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Research Paper

Modelling economic impacts of deficit irrigated maize in Brazil with consideration of different rainfall regimes

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Deficit irrigation is often required to cope with droughts and limited water availability. However, to select an appropriate irrigation management, it is necessary to assess when economic impacts of deficit irrigation are acceptable. Thus, the main goal of this study was to evaluate economic water productivity for maize submitted to various levels of water deficits and different irrigation systems. The study was based on two different experiments conducted in Southern Brazil, one using sprinkler irrigation to supplement rainfall and the other using drip irrigation with precipitation excluded by a rainfall shelter to simulate cultivation under dry conditions. Water productivity indicators were calculated referring to: a) actual field collected data, including yields, commodity prices and production costs; and b) a sensitivity analysis to commodity prices and production costs. Alternative centre-pivot irrigation scenarios were also developed to assess their feasibility in terms of water use and productivity when irrigation is used to supplement rainfall or when rainfall is scarce. Results show that the feasibility of deficit irrigation is highly influenced by commodity prices and by the irrigation (and water) costs when the irrigation costs are a large part of the production costs. Results also show that deficit irrigation applied when rainfall is abundant is easier to implement than deficit irrigation where rainfall is very scarce, when only a mild stress is economically viable. For well-designed and managed centre-pivot systems, results confirm that adopting deficit irrigation when rainfall is scarce is less attractive than under conditions of irrigation to supplement rainfall. It could be concluded that farmers are unlikely to choose a deficit irrigation strategy unless they are facing reduced water availability for irrigation.

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Nomenclature

A_{inv}	investment annuity, BRL year^{-1}
BWU	beneficial water use, m^3
BWUF	beneficial water use fraction, dimensionless
C_a	investment annuity per unit of irrigated area, BRL ha^{-1} year^{-1}
C_d	energy demand tax, BRL kW^{-1}
C_{en}	annual energy costs, BRL ha^{-1} year^{-1}
C_{inv}	investment costs, BRL
C_m	annual maintenance costs, BRL ha^{-1} year^{-1}
CRF	capital recovery factor, dimensionless
CU	Christiansen coefficient of uniformity, %
DU	distribution uniformity, %
ET_o	reference evapotranspiration, mm
ET_a	actual crop evapotranspiration, mm
EWP	economic water productivity, BRL m^{-3}
EWP_{BWU}	economic water productivity relative to beneficial water use, BRL m^{-3}
EWP_{Irrig}	irrigation economic water productivity, BRL m^{-3}
$EWPR_{full\text{-}cost}$	economic water productivity ratio considering all production costs, dimensionless
$EWPR_{irrig\text{-}cost}$	economic water productivity ratio considering only irrigation costs, dimensionless
$f_{r\ mulch}$	fraction of the ground surface covered by mulch, dimensionless
$f_{eff\ mulch}$	fraction of the ground surface that is effectively covered by mulch, dimensionless
IWU	irrigation water use, m^3
NIR	net irrigation requirements, mm
TAW	total available soil water, mm
TWU	total water use, m^3
WP	water productivity, kg m^{-3}
WP_{BWU}	water productivity relative to beneficial water use, kg m^{-3}
WP_{Irrig}	irrigation water productivity, kg m^{-3}
Y_a	actual crop yield, kg ha^{-1}

Acronyms

ISR	irrigation in supplement to rainfall
ILR	irrigation with very low rainfall
BRL	Brazilian Real

1. Introduction

At present, more than 1.5 billion ha are used worldwide for crop production and there is little scope for further expansion of agricultural land; increasing land productivity, mainly adopting irrigation, is definitely required. According to FAO (2012), the world agricultural production has grown between 2.5 and 3 times over the last 50 years while the cultivated area has grown only 12%. More than 40% of the global increase in food production came from irrigated areas. However, at global level, agricultural water use represents 70% of all water use. Thus, and because water scarcity is increasing, the need to optimise water withdrawal is also increasing, mainly for irrigation purposes (Pereira, Cordery, & Iacovides, 2009). Consequently, farmers are forced to adopt an optimised irrigation management in order to decrease the water demand while increasing land and water productivity.

One commonly used technique that aims to decrease water use is deficit irrigation. This approach consists of deliberately applying irrigation depths smaller than those required to fully satisfy the crop water requirements, thus affecting evapotranspiration and consequently yields, but keeping a positive return from the irrigated crop (Pereira, Oweis, & Zairi, 2002). By avoiding water stress during drought-sensitive stages, deficit irrigation also aims to maximise water productivity (Geerts & Raes, 2009; Kang, Shi, & Zhang, 2000). However, particularly in arid regions, appropriate management is necessary to control effects of reduced irrigation on soil salinity (Pereira, Gonçalves, Dong, Mao, & Fang, 2007; Xu et al., 2013). Moreover, depending upon water management and available rainfall during the crop season, the impacts of deficit irrigation on yields and related farmer incomes may or may not be negative, also depending upon the adopted irrigation scheduling, production costs and yield values (Lorite, Mateos, Orgaz, & Fereres, 2007; Rodrigues & Pereira, 2009). Katerji, Mastrorilli, and Chernic (2010) have shown that maize water productivity (WP) varies with total available soil water (TAW), with a high TAW favouring crop responses to deficit irrigation. Various studies have been developed to assess impacts of deficit irrigation on maize yields and economic returns (Domínguez, de Juan, Tarjuelo, Martínez, & Martínez-Romero, 2012; Farré & Faci, 2009; Payero, Melvin, Irmak, & Tarkalson, 2006; Popova, Eneva, & Pereira, 2006). These studies clearly demonstrate that the feasibility of deficit irrigation strategies depends greatly upon the crop variety and the adopted crop and irrigation management, mainly referring to when those deficits are applied, e.g., Grassini et al. (2011) referred to the possibility of reducing irrigation depths by 25% throughout the crop cycle except for a −14 to +7 d window around silking, during which crops must be fully irrigated.

Another way to achieve efficient water use is through increasing WP, including the related economic results; however the term WP may be used with different meanings and at various scales, which may lead to contradictory interpretations. Various studies (Abd El-Wahed & Ali, 2013; Bouman, 2007; Grassini et al., 2011; Molden et al., 2010; Playan & Mateos, 2006; Zwart & Bastiaanssen, 2004) refer to factors influencing WP, including irrigation management (e.g., supplemental and deficit irrigation), irrigation systems and their performance, crop varieties, soil fertility and TAW, pest and diseases, and soil–water conservation practices (e.g., tillage and mulching). Pereira, Cordery, and Iacovides (2012) defined WP in agriculture as the ratio between the actual yield achieved (Y_a) and the total water use (TWU). These authors, and also van Halsema and Vincent (2012), emphasised that WP enables an appropriate thinking about both the numerator and the denominator, i.e., on both crop growth and yield and water use processes. Though expressing WP without assessing the related economic impacts may lead to some misunderstanding, Pereira et al. (2012) also developed some indicators relating to economic water productivity.

