied uniformly. In this context, the amount of water to be applied is calculated based on the average or the most limiting soil condition for the crop. Consequently, within the irrigated area, some locations in the area will receive the ideal amount of water while others will receive more or less water than the ideal. Irrigation managed without considering the spatial variability of soil physical attributes is one of the main factors responsible for irrigation's low efficiency (Kassing et al., 2020; Neupane & Guo, 2019).

Technological advances achieved in recent years, such as global navigation satellite systems, geographic information systems and variable rate water application equipment (Giotto et al., 2016; Resende et al., 2010), has enabled precision irrigation to be practiced in center pivots. By using the right controls, sensors and decision-making tools, these irrigation systems can be managed to apply different water requirements within the irrigated area. Precision irrigation, despite its low adoption, has great potential to contribute to improving irrigation efficiency.

There is a great opportunity to use computer models in this field of knowledge. Computer models have been used in the design and management of irrigation systems. Now they can also be used to create soil moisture maps that could aid the designer to understand yield maps. In recent years, several models have been proposed to manage irrigation considering soil spatial variability (Bhatti et al., 2020; Cambra Baseca et al., 2019; González Perea et al., 2018; Li et al., 2019; O'Shaughnessy et al., 2020; Yari et al., 2020).

There are some studies in literature with the purpose of evaluating the precision irrigation benefits in water savings and increased crop yield (Azevedo, 2003; González Perea et al., 2018; Kang et al., 2011; Pereira et al., 2013; Qiuming et al., 2007; Yari et al., 2017), there is, however, a need to better understand those benefits. Center pivot is the irrigation system particularly suitable for precision irrigation mainly due to its current automation levels and large irrigated area with a single pipeline.

Some studies have indicated the water savings potential by using application systems at varying rates (Hedley & Yule, 2009; Sadler et al., 2005). For instance, Hedley & Yule (2009) compared conventional and precision irrigation methods and found water savings from 9 to 19%. Studies like this that assess the real savings potential need to be expanded and better evaluated for center pivot conditions that irrigate large areas.

Simulations aiming to identify the best irrigation strategy, to obtain the best crop yields and to increase water and energy savings, are extremely important, as they enhance the certainty of decision-making. Given the characteristics of precision irrigation and its high implementation cost in center pivot systems, it is necessary to evaluate its benefits in agricultural production. Although its benefits are recognized, they were not very well quantified and documented, contributing to the low adoption and implementation of this technology. Thus, the present work aimed to assess the precision irrigation potential for increasing soybean crop yield and water savings through simulation.

Material and methods

Study areas

The work was carried out on two center pivots (Fig. 1). The first pivot (Fig. 1A), called PivoBHBV, with an irrigated area of 92.8 ha, has low spatial variability of soil texture, with a predominance of clay (57.2%). The second pivot (Fig. 1B), called PivoBHALPA with an irrigated area of 126.6 ha, has high spatial variability of soil texture.

The region where PivoBHBV is located is characterized by a dry season that starts in April and ends in September and a rainy season that extends from October to March (Wendt et al., 2015). The average annual rainfall is around 1100 mm, from which 85% corresponds to the rainy season (Rodrigues et al., 2012). The average air temperature

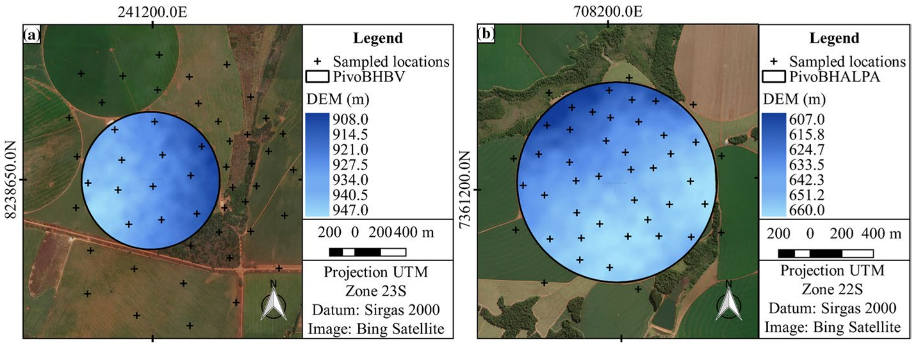

Fig. 1 Location of center pivots used in simulations and sampled locations. **A** PivoBHBV; and **B** PivoBHALPA

is about 22 °C, average relative moisture of 69%, and average maximum reference evapotranspiration around 5.7 mm day^{-1}. It was found in the soil survey that around 94.9% of its drainage area the predominant class is the Red Latosol, followed by 3.0% of Cambisols, and 2.1% of Gleisols (Passo et al., 2014). The watershed's land use and land cover are mainly agricultural (Moreira et al., 2010). Soybeans are the main dry and irrigated crop, along with corn, wheat, and beans.

The region where PivoBHALPA is located has a climate classified as humid tropical with slight variation between regions further inland. The rainy season is from September to March, with January being the month with the highest rainfall. The dry season extends from April to August. The average annual rainfall is about 1300 mm. The average air temperature is approximately 21 °C, average relative moisture of 74%, and average maximum reference evapotranspiration around 5.0 mm day^{-1}. It was found in the soil survey (EMBRAPA, 2011) that in about 60.3% of the watershed's drainage area, the main soil class is Red Latosol, followed by 22.8% of Red Argisol, 11.9% of Cambisols, and 0.45% of Neosols. The land use and land cover are mainly agricultural activities, followed by native vegetation, which represents about 15% of the watershed area. The central portion of the region, which is occupied by the Cerrado biome, has a high water demand for the irrigation of crops such as soy, wheat, corn, beans, sugarcane, forestry and cotton, which are the main crops cultivated in the region.

Database

Climate

The climate data necessary for simulation of irrigation management at PivoBHBV were from a weather station monitored by Embrapa Cerrados about 40 km away from the study area. At PivoBHALPA, the climate data were from a weather station monitored by the pivot's property 2 km away from the study area. Daily data on temperature (̊C), relative moisture (%), wind speed (m s^{-1}), solar radiation (W m^{-2}) and rainfall (mm) were used.

Soil

At PivoBHBV, most of the necessary soil data came from work carried out by Rodrigues & Maia (2011). These authors collected soil samples from 99 sites within the BHBV and presented data about soil moisture at field capacity (FC), soil moisture at permanent wilting point (PWP), bulk density (BD) and soil texture. From the 99 sampled locations, the data from the ones within the pivot and the ones at up to 500 m away from its limit, were used. A total of 42 sampled points were used.

After selecting the points, a visual data spatialization analysis within the pivot area was carried out to identify locations with low sampling density. Based on this analysis, more samples were collected in 8 locations within the pivot area, reaching 50 points (Fig. 1A). The samples taken were disturbed and undisturbed, with five repetitions. The retention curves were determined by the standardized centrifuge method (Silva & Azevedo, 2002) considering the tension points of 1; 6; 33; 100; 300 and 1500 kPa.

At PivoBHALPA, disturbed and undisturbed samples were obtained in 45 locations within the pivot and its surroundings (Fig. 1B). Samples were collected with two replicates. The disturbed soil samples were for soil texture analysis. The undisturbed soil samples were for assessing the retention curve and to determine the overall soil density. In the analysis of the retention curves, the tension points of 1; 10; 33 and 1500 kPa were considered.

At the two pivots, the soil samples were taken from the 0–0.30 m soil layer, which usually represents the crop soil layer.

At PivoBHALPA, soil apparent electrical conductivity data (ECa) were used. These data were obtained through the Elletro II, a drag gauge coupled to a motor vehicle manufactured by GREEN Resultados em Gestão LTDA (Botucatu, São Paulo, Brazil). This equipment measures georeferenced ECa data continuously, considering the 0–0.75 m layer, with data measurement every 5 m in the crossing line and from 25 to 30 m between lines.

Digital terrain elevation model and slope

The digital elevation model (DEM) and the terrain slope for the two pivots were generated based on satellite images from the Alos Palsar sensor, obtained freely from the Alaska Satellite Facility platform (www.vertex.daac.asf.alaska.edu/). This product's sensor has a spatial resolution of 12.5 m.

Irrigation management

The simulations were carried out considering two irrigation management strategies. In the first strategy, the irrigation management considered the soil as homogeneous, meaning that the spatial variability of the soil was disregarded. From now on, this management strategy will be called conventional management (CM). In the other strategy, the management considered the spatial variability of the soil. This management strategy will be called precision irrigation (PI). The spatial resolution used in the simulations was 5×5 m ($25 m^2$).

For PI, the irrigation management was carried out individually in each one of the 37 191 pixels of the PivoBHBV and the 50 649 pixels of the PivoBHALPA, which constitute the total area of the center pivots. CM was managed considering three scenarios based on the soil available water capacity (AWC): (i) using as a reference the lowest AWC value found in the irrigated area (CM1); (ii) using the average AWC value (CM2); and (iii) using the highest AWC value (CM3). In scenario 1, for example, the area was considered homogeneous and the irrigation management was carried out using as a reference the lowest AWC value for the entire irrigated area. This means that, for instance, in the case of PivoBHBV, whose pixels have an area of 25 m^2, the smallest AWC absolute value was used in the management of the 37 191 pixels that constitute the pivot area.