Since the economic value of water is of great importance in a world where water scarcity is growing, it is imperative to maximise the farmer's income that results from water savings while taking into account the irrigation system performance. Grassini et al. (2011) reported that the quantification of water use and WP in actual irrigated cropping systems provides critical information to guide policies and regulations about water use and allocation with the goal of maintaining or increasing productivity while protecting natural resources. In order to achieve improved WP, farmers may upgrade/modernise their irrigation systems since the improvement of irrigation performance, mainly the distribution uniformity, is essential to reduce water demand at the farm level (Brennan, 2007; Pereira et al., 2002). This implies improved design, appropriate selection of the irrigation equipment and careful maintenance. When better distribution uniformity is attained, conditions exist to achieve improved beneficial water use (Pereira et al., 2012). However, there is a contradiction between economic results and the adoption of technologies that provide water saving as reported by Darouich, Gonçalves, Muga, and Pereira (2012) in relation to modernising surface irrigation systems; hence, efforts are required to help farmers investing to achieve better irrigation performance.

Currently, farmers are investing in irrigation modernisation by switching from labour demanding and poorer performing systems to automated ones, such as sprinkler and drip irrigation systems, in order to improve water savings and reduce labour and production costs. However, changes in irrigation systems must consider the need to achieve the best possible distribution uniformity. Several studies have assessed impacts of irrigation non-uniformity on crop yields and evidenced its importance (Brennan, 2007; Dechmi, Playán, Cavero, Faci, & Martínez-Cob, 2003; López-Mata, Tarjuelo, de Juan, Ballesteros, & Domínguez, 2010; Mantovani, Villalobos, Orgaz, & Fereres, 1995; Salmerón, Urrego, Isla, & Cavero, 2012; Sanchez, Zapata, & Faci, 2010).

Many sprinkler systems have neither been properly designed or operated according to the design rules, or their operation has been hampered by poor maintenance. This results in inadequate pressures and discharges along the system, leading to actual application rates deviating from the designed ones (Pereira, 1999). Poorly designed or managed set sprinkler systems with low irrigation uniformity may lead to wasted water and energy as well as to yield losses (Dechmi et al., 2003; Salmerón et al., 2012; Salvador, Martínez-Cob, Cavero, & Playán, 2011). By contrast, well-designed and managed centre-pivot systems may provide highly uniform water application (Valín, Cameira, Teodoro, & Pereira, 2012).

Drip irrigation systems have proved to be an effective alternative in terms of distribution uniformity and water saving. However, the performance of these systems depends greatly on the quality of design and equipment selected (Evans, Wu, & Smajstrala, 2007; Keller & Bliesner, 1990; Pedras, Pereira, & Gonçalves, 2009; Pereira, 1999). Although drip irrigation can provide highly uniform water application when a good design is adopted, related objectives must combine with appropriate irrigation scheduling in practice (Barragan, Cots, Monserrat, Lopez, & Wu, 2010).

Brazil has 12% of the worldwide availability of water resources and the potential for expansion of irrigated agriculture is around 30 million ha (MIN, 2008), which represents an additional 25.5 million ha considering the current irrigated area of approximately 4.5 million ha. Despite the large potential of soils for sustainable irrigation development, only a small fraction is exploited. Therefore in Brazil the ratio of irrigated area/irrigable area is small (about 10%), resulting in a very low value of irrigated land area per capita at 0.018 ha $person^{-1}$, the lowest in South America (ANA, 2009). About 90% of the irrigated area was developed by private enterprise, and less than 10% through public projects. According to the last agricultural census (IBGE, 2009), the irrigation methods used in Brazil are distributed as follows: 24.35% by flooding, 5.76% by furrow, 18.86% by centre-pivot sprinkling, 35.32% with other sprinkler methods, 7.36% by drip irrigation and 8.35% with other methods. In the last 10 years there has been an increase of 39% in the number of farmers using irrigation and of 42% in the total irrigated area, thus resulting an average growth rate of 150,000 ha per year.

Centre-pivot systems are replacing surface and other sprinkler irrigation systems due to easy automation, coverage of a large area, reliability of the systems, high application uniformity, and the ability to operate these systems on relatively rough topography (Montero, Martínez, Valiente, Moreno, & Tarjuelo, 2013; Valín et al., 2012). In Brazil, centre-pivot systems irrigate an estimated area of 840,000 ha, mainly in the Central-West region of the country, due to these advantages and potential for achieving high water distribution uniformity (Sandri & Cortez, 2009). The area irrigated by centre-pivots is rapidly increasing, with 300 new systems (about 20,000 ha) installed in 2012 in Rio Grande do Sul State, where the study reported here was developed.

Recent studies have assessed the impacts of centre-pivot systems in terms of distribution uniformity, energy costs and crop profitability. López-Mata et al. (2010) concluded that improving a centre-pivot to increase the water application uniformity from 75 to 95% may increase the crop gross margin by up to 27%. Ortíz, de Juan, and Tarjuelo (2010) analysed the effect of water application uniformity on the uniformity of soil water content and crop yields for a centre-pivot system irrigating sugar beet. The authors concluded that yields were affected more by the amount of water available in the soil than by the slight differences in soil water uniformity, hence calling attention to the importance of irrigation scheduling. Montero et al. (2013) analysed the main factors influencing annual water application costs in centre-pivot systems and determined the most cost-effective centre-pivot design. They concluded that the cost of water application with centre-pivot machines was quite sensitive to the uniformity of water application. They also observed that, to achieve high distribution uniformity, it is very important to adopt a proper nozzle package and to perform maintenance regularly. Moreno, Medina, Ortega, and Tarjuelo (2012) developed a methodology for relating water application costs in centre-pivot systems with hydraulic factors, mainly relative to the pump and the pipe system, which mainly relate to energy costs. However, the approach did not lead to a clear assessment of the relationships between water saving, investments and yield incomes. Nevertheless, results agree with earlier analyses relating to sprinkler systems (Mantovani et al., 1995; Pereira et al., 2002; Tarjuelo, Montero, Carrión, Honrubia, & Calvo, 1999).

Considering the aspects analysed above and previous developments by Rodrigues and Pereira (2009), the main goal of this study is to assess the economic impacts of water deficits, irrigation systems performance, commodity prices, production costs and water prices upon the physical and economic water productivity of irrigated maize. The application data used in this study are from two experimental maize fields in Santa Maria (Southern Brazil), one irrigated by a set sprinkler system to supplement rainfall, and the other by a drip system where rainfall was excluded through use of a rainfall shelter, as described by Martins et al. (2013). These two experiments made it possible to assess impacts of deficit irrigation comparing situations when rainfall is abundant or scarce. Data were used to develop several alternative centre-pivot irrigation scenarios in the form of different irrigation management options, in order to assess the economic feasibility of deficit irrigation.

2. Materials and methods

2.1. *Experimental area and irrigation experiments*

The experimental study was conducted at the Department of Agricultural Engineering, Federal University of Santa Maria (UFSM), Santa Maria, Brazil, located in the Central Depression of Rio Grande do Sul State. The climate is subtropical humid, a "cfa" according to the climatic classification of Köppen, without a dry season and with hot summers (Moreno, 1961). During the summer months, when the atmospheric evaporative demand is very high, dry spells often occur and rainfall is not sufficient to meet crop needs.

During 2010/2011 growing season, two maize experiments were conducted: one with irrigation to supplement rainfall (ISR) using a set sprinkler system, and the other with very low rainfall (ILR) by using a drip irrigation system under a rainfall shelter. ISR represents rainfall conditions of Southern Brazil, while ILR simulates conditions from dry central Brazil. Conducting the experiments under different rainfall conditions allows an improved basis for the use of the Sistema Irriga™ (Carlesso, Petry, & Trois, 2009) under different climatic conditions and for various irrigation strategies throughout Brazil. Sistema Irriga™ is presently monitoring more than 90,000 ha each year in Brazil, including southern areas with high rainfall and areas in Central Brazil with very low rainfall. The ISR experiments were conducted with three irrigation treatments and 3 replications, with plots of 12×12 m^2, irrigated with a set sprinkler system consisting of 4 sectorial sprinklers per plot with an average application rate of 14.83 mm h^{-1}. The ILR experiments were performed with drip irrigation in an area protected by a rainfall shelter that covered the experimental area when rainfall occurred; rainfall was only allowed during the initial crop stage to ensure adequate and uniform establishment of the crop. The experiments consisted of four irrigation treatments with 4 replications, with experimental plots of 3×6 m^2. The irrigation system consisted of pressure compensating in-line drippers with a discharge of 1.3 l h^{-1} and an application rate of 13 mm h^{-1}. The experiments are described in detail by Martins et al. (2013) including the calibration and validation of the water balance model SIMDualKc (Rosa et al., 2012) used in the present analysis.

Adopting the ISR and ILR experiments to base an analysis of deficit irrigation strategies when rainfall is abundant or is scarce is preferable to just performing simulations with actual weather data because it allows the crop responses to these different strategies to be captured. In subtropical areas the main factor differentiating the crop demand for irrigation is rainfall because it is the main factor controlling the availability of soil water (Rossato, Alvalá, & Tomasella, 2004) and the spatial variability of ET_o is much smaller than the variability of precipitation. This has already been observed for the irrigated areas monitored with the Sistema Irriga™; a better model parameterisation for both high and low rainfall conditions was intended when installing the experiments and analysing them with the model SIMDualKc (Martins et al., 2013).

Both experiments were conducted with mulch since maize is generally cultivated in Brazil with direct seeding. Oats (*Avena strigosa*) crop residues were used for ISR (5 t ha^{-1} of dry biomass spread over all the soil surface, so the cover fraction $f_{r\ mulch} = 1.0$, and achieving an effective soil coverage $f_{eff\ mulch} = 0.9$); beans (*Phaseolus vulgaris* L.) crop residues were used for ILR (3 t ha^{-1} of dry biomass, $f_{r\ mulch} = 1.0$ and $f_{eff\ mulch} = 0.8$). The hybrid AG8011YG was used for ISR and the hybrid P1630H was used for ILR. In both cases the plant density was 6.5 plants m^{-2}. Observations comprised irrigation water depths applied, soil water content down to 0.90 m depth using a calibrated set of FDR (Frequency Domain Reflectometry) sensors, crop height, leaf area index (LAI), ground cover fraction and yields. Detailed information on the experiments and results has been published by Martins et al (2013). Main results for all treatments, either observed or obtained with the model SIMDualKc, are given in Table 1: net and gross irrigation depths (NIWU & IWU, mm), precipitation (*P*, mm), total water use (TWU, mm), actual evapotranspiration (ET_a, mm), beneficial water use fraction (BWUF) and actual yield (Y_a, kg ha^{-1}). These results show that ISR treatments were without or with only a mild water deficit while the ILR treatments all achieved deficit, which increased from ILR1 to ILR4. TWU was obtained by the sum of IWU, *P* and the variation of the soil water storage between planting and harvesting.

The irrigation and production costs were set for each treatment, taking into account the water and labour costs, nutrients applied, seeds, machinery, energy required for irrigation and the investment and maintenance required for each system (Table 2). Data for labour, machinery and harvest costs were obtained from regional data (CONAB, 2010). Costs concerning seeds, fertilisers and irrigation were obtained from the experimental data.

2.2. *Water productivity and water use indicators*

Water productivity (WP) concepts apply to various definitions of water use and at various scales. Therefore, it is of great importance to properly define the related concepts used in

Table 1 – Irrigation water use and grain yield relative to each treatment.

Treatment	Irrigation to supplement rainfall			Deficit irrigation with very low rainfall			
	ISR1	ISR2	ISR3	ILR1	ILR2	ILR3	ILR4
Net irrigation (NIWU, mm)	328	234	91	389	316	218	113
Gross irrigation (IWU, mm)	431	307	120	463	376	259	134
Rainfall (mm)	415	415	415	73	73	73	73
Total water use (TWU, mm)	853	732	615	539	468	421	329
Actual evapotranspiration (ET_a, mm)	502	497	479	365	361	342	272
Beneficial water use fraction (BWUF)	0.59	0.68	0.78	0.68	0.77	0.81	0.83
Actual grain yield (Y_a, kg ha^{-1})	13,212	12,548	12,011	9190	8340	7650	5312

Adapted from Martins et al., 2013.