The simulations considered two crop years with contrasting climatological conditions, in total rainfall terms, one rainy year (RY), and one dry year (DY). The simulations also considered four sowing dates of the soybean crop (SD), three scenarios of management considering homogeneous soil (CM1, CM2 and CM3), and management considering the spatial variability of the soil, totaling 32 scenarios in each center pivot. For PivoBHBV, the year 2014/2015 was considered as rainy and the year 2015/2016 as dry. For PivoBHALPA, the rainy year was 2015/2016 and the dry year was 2016/2017. The four sowing dates of the soybean crop (SD) used in each year were: SD1 = September 10th (Julian Days (JD) = 254); SD2 = October 10th (JD = 284); SD3 = November 10th (JD = 315) and SD4 = December 10th (JD = 345).

To assess the spatial variability of the AWC in the irrigated area, a geostatistical analysis was carried out on the FC, PWP and BD data. Then, data interpolation was made considering the sampling locations inside and outside the center pivot area. The data were interpolated using simple kriging in the R software. v.1.2.1335 (R Core Team, 2019). In cases where the spatial dependence was classified as poor, according to the spatial dependence index (SDI) proposed by Cambardella et al. (1994), the maps were interpolated using the inverse distance method. With the interpolated data of FC, PWP and BD, the AWC values were calculated for each pixel.

Irrigation management strategies simulation model

Conventional irrigation management was made using the irrigation strategy simulation model (ISSM) (Rodrigues & Moreira, 2015). A specific module for precision irrigation was developed in Python language to carry out the precision irrigation management. This module was coupled to the ISSM model. It is necessary to set up the initial characteristics of the soil, climate and plant before carrying out the simulations.

The ISSM used the mass conservation equation to estimate soil moisture and irrigation depth. Disregarding capillary rise, the soil water deficit on the day i (SWDi) is calculated by Eq. 1.

$$\mathrm{SWD_i} = \mathrm{SWD_{i-1}} + \mathrm{ETa_i} - \mathrm{R_i} - \mathrm{I_{ri}} \tag{1}$$

In which: R_i = effective rainfall, mm; I_{ri} = applied irrigation depth, mm; SWD_{i-1} = soil moisture deficit on day i_{-1}, mm; and, ETa_i = current daily crop evapotranspiration, mm day^{-1}.

The current daily crop evapotranspiration is calculated by Eq. 2 (Jensen & Heermann, 1970):

$$\mathrm{ETa_{i,j}} = \mathrm{ETo_{i,j}}\left[\mathrm{Kc_{i,j}}\ \mathrm{Ks_{i,j}} + \mathrm{Ke}\left(0{,}9 - \mathrm{Kc_{i,j}}\right)\right] \tag{2}$$

In which: Kc = average crop coefficient; Ks = soil evaporation reduction coefficient; Ke = crop evapotranspiration correction coefficient; and, ETo_{ij} = reference evapotranspiration, mm day^{-1}.

Reference evapotranspiration was estimated by the Penman–Monteith-FAO method (Allen et al., 1998), by Eq. 3.

$$ETo_i = \frac{0.4082\Delta\left(R_n - G\right) + \gamma^* \frac{900}{T+273} U_2(e_s - e_a)}{\Delta + \gamma^*(1 + 0.34\,U_2)} \tag{3}$$

In which: Δ = slope of the saturation vapor pressure curve, kPa ºC^{-1}; γ^* = psychrometric constant = 0.063 kPa ºC^{-1}; Rn = surface radiation balance, MJ m^{-2} d^{-1}; G = soil heat flux, MJ m^{-2} d^{-1}; T = average air temperature, °C; U_2 = wind speed measured at a height of 2 m, m s^{-1}; es = vapor saturation pressure, kPa; ea = partial vapor pressure, kPa; and, (es–ea) = vapor saturation deficit, kPa.

Evaluation of the water savings potential

To assess the water savings potential for the soybean crop, precision irrigation management was compared with conventional management. The three conventional management scenarios described were considered. Hence, the following were evaluated: (i) water savings potential (WSP), Eq. 4; (ii) deep percolation reduction potential (DPRP), Eq. 5; and (iii) current irrigation adequacy index (IAI), Eq. 7.

$$WSP = Iri_{CM} - Iri_{PI} \tag{4}$$

$$DPRP = DP_{CM} - DP_{PI} \tag{5}$$

In which: WSP = water savings potential, mm; DPRP = potential to reduce deep percolation, mm; Iri = total amount of irrigation applied, mm; DP = total deep percolation, mm; and, CM and PI = indicate conventional management and precision irrigation, respectively.

For the precision irrigation, the total Iri_{PI} and DP_{PI} were calculated using Eq. 6.

$$Iri_{PI}, DP_{PI} = \sum_{i=1}^{j} Y_i \tag{6}$$

In which: Y = Iri or DP; and, j = is pixel number. For example, j = 37,191 for the PivoB-HBV divided into 25 m^2 pixels.

According to Rodrigues et al. (2003), the current irrigation adequacy index (IAI) indicates how well a pre-established goal was achieved. To evaluate the proposed irrigation management strategies, the simulated total irrigation depth for the conventional management conditions in the three scenarios was compared to the total irrigation depth required in each pixel (precision irrigation).

Given this condition, the established goal, according to each irrigation management strategy, was to apply the necessary water amount according to the real AWC characteristics of each pixel.

Therefore, the current irrigation adequacy index was calculated using Eq. 7.

$$IAI = \frac{Iri_{CM}}{Iri_{PI}} \tag{7}$$

Based on the index definition, a value < 1.0 indicates deficit irrigation, a value = 1.0 adequate irrigation and a value > 1.0 excessive irrigation.

Evaluation of the increased yield potential

To evaluate the increased yield potential (IYP), the crop yield for the CM and PI conditions was calculated for each pivot pixel. Crop yield was calculated by Eq. 8, as described by Stewart et al. (1977) and presented by Doorenbos & Kassam (1979).

$$Y_a = Y_m \left[1\text{-}\ K_y\left(1 - \frac{\sum_{i=1}^{110} ET_{ai}}{\sum_{i=1}^{110} ET_{mi}}\right)\right] \tag{8}$$

In which: Y_a = current crop yield, kg ha^{-1}; Y_m = maximum crop yield, kg ha^{-1}; ET_{ai} = current total evapotranspiration, mm; ET_{mi} = maximum total evapotranspiration, mm; and K_y = crop response factor to water stress, dimensionless.

A single Ky value equal to 0.85 was used as a reference for the soybean crop cycle, as proposed by Doorenbos & Kassam (1979).

The crop's increased yield potential (IYP) was evaluated by comparing the crop yield under precision irrigation conditions with the crop yield under conventional management, according to Eq. 9.

$$IYP = Ym_{PI} - Ym_{CM} \tag{9}$$

In which: Y_m = maximum crop yield, kg ha^{-1}; and, PI and CM = indicate precision irrigation and conventional management, respectively.

Water productivity

The irrigation water productivity (WP), in kg m^{-3}, was calculated through the relationship between crop yield and total irrigation depth applied (Eq. 10), according to Payero et al. (2009).

$$WP = \frac{Ya}{I_{ri}} \tag{10}$$

In which: Ya = current crop yield, kg ha^{-1}; and, Iri = applied irrigation depth, mm.

Finally, the evaluation of the increased water productivity potential from irrigation (IWPP) was carried out by comparing the WP obtained under precision irrigation conditions with the WP obtained under conventional management, according to Eq. 11.

$$IWPP = WP_{PI} - WP_{CM} \tag{11}$$

In which: WP = irrigation water productivity, in kg m^{-3}; and, PI and CM = indicate precision irrigation and conventional management, respectively.