this study. Here, following Pereira et al. (2012), WP (kg m^{-3}) is defined as the ratio between the actual crop yield (Y_a, kg) and the total water use (TWU, m^3), thus:

$$WP = \frac{Y_a}{TWU} \quad (1)$$

When considering only the irrigation water use (IWU, m^3), the result is the irrigation water productivity (WP_{Irrig}, kg m^{-3}):

$$WP_{Irrig} = \frac{Y_a}{IWU} \quad (2)$$

Pereira et al. (2012) proposed new water use indicators which include consideration of water reuse and aim to assist in identifying and providing clear distinctions between beneficial and non-beneficial water use because, from the water economy perspective, it is important to recognise both. The beneficial water use fraction (BWUF) may be defined as the fraction of TWU that is used to produce the actual yield. In the present situation, because there is no need for leaching or other processes such as runoff, and the presence of mulch helps limit ET from weeds, the beneficial water use corresponds to the actual ET. Thus, as an alternative to Eqs. (1) and (2), WP may be computed in relation to the beneficial water use (BWU, m^3), thus

$$WP_{BWU} = \frac{Y_a}{BWU} \quad (3)$$

The water productivity may be considered not only in physical terms, as above, but also in economic terms. Replacing the numerator of Eq. (1) by the monetary value of the achieved yield, the economic water productivity (EWP, BRL m^{-3}) is defined by:

$$EWP = \frac{Value(Y_a)}{TWU} \quad (4)$$

The monetary value refers to the Brazilian Real (BRL), for which the exchange rate is 1 BRL = 0.48 USD (as of December 2012). When considering IWU or BWU only, this gives:

$$EWP_{Irrig} = \frac{Value(Y_a)}{TWU} \quad (5)$$

$$EWP_{BWU} = \frac{Value(Y_a)}{BWU} \quad (6)$$

It is important to consider the economic issues relating to water productivity since the objective of a farmer is to achieve the best income and profit. As for this study, the economics of production is better considered when expressing both the numerator and the denominator of Eq. (4) in monetary terms, respectively the yield value and the TWU cost (including all the farming costs), thus yielding the economic water productivity ratio ($EWPR_{full\text{-}cost}$):

$$EWPR_{full-cost} = \frac{Value(Y_a)}{Cost(TWU)} \quad (7)$$

$EWPR_{full\text{-}cost}$ allows assessment of whether a given management option leads to positive ($EWPR \geq 1$) or negative ($EWPR < 1$) income since it compares the value of production with the farming costs. If, as an alternative, one considers the irrigation costs only, it results in:

$$EWPR_{irrig-cost} = \frac{Value(Y_a)}{Cost(IWU)} \quad (8)$$

As referred to above, data on Y_a, IWU, TWU and BWUF (Table 1) were obtained from computing the soil water balance

Table 2 – Operation and irrigation costs used in simulations.

Items	Costs
Operation costs	
Machinery (BRL ha^{-1})[a]	204.00
Labour (BRL ha^{-1})	47.00
Seeds (BRL ha^{-1})	
Set sprinkler	233.00
Drip	208.00
Fertilisers (BRL ha^{-1})	
Set sprinkler	1108.00
Drip	797.00
Harvest (BRL ha^{-1})	265.00
Irrigation costs	
Investment annuity (BRL ha^{-1} year^{-1})	
Set sprinkler	441.00
Drip	778.00
Annual maintenance costs (BRL ha^{-1} year^{-1})	
Set sprinkler	137.50
Drip	225.00
Water (BRL m^{-3})	0.005
Electricity (BRL kWh^{-1})	0.31
Labour (BRL ha^{-1})	40.00

a 1 BRL = 0.48 USD.

Table 3 – Irrigation system scenarios

Sprinkler package	System scenario	Irrigated area	Average land slope (%)	Pivot point pressure (kPa)	CU (%)	DU (%)	C_a (BRL ha^{-1} year^{-1})[a]	C_m (BRL ha^{-1} year^{-1})[a]
Senninger®	S1	32.13	1.46	290	95.27	90.79	385	53
Super Spray	S2	46.34	1.52	385	96.51	93.00	369	51
	S3	65.03	2.47	455	95.98	91.83	291	40
	S4	81.27	0.65	410	96.61	93.01	269	37
	S5	110.22	1.47	430	96.31	92.65	254	35
Nelson®	R1	32.13	1.46	330	92.16	87.80	417	56
Rotator R3000	R2	46.34	1.52	410	95.83	91.68	395	53
	R3	65.03	2.47	480	93.73	89.81	314	42
	R4	81.27	0.65	440	95.27	91.45	289	39
	R5	110.22	1.47	470	94.19	90.48	272	37

CU = Christiansen coefficient of uniformity; DU = distribution uniformity; C_a = investment annuity per unit of irrigated area; C_m = annual maintenance costs.
a 1 BRL = 0.48 USD.

(Martins et al., 2013). The monetary values of yields were computed using a grain price of 0.40 BRL kg^{-1}. The irrigation and production costs are summarised in Table 2.

2.3. Alternative irrigation system scenarios

In order to assess the impacts of adopting centre-pivot systems, the most common system for maize in Brazil at present, several scenarios were developed that allow the economic results of the corresponding investment to be assessed. Simulation scenarios were created with irrigated areas, land slopes, pivot point pressures and sprinkler packages corresponding to five different centre-pivot systems in operation in Rio Grande do Sul monitored by Sistema Irriga™. Data collected from field assessments included the irrigated area, pipe sizes, working pressure and discharge, and pump characteristics. The simulation scenarios were developed with the model DEPIVOT (Valín et al., 2012) using the actual system characteristics.

The model DEPIVOT consists of a simulation package developed in Visual Basic and database in Access. It allows alternative sprinkler packages to be developed and compared based on irrigation performance, including potential runoff. The model comprises five main sub-models for: (a) computation of the gross irrigation requirements; (b) sizing the lateral pipe spans through the hydraulics computation of the friction losses and respective operative simulation considering the effects of topography; (c) selecting a sprinkler package with computation of pressure and discharge at each outlet and including the consideration of pressure regulators; (d) verification of the sprinkler package through estimation of runoff potential by comparing application and infiltration rates at selected locations along the lateral; and (e) estimating uniformity performance indicators expected when in operation. The user should verify if performance is within target values set at the start and should develop and compare alternative sprinkler packages until appropriate conditions are obtained (Valín et al., 2012).

DEPIVOT was adopted in this study to create alternative sprinkler packages and to compare various working conditions, mainly relating to pressure at the pivot point, pressure variation due to land elevation and the area irrigated. Hence, different sprinkler packages were created adopting equipment from two major sprinkler manufacturers: Super Spray (S) from Senninger® and Rotators R3000 (R) from Nelson®. The corresponding irrigation systems scenarios are presented in Table 3, which includes the irrigated area, average slope, pivot point pressure, distribution uniformity (DU) and Christiansen coefficient of uniformity (CU).

Investment costs (C_{inv}, BRL) were computed for each system scenario. They comprise the pump and respective pipe system, the conveyance and distribution pipe and the centre-pivot costs, including the selected sprinkler package. The investment annuity A_{inv} (BRL year^{-1}) relative to the investment cost C_{inv} is:

$$A_{inv} = \mathrm{CRF}\, C_{inv} \tag{9}$$

where CRF is the capital recovery factor. A_{inv} was computed considering a life-time $n = 24$ years for the pump and respective pipe system, the conveyance and distribution pipe and the centre-pivot equipment, and a life-time $n = 12$ years for the sprinklers. An interest rate, i, of 5% was considered. CRF was then calculated from the life-time and the interest rate as:

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{10}$$

The investment annuity per unit of irrigated area is C_a (BRL ha^{-1} year^{-1}) and is the ratio of A_{inv} to the irrigated area. The investment annuity values are presented in Table 2 for the set sprinkler and drip systems used in experiments, and in Table 3 for the various centre-pivot scenarios.

The operation costs were obtained from the sum of the annual energy costs (C_{en}), the energy demand tax (C_d), and the annual maintenance costs (C_m). C_{en} is calculated as:

$$C_{en} = P E_r T_i \tag{11}$$

where P is the power of the pumping station (kW), E_r is the energy rate (BRL kWh^{-1}) and T_i is the total annual operation time (h) of the pump. The energy cost per unit of irrigated area (BRL ha^{-1}) is calculated by dividing the annual energy cost C_{en} by the irrigated area. Calculations were based upon the energy prices in Southern Brazil. The energy demand tax, C_d, is the fixed amount per kW charged by the regional authorities to operate the pump; the value used herein is 10.07 BRL kW^{-1}. The annual maintenance costs (C_m) were assumed to be equal to 1% of the investment cost and are also included in Tables 2 and 3.

3. Results

3.1. Water productivity

Considering the actual commodity prices, where the unit value of maize grain is of 0.40 BRL kg^{-1}, results for the physical (WP, WP_{Irrig} and WP_{BWU}) and economical (EWP, EWP_{Irrig} and EWP_{BWU}) water productivity for all the field treatments (Table 1) are presented in Table 4. An analysis of variance (ANOVA) was used to test all water productivity indicators for treatment differences using the least significant difference method with $P < 0.05$.

Results in Table 4 show that adopting a deficit irrigation strategy when farming maize often leads to higher WP and WP_{Irrig} when compared with full irrigation. This is particularly evident for WP_{Irrig} because it depends only from the irrigation water use. WP for ISR treatments varied from 1.55 to 1.95 kg m^{-3}, with the highest value for ISR3. For ILR, because TWU is smaller (Table 1), WP results were generally higher than for ISR, ranging from 1.61 to 1.82 kg m^{-3}, with ILR3 leading to the highest WP results but with the lowest value for the more stressed treatment ILR4. WP values obtained in this study compare well with the values proposed by Kiziloglu, Sahin, Kuslu, and Tunc (2009), with 1.50 kg m^{-3} for full irrigation, and by Rodrigues and Pereira (2009) with 1.72 kg m^{-3} for deficit irrigation, both under sprinkler irrigation. However, these WP values for sprinkler irrigation are slightly higher than those obtained by O'Neill, Humphreys, Louis, and Katupitiya (2008), with 1.4 kg m^{-3} for full irrigation. As for drip systems, results are comparable with the ones proposed by Karam, Breidy, Stephan, and Rouphael (2003), ranging from 1.54 to 1.68 kg m^{-3} and from 1.87 to 1.88 kg m^{-3} for full and deficit irrigation, respectively. Other authors also present similar values for drip irrigation, such as O'Neill et al. (2008) with 1.7 kg m^{-3} for full irrigation, and Sampathkumar, Pandian, Ranghaswamy, and Manickasundaram (2012) ranging from 1.60 to 1.72 kg m^{-3} and 1.80 to 1.92 kg m^{-3} for full and deficit irrigation, respectively.

WP_{Irrig} values ranged from 3.07 to 10.05 kg m^{-3} for ISR while they varied from 1.99 to 3.95 kg m^{-3} for ILR. Higher values of WP_{Irrig} for ISR resulted from high precipitation received during the farming season, which contrasted with ILR experiments, conducted without rainfall for most of time, which led to smaller differences between WP and WP_{Irrig} for ILR. For both irrigation systems, deficit irrigation strategies generally lead to higher WP_{Irrig} due to lower TWU and low yield losses, as previously discussed by Rodrigues and Pereira (2009). However, this assumption contrasts with the results presented by other authors (Abd El-Wahed & Ali, 2013; Igbadun, Salim, Tarimo, & Mahoo, 2008), where WP_{Irrig} decreased with the increase of water deficits due to higher yield losses.

WP_{BWU} showed a contrasting behaviour as it decreased with higher deficits. This may be explained by the fact that the rate of yield decrease is higher than the one for BWU, thus leading to higher WP_{BWU} values for the irrigation treatments receiving more water and yielding more (ISR1 and ILR1).

EWP for ISR varied from 0.62 to 0.78 BRL m^{-3} while it ranged from 0.65 to 0.73 BRL m^{-3} for ILR. EWP_{Irrig} ranged from 1.23 to 4.02 BRL m^{-3} and from 0.79 to 1.58 BRL m^{-3} for ISR and ILR, respectively. The full irrigation treatment under the sprinkler system (ISR1) had the lowest EWP value among all treatments and systems. As for WP_{Irrig}, EWP_{Irrig} increased at a smaller rate for ILR compared to ISR due to reduced rainfall contribution to ET. However, this indicator showed a similar behaviour for both ISR and ILR, which reflects the effect of a smaller denominator when deficit irrigation is considered. EWP values were also in accordance with the ones presented by Rodrigues and Pereira (2009) for Portugal. As for WP_{BWU}, the behaviour of EWP_{BWU} is contrasting, i.e., because BWU corresponds to the water used for achieving the desired yield, EWP_{BWU} decreases when water deficits increase.

To assess the feasibility of different irrigation strategies in terms of defining the economic return threshold at which farming becomes profitable, the economic water productivity ratio (EWPR) was used, particularly the indicators $EWPR_{irrig\text{-}cost}$ and $EWPR_{full\text{-}cost}$ that compare the yield values per unit of irrigation and of farming costs respectively. Table 5 shows the variation of both indicators for all the irrigation experiments. When considering the irrigation costs only, $EWPR_{Irrig\text{-}cost}$ was larger when adopting moderate deficit irrigation for the ISR treatments (ISR3 in Table 5); however, differences between treatments were small. For the ILR deficit irrigation treatments $EWPR_{Irrig\text{-}cost}$ was larger for ILR1 and decreased when water deficits increased, with the lowest values for ILR4. Results indicate that moderate to heavy deficits are less profitable than mild ones. Apparently, results are in accordance

Table 4 – Physical and economic water productivity (WP and EWP) for all treatments.