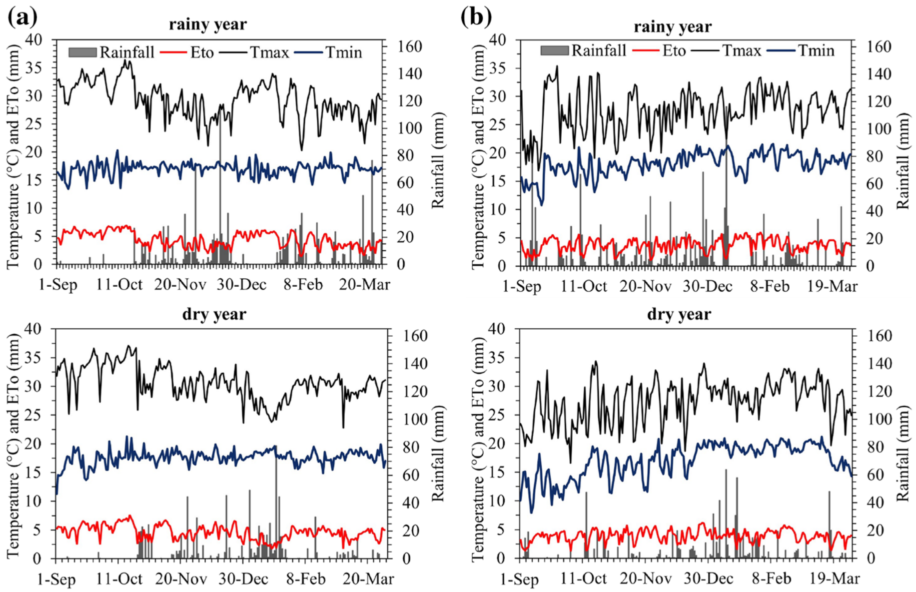

Fig. 2 Daily climate data observed during the four sowing dates (SD) of the soybean crop (SD1 = September 10; SD2 = October 10; SD3 = November 10; and SD4 = December 10) in 2 years with contrasting rainfall. **A** PivoBHBV (Rainy year = 2014/2015; and Dry year = 2015/2016); and **B** PivoBHALPA (Rainy year = 2015/2016; and Dry year = 2016/2017)

Results and discussion

Observed climate data

Figure 2 shows the daily climate data observed at PivoBHBV (Fig. 2A) and PivoBHALPA (Fig. 2B) for the soybean crop in the four sowing dates for the rainy and dry years.

PivoBHBV (Fig. 2A) in RY had a total rainfall of 1230 mm and 106 rainfall events. DY had a total rainfall of 792 mm and 86 rainfall events. On the evaluated sowing dates in RY, the occurrence of 18-day dry spells were observed in SD2, SD3 and SD4. These dry spells happened when the soybean crop was in 87, 54 and 24 days after sowing (DAS) and extended to 105, 72 and 42 DAS, respectively. In DY, considering SD3 from 79 to 110 DAS, and SD4 from 49 to 110 DAS, long intervals without rainfall events were verified.

In RY, the reference evapotranspiration (ETo) ranged from 1.4 to 6.9 mm d^{-1}, with an average ETo of 4.4 mm d^{-1}. The average maximum temperature (Tmax) was 29.3 °C, ranging from 20.3 to 36.4 °C. The average minimum temperature (Tmin) was 17.1 °C, ranging from 13.5 to 20.3 °C. In DY, ETo ranged from 1.7 to 7.6 mm d^{-1}, with an average ETo of 4.6 mm d^{-1}. The average Tmax was 30.6 °C, ranging from 22.8 to 37.1 °C. The average Tmin was 17.7 °C, ranging from 13.7 to 21.3 °C.

PivoBHALPA (Fig. 2B) in RY had a total rainfall of 1440 mm and 117 rainfall events. DY had a total rainfall of 798.6 mm and 94 rainfall events. On the evaluated sowing dates in RY, occurrence of 14-day dry spells were observed in SD3 and SD4.

These dry spells happened when the soybean crop was in 64 and 34 DAS and extended to the 77 and 47 DAS, respectively. In DY, considering SD3 from 7 and 26 DAS and from 83 to 103 DAS, long intervals without rainfall events were verified.

In RY, the reference evapotranspiration (ETo) ranged from 1.0 to 6.0 mm d^{-1}, with an average ETo of 3.7 mm d^{-1}. The average maximum temperature (Tmax) was 27.6 °C, ranging from 16.9 to 35.4 °C. The average minimum temperature (Tmin) was 18.2 °C, ranging from 10.8 to 21.6 °C. In DY, ETo varied from 1.2 to 6.2 mm d^{-1}, with an average ETo of 4.0 mm d^{-1}. The average Tmax was 27.6 °C, ranging from 16.6 to 34.4 °C. The average Tmin was 17.2 °C, ranging from 9.3 to 21.2 °C.

Comparing the two locations, PivoBHALPA had the greatest rainfall and also the best rainfall distribution during the two years evaluated. At PivoBHBV, the occurrence of dry spells with higher frequencies and longer intervals of days without rain was due to the bad rainfall distribution. At PivoBHBV, about 40% (491 mm) of the total rainfall during the RY was concentrated between November 22 and December 26, and 45% (355 mm) of the total rainfall during the DY was concentrated between January 03 and January 27.

Soil hydro-physical variables

The descriptive statistical analysis of the soil hydro-physical variables from both pivots studied are shown in Fig. 3.

Texture is one of the main indicators of soil water retention (Reichardt, 1987). The PivoBHBV soil was classified as clayey, with an average clay content of 57.2%, a standard deviation of 11.5% and a variation coefficient of 20.2%. As a rule, soils with high clay content have great soil water retention capacity (Klein et al., 2010).

The average moisture values of field capacity and permanent wilting point were 41.4 and 25.5%, respectively. The average soil bulk density (BD) was 1.01 g cm^{-3}, indicating low compaction in the agricultural layer. The AWC was 1.58 mm cm^{-1}, indicating a good storage capacity typical of clayey soils.

The PivoBHALPA soil was classified as clayey-sandy with average clay and sand contents around 45.4 and 45.5%, respectively. The sand and clay fractions have a standard deviation of 13.6 and 11.0% and a variation coefficient of 29.9 and 24.1%, respectively, which indicates great variability of soil properties in the pivot area.

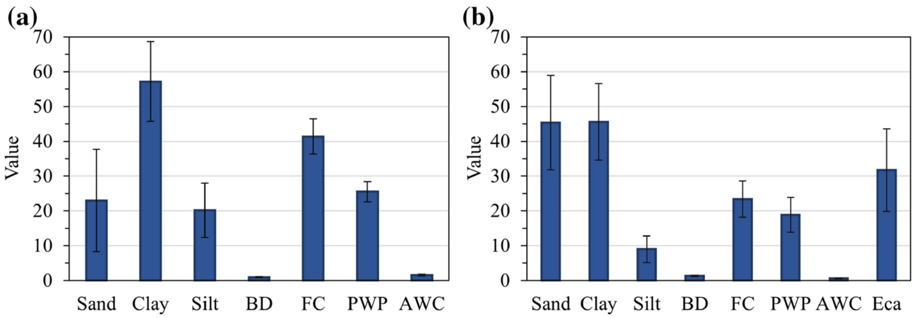

Fig. 3 Soil hydro-physical variables average values observed in the two pivots. **A** PivoBHBV; e **B** PivoBHALPA. Sand (%); Clay (%); Silt (%); *BD* bulk density (g cm^{-3}); *FC* field capacity (%); *PWP* permanent wilting point (%); *AWC* available water content (mm cm^{-1}); and ECa = soil apparent electrical conductivity (mS m^{-1})

The average FC and PWP were 23.4 and 18.8%, respectively. The average BD was 1.38 g cm^{-3}, indicating large compaction and, as a consequence, low total porosity and great restrictions for the root system and plant growth. The smaller the growth of the root system, the less total volume of soil water is available for plants, directly impacting the irrigation frequency. AWC had an average value of 0.63 mm cm^{-1}, a sandy textured soil characteristic value. ECa had an average value of 31.7 mS m^{-1}, with a standard deviation of 11.9 mS m^{-1} and variation coefficient of 37.5%.

High values of standard deviation and variation coefficient were observed at PivoB-HALPA. These values demonstrate the high variability of soil characteristics, which means that the variables have high dispersion around their respective averages. As evidenced by Vories et al. (2021), soil texture variability reduces the effectiveness of conventional irrigation management, while variable rate irrigation management, that is, precision irrigation, can address soil variability, and for the prescription of the ideal application of water requires guidance based on variability maps and monitoring of available water conditions in the soil.

The spatial variability maps of the digital elevation model (DEM), slope and hydro-physical variables are shown in Fig. 4. Large hydro-physical parameters spatial

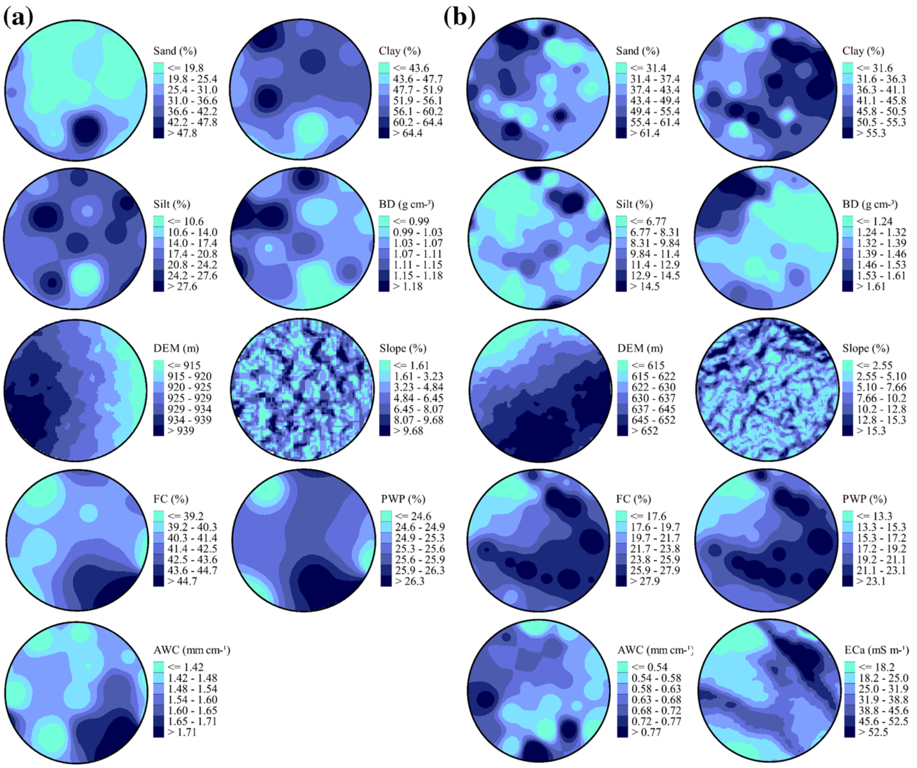

Fig. 4 Soil texture spatial variability, digital elevation model (DEM), slope and soil hydro-physical variables. **A** PivoBHBV; and **B** PivoBHALPA. *BD* soil density (g cm^{-3}); *DEM* digital elevation model (m); Slope (%); *FC* field capacity (%); *PWP* permanent wilting point (%); *AWC* available water content (mm cm^{-1}); and ECa = soil apparent electrical conductivity (mS m^{-1})

variability is observed at PivoBHALPA (Fig. 4B). This great variability is reflected in the AWC values, indicating different water storage capacities that impact irrigation efficiency.

Figure 4 shows that PivoBHBV's elevation ranged from 915 to 939 m, while PivoBHALPA's elevation ranged from 615 to 652 m, with amplitudes of 24 and 37 m, respectively. The slope of the pivots was mostly below 8.0%, which corresponds to relief from plane to gentle slope (EMBRAPA, 1979). In some regions of the pivots, slopes greater than 8.0% are observed. PivoBHALPA, for example, has slopes of up to 15.3%, which indicates rather steep slopes.

It appears that the spatial patterns of FC and PWP are directly proportional to each other and inversely proportional to BD. It means that the areas with the highest FC values also have the highest PWP values and the lowest BD values. At PivoBHBV, the highest values of FC, PWP and AWC are observed in the lower portions of the pivot, with high clay percentages and low bulk density values. At PivoBHALPA, the highest values of FC and PWP are in the high portions of the pivot portions since their clay percentage is higher than the sand percentage. There is a certain similarity in the spatial behavior of FC and PWP and ECa in some portions of PivoBHALPA.

Since the irrigation management strategies evaluated in this work are based on the AWC value, after interpolating the AWC data, the frequency of the AWC's values in the pixels from each study pivot was verified (Fig. 5).

It is observed at PivoBHBV (Fig. 5A) that 57.6% of the pixels have AWC values from 1.45 to 1.55 mm cm^{-1}. Based on the total number of pixels from PivoBHBV and considering the pixel's area of 25 m^2, it was found that 236 pixels (0.63%) have AWC values equal to the smallest value (1.35 mm cm^{-1}), 189 pixels (0.51%) have AWC values equal to the average (1.52 mm cm^{-1}) and only 4 pixels (0.01%) have AWC values equal to the highest value (1.89 mm cm^{-1}). In 11 691 pixels (31.3%) and 25,311 pixels (68.1%), the AWC values were below and above the average value, respectively. This variability demonstrates that it is impracticable to operationalize the management to meet the reality of each pixel and that there will always be areas receiving a greater or lesser water amount.

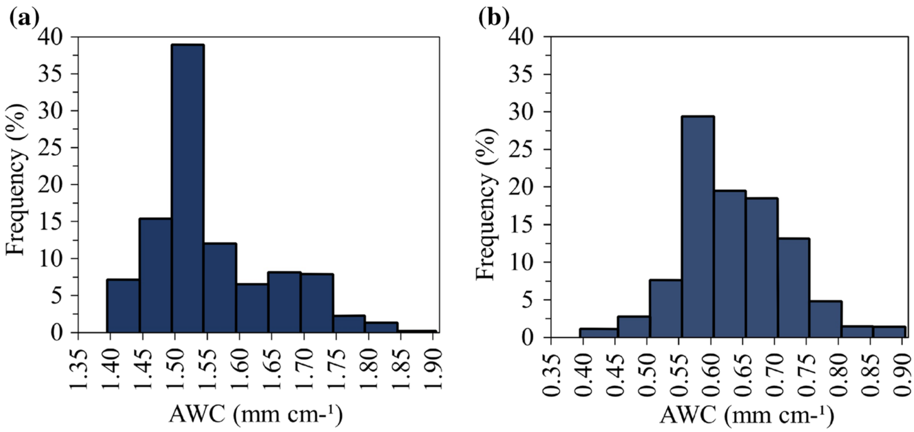

Fig. 5 Available soil water frequency analysis (AWC) after interpolation. **A** PivoBHBV; and **B** PivoBHALPA

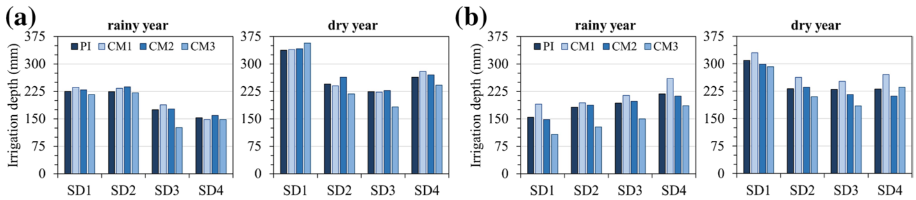

Fig. 6 Total irrigation depth considering the irrigation management under precision irrigation conditions (PI) and conventional managements (CM1, CM2 and CM3) for four soybean crop sowing dates (SD1, SD2, SD3 and SD4) in the rainy and dry years. **A** PivoBHBV and **B** PivoBHALPA

At PivoBHALPA (Fig. 5B), 58.07% of the pixels have AWC values from 0.55 to 0.70 mm cm^{-1}. In 228 pixels (0.45%), AWC values equal to the smallest value (0.42 mm cm^{-1}) are observed. 1890 pixels (3.70%) have AWC values equal to the average value (0.64 mm cm^{-1}) and 179 pixels (0.35%) have AWC values equal to the highest value (0.89 mm cm^{-1}). In 22 331 pixels (44.1%) and 26 428 pixels (52.2%), respectively, AWC values below and above the average value were observed.

Total irrigation depths applied

Figure 6 shows the total irrigation depths obtained in the PI and CM irrigation management in the soybean crop four sowing dates in the rainy and dry years.

Figure 6 shows that in RY at PivoBHBV, the average total irrigation depth during the crop cycle ranged from 178 mm in CM3 to 201 mm in CM1. In DY, the average total irrigation depth during the crop cycle ranged from 250 mm in CM3 to 276 mm in CM2. CM3 had the lowest total irrigation values. Note that the average total irrigation depth in DY was 25.6% greater than in RY for CM1, 27.2% for CM2, 28.9% for CM3 and 27. 4% for PI.

At PivoBHALPA, both in RY and DY, the highest total irrigation average values were 215 and 279 mm, respectively, and were observed in CM1. The smallest differences in the total irrigation average values were between the CM2 and PI managements. At PivoBHALPA, the average total irrigation depth in DY was 23.1% greater than RY for CM1, 22.5% for CM2, 38.0% for CM3, 25.1% and 25.4% for PI.

Relating Fig. 6 to the management adopted, it is observed that the average total irrigation depth in PI was similar to CM2. The highest values were in CM1 and the lowest in CM3. Considering both pivots, the average total irrigation depth at PivoBHALPA is about 4.8% smaller than at PivoBHBV in RY and 6.0% in DY.

The total irrigation depth high values found in CM1 in RY can be justified by a combination of rainfall pattern and management strategy that results in more frequent irrigations and a lower effective rainfall value. In CM3, irrigation is less frequent, and the soil water deficit and the effective rainfall are greater. Irrigation systems based on conventional irrigation management apply irrigation water disregarding the spatial and temporal variability of soil characteristics and changes in meteorological variables that affect the current evapotranspiration of the crop (Vories et al., 2021). Subsequently, this causes the spatial variation of the irrigation depth received by the plants.

Table 1 shows the percentages of pixels at PivoBHBV and PivoBHALPA that receive irrigation depths greater than the management deficit, equal to the management deficit, and smaller than the management deficit.