Treat.	WP (kg m^{-3})		WP_{Irrig} (kg m^{-3})		WP_{BWU} (kg m^{-3})		EWP (BRL m^{-3})		EWP_{Irrig} (BRL m^{-3})		EWP_{BWU} (BRL m^{-3})	
	ISR	ILR	ISR	ILR	ISR	ILR	ISR	ILR	ISR	ILR	ISR	ILR
1	1.55a	1.71a,b	3.07a	1.99a	2.63a	2.52a	0.62a	0.68a	1.23a	0.79a	1.05a	1.01a
2	1.71a	1.80a	4.08a	2.24a	2.52a	2.33a,b	0.69a	0.72a	1.63a	0.89a	1.01a	0.93a,b
3	1.95c	1.82a	10.05b	2.95a	2.51a	2.24b	0.78a	0.73a	4.02b	1.18a	1.00a	0.89b
4	–	1.61b	–	3.95a	–	1.95c		0.65a	–	1.58a	–	0.78c

Within column, values with the same letter are not significantly different at $p < 0.05$.
WP_{Irrig} = irrigation water productivity; WP_{BWU} = water productivity relative to the beneficial water use; EWP_{Irrig} = irrigation economic water productivity EWP_{BWU} = economic water productivity relative to the beneficial water use.

Table 5 – Comparison between economic water productivity ratio for irrigation costs ($EWPR_{irrig\text{-}cost}$) and total farming costs ($EWPR_{full\text{-}cost}$) for all the irrigation experiments.

Treatment	$EWPR_{full\text{-}cost}$	$EWPR_{Irrig\text{-}cost}$	Treatment	$EWPR_{full\text{-}cost}$	$EWPR_{Irrig\text{-}cost}$
ISR1	1.83	7.00	ILR1	1.27	3.36
ISR2	1.75	6.95	ILR2	1.16	3.09
ISR3	1.71	7.16	ILR3	1.06	2.84
			ILR4	0.74	1.99

with those obtained by Abd El-Wahed and Ali (2013). The difference in behaviour between ISR and ILR indicates that $EWPR_{Irrig\text{-}cost}$ is particularly sensitive to the amount of rainfall that is available for the crop in addition to irrigation. These results show that it is probable that this indicator should not be used to compare situations referring to supplemental irrigation with those where irrigation is largely the main source for evapotranspiration.

Results for $EWPR_{full\text{-}cost}$ (Table 5) show a different behaviour relative to $EWPR_{Irrig\text{-}cost}$ when considering the ISR treatments. Values tend to decrease from a maximum for full irrigation to smaller values relative to deficit irrigation. This is probably due to the fact that irrigation costs in Southern Brazil play a minor role in the total farming costs. The $EWPR_{full\text{-}cost}$ values ranged from 1.71 to 1.83 for ISR and from 0.74 to 1.27 for the ILR experiments, with smaller values for the larger deficit treatments. These lower values for ILR are due to less water availability, thus smaller ET_a and smaller yields (Table 1). The adoption of irrigation at large deficits when rainfall is lacking, as simulated for ILR4, leads to a negative income (EWPR < 1.0). In other words, for the conditions observed, yield losses due to high irrigation deficits are not acceptable when the rainfall contribution is small.

3.2. *Assessing the impacts of commodity prices and farming costs*

Changes in commodity prices and in production costs may have strong effects on water use and economic results. Higher commodity prices may lead farmers to increase the optimal levels of input use, thus achieving higher yields (Finger, 2012). To better understand the effects of these economic factors, a sensitivity analysis was conducted considering various levels of change of commodity prices combined with various levels of increase/decrease of production costs, mainly water and labour costs. The analysis was performed by assessing the impacts on $EWPR_{full\text{-}cost}$ due to increasing the present commodity prices and production costs by 20, 50 and 100% and decreasing by 20 and 50% (Table 6).

As shown in Table 5, the $EWPR_{full\text{-}cost}$ ranged from 0.74 to 1.83 for the current commodity prices and production costs. The lower ratio refers to treatment ILR4 due to the low yield achieved as a consequence of a very high irrigation deficit in absence of rainfall. When cutting commodity prices by half, $EWPR_{full\text{-}cost}$ decreased to values not exceeding 0.93 for treatment ISR1 (Table 6). A further reduction would occur if the production costs were to increase by 100%; the highest value would then be 0.88 for ISR1. Lower values were obtained for all other treatments, particularly for the ILR ones. By contrast, considering a decrease of only 20% on the commodity prices, all ISR treatments would have positive but low incomes (Table 6). ILR1 then had $EWPR_{full\text{-}cost}$ slightly above 1.0, thus showing it to be somewhat sensitive to commodity price changes. However, because it involves low water availability and high ET deficits, ILR1 is very sensitive to market variations. This indicates that economic results are particularly sensitive to commodity prices as already observed by Rodrigues, Silva, and Pereira (2010) for Portugal in a period when maize prices were lower than at present. These results are however different from but not opposed to those by Cortignani and Severini (2009) for Italy, where the adoption of deficit irrigation is mainly motivated by less water availability for irrigation and is favoured by higher commodity prices.

Variations due to labour and water costs were relatively small because their share in the production costs is small. For the present commodity prices, if those production costs increased by 100%, $EWPR_{full\text{-}cost}$ would decrease by 3.1–4.6% only; similarly, if the water and labour costs decrease to half of the actual values, $EWPR_{full\text{-}cost}$ would increase by 1.6–1.9%.

If the commodity price were to increase by 20%, all treatments, except ILR4, would lead to positive incomes, even for increased production costs (Table 6). Nevertheless, the treatment ILR4 has shown $EWPR_{full\text{-}cost}$ values close to 1. An increase of commodity prices by 50% would lead to $EWPR_{full\text{-}cost}$ values ranging from 1.08 to 2.64 if water and labour costs increase 100%, and ranging from 1.13 to 2.79 if the production costs were to decrease to half of the present values. If production costs were to double, $EWPR_{full\text{-}cost}$ would be improved by between 44.5 and 45.2% when commodity prices increased by 50%. Summarising, results show that the viability of deficit irrigation is extremely dependent of commodity prices, while changes in water and labour costs have a low impact on related economic results. This behaviour is due to the price structure actually prevailing in maize farming in Brazil. Results also show that deficit irrigation results are highly influenced by the availability of rainfall in addition to irrigation, i.e., deficit irrigation with supplemental irrigation is more easily viable.

Results presented by other authors on the effects of irrigation costs, mainly water prices, are somewhat contradictory. Gómez-Limón and Riesgo (2004) have shown a great impact of water prices on irrigation water use though the effect depended upon the orientation of farming and the structure of production costs. Bazzani et al. (2005) have also shown a great impact of water prices on water use but varying with the farming systems considered. Bartolini, Bazzani, Gallerani, Raggi, and Viaggi (2007) suggested that a water price increment has a lower effect than a production cost increase; however, the water costs considered were quite low. By contrast, Huffaker and Whittlesey (2003) concluded that increasing the cost of applied water may be an effective water

Table 6 – Sensitivity analysis of the economic water productivity ratio, when considering the total farming costs ($EWPR_{full-cost}$), to commodity prices and production costs.