Table 1 Percentages of pixels at PivoBHBV and PivoBHALPA that received greater irrigation depths (Igr) than the management deficit, equal (Ieq) to the management deficit, and smaller (Ism) than the management deficit

Management strategies	PivoBHBV (%)			PivoBHALPA (%)		
	Igr	Ieq	Ism	Igr	Ieq	Ism
CM1	0.0	0.6	99.4	0.0	0.4	99.6
CM2	31.4	0.5	68.1	44.1	3.7	52.2
CM3	99.9	0.1	0.0	99.6	0.4	0.0

Pixel areas = 25m^2; Total number of pixels: PivoBHBV = 37,191; PivoBHALPA = 50,649

It is noted from Table 1 that in CM1, some pixels (areas) receive the ideal amount of water (PivoBHBV = 0.6% and PivoBHALPA = 0.4%) and a large number of areas receive insufficient amount (PivoBHBV = 99.4% and PivoBHALPA = 99.6%). In CM3, for both PivoBHBV and PivoBHALPA, 0.1% and 0.4% of the pivots receive the ideal amount of water, based on the water deficit management. In these same pivots, it is observed that 99.9% and 99.66% of the pixels receive a greater amount of water than the one simulated in the management.

In CM2, some pixels will always receive less water than the ideal (PivoBHBV = 68.1% and PivoBHALPA = 52.2%) whereas pixels whose AWC is equal to average will receive the ideal amount (PivoBHBV = 0.5% and PivoBHALPA = 3.7%), and some other pixels will receive water in excess (PivoBHBV = 31.4% and PivoBHALPA = 44.1%). Application of more irrigation water than necessary results in deep percolation, nutrient leaching, puddles and surface runoff, while application of less irrigation water than necessary can result in crop stress, due to the water deficit in the soil, which, consequently, can lead to a reduction in crop yield and in the quality of the marketable final product (Bwambale et al., 2022). The precision irrigation is managed according to the real AWC value in the pixel, meaning that 100% of the pixels receive the ideal amount of water.

Deep percolation

Deep percolation is a variable that greatly impacts irrigation efficiency and is almost always neglected in evaluations. The DP presented in this work refers to excessive irrigation. It happens when the applied irrigation depth is greater than the management deficit.

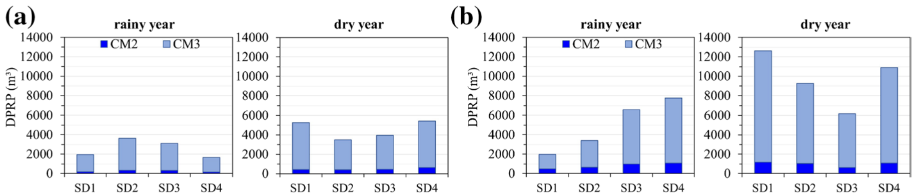

Fig. 7 The irrigation water deep percolation reduction potential (DPRP), obtained from the difference between the deep percolation calculated in the management with precision irrigation (PI) and conventional management (CM1, CM2, and CM3) for four soybean crop sowing dates (SD1, SD2, SD3, and SD4) considering the rainy and dry years. **A** PivoBHBV and **B** PivoBHALPA

The water applied in excess percolates deeper than the root system's effective depth and becomes unavailable to the plant.

In the PI and CM1 managements, the DP is zero. In PI, the management was based on each pixel's real AWC, meaning that the irrigation is never applied in excess. CM1considered that all pixels in the irrigated area have an AWC value equal to the lowest AWC value. In other words, the irrigation depth will always be smaller or, at most, equal to the management deficit. In CM2 and CM3, the calculated DP values represent the potential for deep percolation reduction.

Based on the total volume of water percolated in the two evaluated pivots, very expressive DPRP values were observed in CM3 at all sowing dates evaluated (Fig. 7).

Analyzing the average values obtained in the four sowing dates at PivoBHBV, the PI, compared with CM2 and CM3, had DPRP equal to 249.1 and 2 343.2 m^3 in the RY, and 477.8 and 4 054.0 m^3 in the DY, respectively. These values correspond to 0.14 and 1.5% (RY) and 0.19 and 1.7% (DY) of the irrigation volume applied in the crop cycle. At PivoBHALPA, due to the larger irrigated area and greater spatial variability of the soil hydro-physical characteristics, the DPRP values were even higher than the ones at PivoBHBV. For CM2 and CM3, respectively, the DPRP values were 799.7 and 4 135.4 m^3 in the RY, and 983.0 and 8 587.7 m^3 in the DY. These values correspond to 0.35 and 2.3% (RY) and 0.32 and 3.0% (DY) of the irrigation volume applied in the soybean crop cycle.

Considering the CM2 strategy, DP was observed in 11 691 pixels (31.43%) at PivoBHBV and 27 357 pixels (54.01%) at PivoBHALPA. In CM3, DP was observed in 37 187 pixels (99.99%) at PivoBHBV and 50 470 pixels (99.65%) at PivoBHALPA. Considering SD2 at PivoBHBV, for example, the average DP in CM3 was about 11.1% higher than in CM2. At PivoBHALPA, the average DP in CM3 was about 13.8% higher than in CM2.

The DY had a higher DP than the RY. This is because the simulated DP refers to the excess of irrigation, i.e., the irrigation depth higher than the irrigation management factor (50% AWC). During the RY the number and the amount of irrigation applied was lower when compared to the DY, as can be observed in Fig. 6.

Irrigation adequacy index

The irrigation adequacy index is an interesting criterion to be analyzed as it identifies how well a pre-established goal was achieved. In this work, the IAI was calculated by comparing the irrigation depth applied in CM with PI in each pixel. Based on the index definition, an IAI value less than 1.0 indicates deficit irrigation, a value equal to 1.0 indicates adequate irrigation, and a value greater than 1.0 indicates excessive irrigation. The IAI values are shown in Fig. 8.

Considering the CM strategies at PivoBHBV in the RY, the IAI ranged, on average, from 0.95 to 1.25 (CM1), 0.95–1.23 (CM2) and 0.85–1.10 (CM3). In the DY, the IAI ranged, on average, from 0.88 to 1.18 (CM1), 0.91–1.22 (CM2) and 0.83–1.10 (CM3). While at PivoBHALPA in the RY, the IAI ranged from 1.00 to 1.53 (CM1), 0.83–1.30 (CM2) and 0.65–1.00 (CM3), and in the DY, from 0.95 to 1.30 (CM1), 0.80–1.15 (CM2) and 0.80–1.10 (CM3).

Among the CM strategies, even though all evaluated conditions had areas with deficient and excessive total depth application for the two center pivots studied, the IAI values closest to the target were obtained with CM2. While for CM1 and CM3 most of the points of the simulation had excess ($IAI > 1.0$) and deficit ($IAI < 1.0$) irrigation depth, respectively.

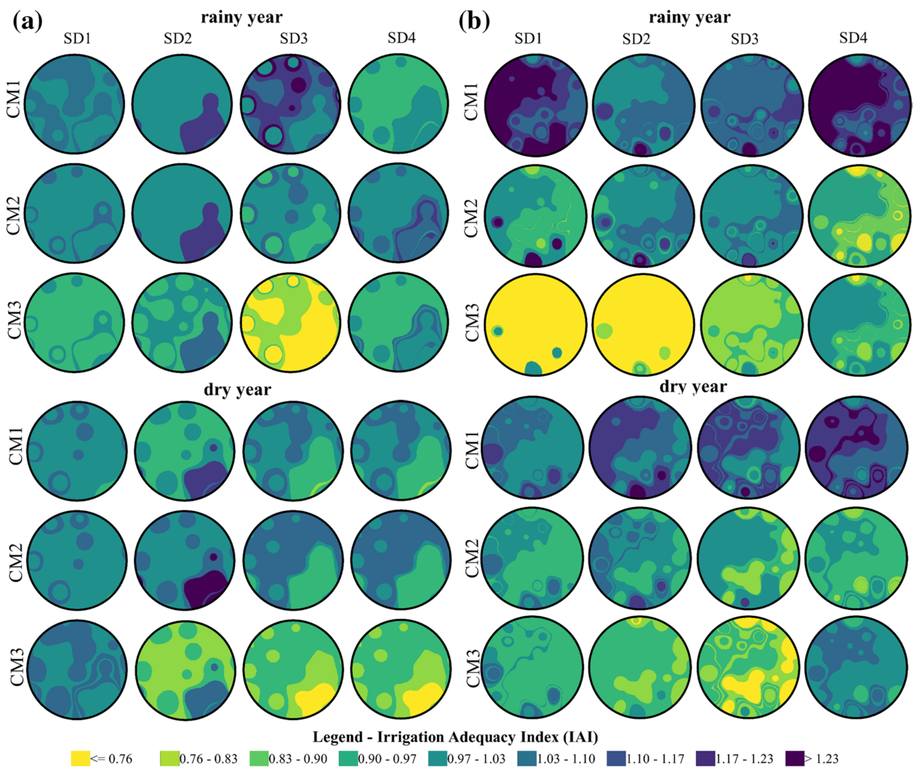

Fig. 8 Irrigation Adequacy Index (IAI) values for the soybean crop in four sowing dates (SD1, SD2, SD3, and SD4) considering the rainy and dry years. **A** PivoBHBV; **B** PivoBHALPA

Analyzing the average IAI values at PivoBHBV (Fig. 8A) with different irrigation management strategies and different sowing dates, it was observed in the RY that in CM1, the highest average IAI value was in SD3 (1.13), and the smallest in SD4 (0.94). SD1 and SD2 behaved similarly to SD3, with average IAI values of 1.06 and 1.04. However, SD4 tended towards deficit irrigation, which is justified by the lower irrigation frequency. Regarding CM2, average IAI values above 1.0 were observed in SD1, SD2 and SD4 (1.02, 1.04 and 1.05), and average IAI values below 1.0 were observed in SD3 (0.99). As for CM3, all sowing dates had average IAI values below 1.0 (SD1 = 0.92; SD2 = 0.97; SD3 = 0.75 and SD4 = 0.95), indicating deficit irrigation.