Treatments	Changes in water and irrigation labour costs					
	+100%	+50%	+20%	No change	−20%	−50%
50% Decrease in commodity prices						
ISR1	0.88	0.90	0.91	0.91	0.92	0.93
ISR2	0.85	0.86	0.87	0.88	0.88	0.89
ISR3	0.83	0.84	0.85	0.85	0.86	0.87
ILR1	0.61	0.62	0.63	0.63	0.64	0.65
ILR2	0.56	0.57	0.58	0.58	0.58	0.59
ILR3	0.51	0.52	0.53	0.53	0.53	0.54
ILR4	0.36	0.36	0.37	0.37	0.37	0.38
20% Decrease in commodity prices						
ISR1	1.41	1.43	1.45	1.46	1.47	1.49
ISR2	1.36	1.38	1.39	1.40	1.41	1.43
ISR3	1.32	1.35	1.36	1.37	1.38	1.39
ILR1	0.98	1.00	1.01	1.01	1.02	1.03
ILR2	0.90	0.91	0.92	0.93	0.94	0.95
ILR3	0.82	0.83	0.84	0.85	0.85	0.86
ILR4	0.57	0.58	0.59	0.59	0.60	0.60
Present commodity prices						
ISR1	1.76	1.79	1.81	1.83	1.84	1.86
ISR2	1.69	1.72	1.74	1.75	1.77	1.79
ISR3	1.66	1.68	1.70	1.71	1.72	1.74
ILR1	1.22	1.24	1.26	1.27	1.28	1.29
ILR2	1.12	1.14	1.15	1.16	1.17	1.18
ILR3	1.03	1.04	1.05	1.06	1.07	1.08
ILR4	0.72	0.73	0.74	0.74	0.74	0.75
20% Increase in commodity prices						
ISR1	2.11	2.15	2.18	2.19	2.21	2.23
ISR2	2.03	2.07	2.09	2.11	2.12	2.14
ISR3	1.99	2.02	2.04	2.05	2.07	2.09
ILR1	1.47	1.49	1.51	1.52	1.53	1.55
ILR2	1.34	1.37	1.38	1.39	1.40	1.42
ILR3	1.23	1.25	1.26	1.27	1.28	1.30
ILR4	0.86	0.87	0.88	0.89	0.89	0.90
50% Increase in commodity prices						
ISR1	2.64	2.69	2.72	2.74	2.76	2.79
ISR2	2.54	2.59	2.61	2.63	2.65	2.68
ISR3	2.48	2.52	2.55	2.56	2.58	2.61
ILR1	1.83	1.87	1.89	1.90	1.92	1.94
ILR2	1.68	1.71	1.73	1.74	1.75	1.77
ILR3	1.54	1.56	1.58	1.59	1.60	1.62
ILR4	1.08	1.09	1.10	1.11	1.12	1.13
100% Increase in commodity prices						
ISR1	3.52	3.59	3.63	3.65	3.68	3.72
ISR2	3.39	3.45	3.48	3.51	3.53	3.57
ISR3	3.31	3.36	3.40	3.42	3.44	3.48
ILR1	2.44	2.49	2.52	2.54	2.56	2.58
ILR2	2.24	2.28	2.31	2.32	2.34	2.37
ILR3	2.05	2.09	2.11	2.12	2.14	2.16
ILR4	1.43	1.46	1.47	1.48	1.49	1.50

conservation policy, i.e., the impacts of water costs may be important in terms of water use. Also, Kampas, Petsakos, and Rozakis (2012) state that deficit irrigation is highly dependent upon the irrigation and water costs. Thus, considering the results above, where impacts of commodity prices are much more relevant than those of irrigation and water costs due to the low share of related costs in the production costs, is important to assess the possible impacts of changing that share fraction. This is shown in Fig. 1, where changes in $EWPR_{full-cost}$ are presented as a function of the irrigation costs share in the total production costs for all the ISR and ILR treatments considering the current commodity prices.

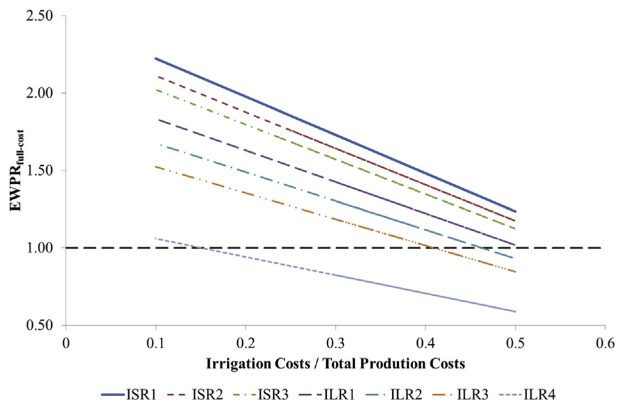

Fig. 1 – Impacts of a variation of the fraction of irrigation costs over the total production costs on the full costs economic water productivity ratio ($EWPR_{full-cost}$) for all treatments.

Figure 1 shows that ISR treatments would lead to a positive farm income even if the irrigation costs were to represent half of the total production costs, with $EWPR_{full-cost}$ decreasing by 32.3–34.3% relative to present conditions. A decrease of the irrigation costs to only 10% of the total production costs would lead to $EWPR_{full-cost}$ values greater than 2.0, representing an increase ranging from 18.2 to 21.8% when compared to the current price/costs scenario.

By contrast, ILR seems to be more sensitive to the variation of irrigation costs. An increase of these costs to half of the total production costs would lead to negative farm incomes, i.e., $EWPR_{full-cost} < 1.0$ when that share reaches 40%. ILR 4 is already below that threshold. However, if the irrigation costs were to decrease to only 10% of the total production costs all ILR treatments would lead to positive incomes, with $EWPR_{full-cost}$ increasing more than 43.2%.

These results in Fig. 1 show that deficit irrigation results are not only highly influenced by commodity prices but may also be influenced by the irrigation (and water) costs when the share of these costs in the total costs are modified, i.e., when the structure of production costs change as referred to above for a few reported research results (Bartolini et al., 2007; Bazzani et al., 2005; Gómez-Limón & Riesgo, 2004; Huffaker & Whittlesey, 2003; Kampas et al., 2012). These results also support the previous assumption that deficit irrigation results are highly influenced by the availability of rainfall, which is in agreement with Grové, Nel, and Maluleke (2006) who stated that more efficient use of rainfall, as for irrigation that supplements rainfall, favours the adoption of deficit irrigation when facing risks due to a variation in production costs.