In the DY, CM1 had average IAI values above 1.0 in SD1 and SD4 (1.01 and 1.07), equal to 1.0 in SD3, and below 1.0 in SD2 (0.98). Regarding CM2, all sowing dates had average IAI values above 1.0 (SD1 = 1.01; SD2 = 1.07; SD3 = 1.03 and SD4 = 1.02). CM3 had an average IAI value above 1.0 in SD1 (1.05) and values below 1.0 in SD2, SD3 and SD4 (0.88, 0.85 and 0.92).

At PivoBHALPA (Fig. 8B) in CM1, all sowing dates had average IAI values above 1.0 (SD1 = 1.25; SD2 = 1.06; SD3 = 1.11 and SD4 = 1.24). Regarding CM2, average IAI values above 1.0 were observed in SD2 and SD3 (1.03 and 1.02), and average IAI values below 1.0 were observed in SD1 and SD4 (0.96 and 0.94). Regarding CM3, all sowing dates had average IAI values below 1.0 (SD1 = 0.69; SD2 = 0.70; SD3 = 0.83 and SD4 = 0.94), indicating deficit irrigation.

In the DY, CM1 also had values above 1.0 in all sowing dates (SD1 = 1.05; SD2 = 1.12; SD3 = 1.11 and SD4 = 1.17). Regarding CM2, average IAI values below 1.0 were observed in SD1, SD3 and SD4 (0.95, 0.94 and 0.92), and average value equal to 1.0 in SD2. Regarding CM3, values below 1.0 were observed in SD1, SD2 and SD3 (0.93, 0.88 and 0.82), and values above 1.0 in SD4 (1.03).

At PivoBHBV, the average IAI of the irrigation management strategies considering the CM1, CM2 and CM3, respectively, were 1.04, 1.02 and 0.90 in the RY and 1.01, 1.03 and 0.92 in the DY. At PivoBHALPA, the average IAI considering CM1, CM2 and CM3, respectively, were 1.17, 0.99 and 0.79, in the RY and 1.11, 0.95 and 0.91 in the DY. As expected, the PivoBHALPA pivot has the greatest IAI variability.

Water savings potential

Figure 9 shows the water savings potential calculated by the difference between the total irrigation depths applied in PI and CM managements considering the four soybean crop sowing dates in the rainy and dry years. The water savings potential is when the irrigation depth applied to a given pixel is greater than the irrigation depth calculated in PI.

Analyzing the WSP in CM1 at PivoBHBV (Fig. 9A) for the four sowing dates in the RY, PI resulted in water savings. In SD3, the WSP was 12 787 m^3, being the highest value and corresponding to 7.9% of the total water volume applied in the PI. The WSP in SD1 was 10 214 m^3 (4.9%), in SD2 it was 9655 m^3 (4.6%), and in SD4 it was 1984 m^3 (1.4%). As for CM2, the highest WSP was in SD2, with a value equal to 12 774 m^3 (6.1%). In SD1, SD3 and SD4, respectively, the WSPs were 4685, 4095 and 6108 m^3 (2.2, 2.5, and 4.3%). Regarding CM3, the use of PI showed water savings in SD2 and SD4, with the WSP values of 5086 and 1791 m^3 (2.4 and 1.3%), respectively. In SD1, the WSP was only 493 m^3 (0.2%). SD3 did not have WSP.

CM1 in the DY had the greatest water savings due to PI in SD4, whose value was 18 718 m^3 (7.6%). A WSP of 3848 m^3 (1.2%) was obtained in SD1, 5512 m^3 (2.4%) in SD2 and 6618 m^3 (3.2%) in SD3. In CM2, PI had WSP in all sowing dates. The greatest water savings was in SD2, about 17 328 m^3 (7.6%), while in SD1, SD3 and SD4 the WSP were 4677, 9030 and 12 304 m^3 (1.5, 4.3 and 5.0%), respectively. In CM3, PI had the highest WSP in SD1, being 18,827 m^3 (6.0%), while in SD2 and SD4 the WSPs were 2415 and 3017 m^3 (1.1 and 1.2%), respectively. SD3 did not have WSP. In SD1 in the DY, low rainfall levels were identified that increased the irrigation frequency in the CM3 strategy. This high irrigation frequency combined with the highest irrigation depths per event,

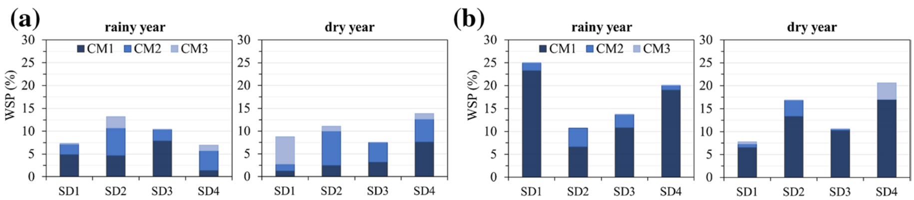

Fig. 9 Water savings potential (WSP) comparing irrigation management under precision irrigation (PI) with conventional managements (CM1, CM2, and CM3) for four soybean crop sowing dates (SD1, SD2, SD3 and SD4) in the rainy and dry years. **A** PivoBHBV and **B** PivoBHALPA

which were necessary to replace the deficit of the pixel with the highest AWC, resulted in higher water use in the soybean crop cycle than PI.

At PivoBHALPA (Fig. 9B) in the RY, the use of PI over CM1 resulted in water savings in all conditions, while SD1 and SD4 had the greatest savings, with WSPs values of 45 384 and 52 568 m^3 respectively, corresponding to savings equivalent to 23.3 and 19.0% of the total water volume used in the soybean cycle. On the other sowing dates, the WSPs were smaller, but still quite expressive if compared to PivoBHBV. In SD2, the WSP was 15 301 m^3 (6.6%) and, in SD3, 26 555 m^3 (10.8%). As for CM2, the highest WSP value occurred in SD2, with a WSP of 9416 m^3 (4.1%). In SD1, SD3 and SD4, respectively, the WSPs values were 3383, 7048 and 2871 m^3 (1.7, 2.9 and 1.0%). In CM3, none of the SD had expressive WSP values since the simulated water volumes for CM3 remained close to the ones for PI. The highest WSP observed in CM3 was 95 m^3 (0.01%), in SD1.

In DY in CM1, WSP was also verified in all conditions. SD2 and SD4 had the highest WSPs, 39 142 and 49 649 m^3 corresponding to 13.3 and 17.0% of the total water volume used in the soybean cycle with PI, respectively. SD1 had a WSP of 25 661 m^3 (6.6%) and SD3 of 29 833 m^3 (10.2%). As for CM2, the highest WSP value was in SD2, 10 149 m^3 (3.5%). In SD1, SD3 and SD4, respectively, the WSPs were 3046, 1006 and 80 m^3 (0.8, 0.3 and 0.1%).

At PivoBHBV, the average WSPs in the irrigation management strategies CM1, CM2 and CM3, respectively, were 8660, 6915 and 1844 m^3 (4.7, 3.8 and 1.0%) in the RY, and 8674, 10 835 and 6065 m^3 (3.6, 4.6 and 2.8%) in the DY. At PivoBHALPA, the average WSPs in CM1, CM2 and CM3, respectively, were 34 952, 5680 and 24 m^3 (14.9, 2.4 and 0.1%) in the RY, and 36 071, 4734 and 3130 m^3 (11.8, 1.5 and 1.0%) in the DY.

Evaluating the average WSP per year, in volumetric terms, it is a large potential was observed for saving water in the DY, because the irrigation depth in all management strategies is greater in the DY than in the RY. At PivoBHBV, the average WSP was 5806 m^3 (3.2%) in the RY and 9200 m^3 (3.7%) in the DY. At PivoBHALPA, the average WSP was 13 552 m^3 (5.8%) in the RY and 14 645 m^3 (4.8%) in the DY.

Comparing both pivots, it was observed that PI expressed greater potential for saving water at PivoBHALPA due to its greater spatial variability of soil characteristics. At PivoBHALPA, the WSP was 2.3 times greater than in PivoBHBV during the RY, and 1.6 times during the DY. The average water savings potential at PivoBHBV and PivoBHALPA, respectively, represents about 1.2 and 2.4% of the average total demand from the crop cycle in the RY and 1.9 and 2.5% in the DY. Although in the comparison of precision irrigation with conventional irrigation management, potential for water savings was observed in most of the evaluated scenarios, in some cases this potential is not very expressive.

Variable rate irrigation in some situations can work as a tool for allocating water, making necessary adjustments to meet the demands of crops at specific points in the area. This water allocation behavior was mostly observed in the comparison of PI with CM3 and some sowing dates of CM2. In this way, the water that would be applied in excess in the conventional irrigation management in regions where there is a lower water retention capacity, leading to deep percolation losses, with the variable rate irrigation management these waters that would be lost are allocated for areas where there is a greater capacity to retain water, being better used by the culture Abioye et al., 2021).

LaRue (2011) reported the benefits of a center pivot system with a variable rate of application in a study that had a 12% reduction in water application. In another field study, Yari et al. (2017) achieved water savings of up to 25 and 34% using precision irrigation management during the 2013 and 2014 harvests, respectively. In the 2015 harvest, the water savings obtained were even more expressive. In this case, the authors found a reduction of up to 43% in the water applied. Miller et al. (2018) obtained a reduction in water application of up to 18 mm, with an average variation within the field of 12 mm. Such evidence indicates that the benefits originating from the precision irrigation use are very specific to the location and conditions evaluated.

Increased yield potential

PI calculated and applied the water requirement according to the real AWC, so the yield in all pixels, estimated at 4200 kg ha^{-1}, was equal to the average potential yield. When using the CM, the management is conducted considering a single AWC value, which means that the yield in the irrigated area is uneven and smaller than the potential yield in most cases.

At PivoBHBV, the lowest average yield values were in CM3, being 3723 kg ha^{-1} in the RY and 3860 kg ha^{-1} in the DY. It appears that in CM1, the average yield in the DY was 0.50% lower than the average yield in the RY, while, in CM2 and CM3, they were 1.7 and 3.6% higher than the average yield in RY, respectively.

PivoBHALPA behaved similarly. The lowest average yield value was in the RY in CM3, 3346 kg ha^{-1}. At PivoBHALPA, the greatest impact on average yield between the years also occurred in CM3, and the DY was 16.0% higher than the average yield in the RY. In CM1 and CM2, respectively, the average yield in the DY was 0.1 and 2.1% lower than in the RY.

Regarding the adopted management, the average yield in PI was closest to the values in CM1. The lowest values were in CM3. Considering both pivots, the average yield in PivoBHALPA is about 1.4% lower than in PivoBHBV in the RY, and 0.30% in the DY.

The observed difference in yield between RY and DY for the same CM was very small due to a combination of factors that reduced ETa. For instance, in the ISSM model, irrigation happens when the ETa accumulated in the period is greater than the allowed management deficit. On a given day, the accumulated Eta might be very close to the deficit, which means that although the difference between the deficit and the accumulated Eta is still positive, it is very small. On the next day, accounting for the last ETa, the accumulated ETa value becomes greater than the deficit value, reducing the ETa value and, consequently, the yield.

Another factor that can contribute to the reduction of productivity is the variation in soil texture, as occurs in the two pivots. In a study carried out by Vories et al. (2021), comparing precision irrigation management and conventional irrigation management in cotton and the impact of soil texture on productivity, they observed a strong influence of soil texture on cotton yield in two growing seasons. The authors reported that the irrigation system under precision irrigation management conditions showed greater efficiency in the use of irrigation water, and consequently, higher productivity.

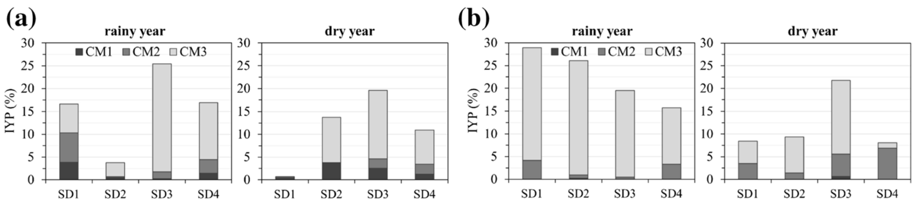

Fig. 10 Increased yield potential (IYP) calculated by comparing irrigation management under precision irrigation conditions (PI) with conventional managements (CM1, CM2, and CM3) for four soybean crop sowing dates (DS1, DS2, DS3 and DS4) in the rainy and dry years. **A** PivoBHBV and **B** PivoBHALPA

Figure 10 shows the increased yield potential values for the soybean crop, calculated by comparing the total simulated yield with irrigation management under PI conditions with the total simulated yield with the CMs for four soybeans crop sowing dates in the rainy and dry years.

At PivoBHBV (Fig. 10A), among all conditions evaluated, the only condition that did not have IYP was SD1 in the DY. In the RY, except for SD1, the highest IYP values were in CM3. Comparing PI with CM3, the increased yield potential observed in SD1, SD2, SD3 and SD4 were 6.3% (264.0 kg ha^{-1}), 3.0% (127.2 kg ha^{-1}), 23.7% (994.7 kg ha^{-1}) and 12.4% (522.9 kg ha^{-1}), respectively. Evaluating the CM1 strategy, the highest IYP values obtained due to the use of PI were 3.9% (162.9 kg ha^{-1}) in SD1 and 1.4% (60.6 kg ha^{-1}) in SD4. In SD2, the IYP was 0.5% (22.3 kg ha^{-1}) in SD3 it was 0.3% (11.9 kg ha^{-1}). Regarding CM2, the IYP values in SD1, SD2, SD3 and SD4 were 6.5% (271.2 kg ha^{-1}), 0.2% (8.2 kg ha^{-1}), 1.5% (61.8 kg ha^{-1}) and 3.0% (126.3 kg ha^{-1}), respectively.

The highest IYP values in the DY, comparing PI with CM1, were 3.8% (159.8 kg ha^{-1}) in SD2, 2.6% (108.5 kg ha^{-1}) in SD3 and 1.3% (53.2 kg ha^{-1}) in SD4. SD1 had an IYP value equal to 0.4% (16.5 kg ha^{-1}). Regarding CM2, the highest IYP values were 2.1% (86.6 kg ha^{-1}) in SD3, and 2.2% (91.0 kg ha^{-1}) in SD4. SD1 had an IYP value equal to 0.2% (10.1 kg ha^{-1}). SD2 did not have IYP. The highest IYP values in the DY were also observed when comparing PI with CM3. In CM3, the IYP values in SD2, SD3 and SD4 were 9.9% (415.7 kg ha^{-1}), 14.9% (627.8 kg ha^{-1}) and 7.5% (316.2 kg ha^{-1}), respectively.

At PivoBHALPA (Fig. 10B), CM1 had very small IYP values both in the RY and the DY. This indicates a low potential to increase yield when using this strategy. In the RY with other management strategies, mainly CM3, the use of PI provided a high potential to increase yield. CM3 in SD1, SD2, SD3 and SD4 had IYP values equal to 24.8% (1040.4 kg ha^{-1}), 25.1% (1053.7 kg ha^{-1}), 19.0% (799.5 kg ha^{-1}) and 12.4% (522.2 kg ha^{-1}), respectively. Comparing PI and CM1, an IYP value greater than zero was observed only in SD2, equal to 0.2% (8.9 kg ha^{-1}). Regarding CM2, the most expressive IYP values were observed in SD1 and SD4, 4.2% (175.2 kg ha^{-1}) and 3.3% (139.4 kg ha^{-1}). SD2 and SD3 had IYP values of 0.8% (31.5 kg ha^{-1}) and 0.5% (19.4 kg ha^{-1}), respectively.

Comparing PI and CM1 in the DY, an IYP above zero was observed only in SD3, 0.6% (26.2 kg ha^{-1}). Regarding CM2, the IYP values in SD1, SD2, SD3 and SD4 were 3.5% (146.2 kg ha^{-1}), 1.4% (59.4 kg ha^{-1}), 5.0% (208.1 kg ha^{-1}) and 6.9% (290.3 kg ha^{-1}), respectively. The highest IYP values during DY were also in CM3, whose values in SD1, SD2, SD3 and SD4 were 4.9% (207.7 kg ha^{-1}), 8.0% (335.2 kg ha^{-1}), 16.2% (680.0 kg ha^{-1}) and 1.2% (49.3 kg ha^{-1}), respectively.

At PivoBHBV, the IYPs obtained due to the use of PI considering the CM1, CM2 and CM3 strategies, respectively, were 1.5, 2.8 and 11.4% (64.5, 116.9 and 477, 2 kg ha^{-1}) in the RY and 2.0, 1.1 and 8.1% (84.5, 47.0 and 340.0 kg ha^{-1}) in the DY. At PivoBHALPA, they were 0.2, 2.2 and 20.3% (8.9, 91.4 and 854.0 kg ha^{-1}) in the RY and 0.6, 4.2 and 7.6% (26.2, 176.0 and 318.1 kg ha^{-1}) in the DY.

Considering the average IYP per year, it is observed that the RY had a higher IYP than DY since the RY has more rainfall. At PivoBHBV, the average IYP was 5.2% (219.5 kg ha^{-1}) in the RY and 3.7% (157.2 kg ha^{-1}) in the DY, corresponding, respectively, to 20.4 and 14.6 t. At PivoBHALPA, the average IYP was 7.6% (318.1 kg ha^{-1}) in the RY and 4.1% (173.4 kg ha^{-1}) in the DY, corresponding, respectively, to 40.3 and 22.0 t.

Comparing both pivots, it was observed that PI had the greatest IYP in PivoBHALPA due to the greater study area extension combined with greater spatial variability of the soil characteristics than PivoBHBV. In PivoBHALPA, the IYP was 1.9 times higher than in PivoBHBV during the RY, and 1.5 times higher during the DY.

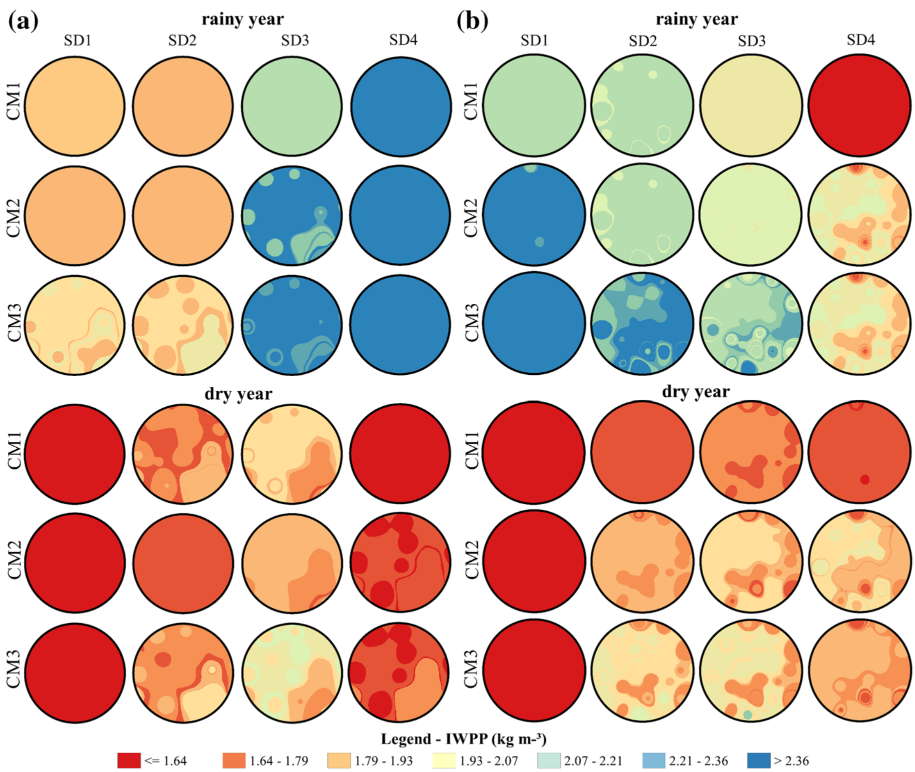

Fig. 11 Increased water productivity potential from irrigation (IWPP), in kg m^{-3}, calculated for four soybean crop sowing dates (SD1, SD2, SD3, and SD4) considering the rainy and dry years. **A** PivoBHBV; **B** PivoBHALPA

Analyzing the 2020 average soybean sack price (60 kg) (PivoBHBV = US$ 20.56 per sack; and PivoBHALPA = US$ 18.58 per sack), it was observed that by using PI the increase in soybean yield at PivoBHBV was equivalent to 292 sacks that correspond to US$ 6004.17. At PivoBHALPA, the increase in soybean yield was equivalent to 520 sacks, corresponding to US$ 9659.61.

Increased water productivity potential

Figure 11 shows maps of the increased water productivity potential from irrigation (IWPP) in CM for four soybean crop sowing dates in the rainy and dry years. The irrigation water productivity (WP) represents the yield per volume of irrigation used. The more that is produced with the smaller amount of water, the greater this indicator will be. Hence, it is natural that the WP is higher in rainy years.

Analyzing the average IWPP at PivoBHBV (Fig. 11A) in the RY for the different irrigation management strategies and different sowing dates, the highest average IWPP values occurred in SD4 and SD3, in this order. The average IWPP values considering the CM1, CM2 and CM3 were, respectively, 2.80, 2.60 and 2.74 kg m^{-3} in SD4, and 2.20, 2.45 and

2.63 kg m^{-3} in the SD3. SD1 and SD2 had the lowest average WP values, 1.80 kg m^{-3}, for all strategies except for CM3, whose average WPs were 1.90 kg m^{-3} in SD1 and 1.89 kg m^{-3} in SD2.

In the DY, the highest average IWPP values occurred in SD3 and SD2, in this order. The average IWPP values considering CM1, CM2 and CM3, respectively, in SD3, were 1.84, 1.77 and 1.95 kg m^{-3}, and in SD2, 1.69, 1.60 and 1.75 kg m^{-3}. The lowest WP values were in SD1, whose average value considering all strategies was 1.20 kg m^{-3}. In SD4 for CM1, CM2 and CM3, respectively, the average IWPP values were 1.48, 1.55 and 1.58 kg m^{-3}.

In PivoBHALPA (Fig. 11B) in the RY, the highest average IWPP values occurred in SD1 and SD2. Considering CM1, CM2 and CM3, respectively, the average IWPP values in DS1 were 2.20, 2.69 and 2.90 kg m^{-3}, and in SD2 2.19, 2.19 and 2.46 kg m^{-3}. In SD3, the average WP values were 2.00, 2.10 and 2.25 kg m^{-3} considering CM1, CM2 and CM3, respectively. The lowest average IWPP values were observed in SD4, in which CM1 was 1.50 kg m^{-3}, and CM2 and CM3 were 1.95 kg m^{-3}.

In the DY, the highest average IWPP values occurred in SD3 and SD4, in this order. Considering CM1, CM2 and CM3, respectively, the average IWPP values in SD3 were 1.68, 1.83 and 1.90 kg m^{-3}, and in SD4 1.60, 1.85 and 1.77 kg m^{-3}. In SD2, the average IWPP values were 1.60, 1.77 and 1.89 kg m^{-3}, considering CM1, CM2 and CM3, respectively. The lowest average IWPP values were in SD1, being CM1 equal to 1.30 kg m^{-3}, CM2 equal to 1.34 kg m^{-3}, and CM3 equal to 1.35 kg m^{-3}.

At PivoBHBV, the average IWPP values for the irrigation management strategies considering CM1, CM2 and CM3, respectively, were 2.15, 2.16 and 2.29 kg m^{-3} in the RY and 1.55, 1.53 and 1.65 kg m^{-3} in the DY. At PivoBHALPA, IWPPs, respectively, were 1.97, 2.23 and 2.39 kg m^{-3} in the RY and 1.54, 1.70 and 1.72 kg m^{-3} in the DY. Comparing the CM strategies, CM3 had the highest average IWPP values, indicating that the reduction in the irrigation depth in this strategy did not compensate for the drop in yield. Hassan et al. (2021) showed that poor irrigation management, as in conventional irrigation management, results in insufficient or excessive irrigation, which affects the productivity of irrigation water use.

Comparing both years, it is observed that the RY had the highest IWPPs values. This is because the rainfall amount in RY was 35.6% higher than in DY at PivoBHBV, and 44.5% at PivoBHALPA. This helped to reduce the irrigation depth without affecting the yield. The average IWPP values observed in the RY for PivoBHBV and PivoBHALPA, respectively, were 2.19 and 2.20 kg m^{-3}, while in the DY they were 1.56 and 1.66 kg m^{-3}. RY had, both spatially and in magnitude, smaller variations in the IWPP values than DY.

Overall, at PivoBHALPA, the irrigation water productivity was higher, although greater variations in IWPP values among sowing dates and between irrigation management strategies are observed. However, PivoBHBV had greater variation among sowing dates.

Conclusions

The results obtained showed that precision irrigation contributed to save on average 3.8% of the applied water.

Precision irrigation contributed to reduce deep percolation from irrigation in about 2704 m^3. The adoption of precision irrigation could have a potential to reduce deep percolation up to 11 450 m^3.

The average water savings potential with precision irrigation was equal to 4.4% (10 802 m^3). The adoption of precision irrigation could have a potential to save up to 23.3% of water.

The average increased yield potential with precision irrigation was 5.3% (217.1 kg ha^{-1}). The adoption of precision irrigation could increase yield potential up to 25.1%.

The average increased water productivity from irrigation was 1.91 kg m^{-3} with the potential to reach values up to 2.90 kg per m^3 of water applied.

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Declarations

Conflict of interest The authors have no conflict of interest in publishing this research.

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