3.3. *Impacts of deficit irrigation with centre-pivot sprinkler systems*

Potential water savings due to adopting centre-pivot sprinkler systems (CPs) and resulting from related improved BWUF can be assessed by comparing the different water use and productivity indicators that are expected from their implementation in the practice. Considering the observed ISR and ILR treatments analysed above (Section 3.1 and 3.2) and assuming that the CPs are well-designed and managed as described in Section 2.3 and Table 3, it is possible to assess deficit irrigation and water saving assuming two different scenarios, one for irrigation supplementing rainfall, as happens in Southern Brazil, and the other for irrigation in conditions where rainfall is scarce, as occurs in Central-West and Northeast Brazil. For the first scenario, with abundant rainfall, the ISR management treatments are adopted; for the second, representing water scarcity conditions, the management treatments ILR1 and 3 are selected.

Water use and productivity indicators resulting from adopting the well-designed and managed CPs, described in Table 3, and obtained by simulating the three ISR management treatments analysed before, are presented in Table 7. The same indicators relative to the same CPs but managed according to treatments ILR1 and ILR3 are presented in Table 8.

BWUF increase for all CPs scenarios from ISR1 to ISR3. Since the BWUF is herein defined as the ratio of ET_a to TWU, ISR3 leads to the highest values due to the fact that TWU is smaller for this treatment, thus increasing that ratio. Consequently, the treatment ISR1 presents the lowest BWUF among all treatments, which results from the highest TWU. Between all CPs, the lowest BWUF correspond to R1 and highest to S4, due to lowest and highest uniformity of distribution DU (and CU), respectively (*vide* Table 3).

As for BWUF, WP would increase from ISR1 to ISR3 due to the water savings attained during crop season, which are sufficient to overcome the effects of the corresponding yield losses. WP would vary from 1.66 to 1.71 $kg\,m^{-3}$ for all systems under ISR1 treatment, increasing to the range 2.01–2.03 $kg\,m^{-3}$ when adopting ISR3. S4 presents the highest WP for all treatments, with R1 presenting the lowest. This is due to a slightly higher distribution uniformity for CPs equipped with Super Spray emitters (Table 3), leading to a lower TWU. Wind effects could easily change these results. Thus, we may conclude that results are effectively not different among CPs, which could be expected as a consequence of progress in centre-pivot equipment and emitter characteristics. Results are similar to those presented by Schneider and Howell (1999) for CPs in U.S.A., with $WP = 1.70\,kg\,m^{-3}$ for full irrigation. As for WP, EWP values are not distinct among CPs.

$EWPR_{irrig-cost}$ increased from the smaller systems (S1 and R1, with 32 ha) to the larger ones because the irrigation costs per unit area decrease when the irrigated area increases, thus also with the increased size of the centre-pivot system. The analysis by Dalton, Porter, and Winslow (2004) showed that positive economic impacts of CPs in controlling risks in humid climates is higher for larger systems. Also, O'Brien, Rogers, Lamm, and Clark (1998) and Lamm, O'Brien, Rogers, and Dumler (2002) reported that CP irrigation was more advantageous for larger fields. $EWPR_{irrig-cost}$ increased when deficit irrigation was applied (ISR2 and ISR3), thus decreasing the irrigation costs when less water was used, since yields were not highly affected by the mild deficit irrigation considered. Better values were observed for the S equipped CPs because they require less pressure, and therefore have a reduced energy cost relative to the R systems (Table 3). CPs equipped with rotators would be advantageous in conditions of wind and low infiltration soils, though these aspects are not considered

Table 7 – Water use and productivity indicators relative to the centre-pivot systems described in Table 3 when adopting the management scenarios ISR1, 2 and 3 for irrigation in supplement of rainfall.

System symbol	Super spray emitters					Rotator R3000 sprinklers				
	S1	S2	S3	S4	S5	R1	R2	R3	R4	R5
Irrigated area (ha)	32.13	46.34	65.03	81.27	110.2	32.13	46.34	65.03	81.27	110.2
ISR1										
BWUF	0.641	0.648	0.644	0.648	0.647	0.631	0.644	0.638	0.643	0.640
WP	1.69	1.71	1.70	1.71	1.70	1.66	1.69	1.68	1.69	1.68
EWP	0.67	0.68	0.68	0.68	0.68	0.66	0.68	0.67	0.68	0.67
$EWPR_{irrig\text{-}cost}$	4.78	4.81	5.18	6.33	5.40	4.51	4.65	5.02	6.10	5.21
$EWPR_{full\text{-}cost}$	1.63	1.63	1.67	1.78	1.70	1.60	1.61	1.66	1.76	1.68
ISR2										
BWUF	0.728	0.735	0.731	0.735	0.734	0.719	0.731	0.725	0.730	0.727
WP	1.84	1.85	1.85	1.85	1.85	1.81	1.84	1.83	1.84	1.84
EWP	0.74	0.74	0.74	0.74	0.74	0.73	0.74	0.73	0.74	0.73
$EWPR_{irrig\text{-}cost}$	5.39	5.43	5.97	7.18	6.29	5.07	5.23	5.77	6.89	6.06
$EWPR_{full\text{-}cost}$	1.63	1.64	1.68	1.77	1.71	1.60	1.62	1.67	1.75	1.69
ISR3										
BWUF	0.805	0.808	0.806	0.808	0.807	0.800	0.806	0.803	0.806	0.804
WP	2.02	2.03	2.02	2.03	2.02	2.01	2.02	2.01	2.02	2.02
EWP	0.81	0.81	0.81	0.81	0.81	0.80	0.81	0.81	0.81	0.81
$EWPR_{irrig\text{-}cost}$	7.19	7.29	8.48	9.73	9.17	6.75	6.96	8.09	9.26	8.77
$EWPR_{full\text{-}cost}$	1.71	1.72	1.78	1.83	1.80	1.69	1.70	1.76	1.81	1.79

BWUF = beneficial water use fraction; WP = water productivity; EWP = economic water productivity; $EWPR_{irrig\text{-}cost}$ = economic water productivity ratio for irrigation costs; $EWPR_{full\text{-}cost}$ = economic water productivity ratio for total farming costs.

here. $EWPR_{full\text{-}cost}$ showed very similar behaviour among all CPs, with only very small differences between S and R equipped systems (Table 7), and with all values largely above 1.0, thus indicating that farm returns would be always positive. The very small differences in $EWPR_{full\text{-}cost}$ among all systems are due to the fact that irrigation costs constitute only a small share of the production costs and differ little among treatments (Table 3). Results allow the ISR3 management (mild deficit) to be identified as the scenario that would lead to higher economic results when compared with ISR1 and 2. However differences are small and farmers would probably select this management if water availability for irrigation is limited, as referred to by Cortignani and Severini (2009) for Italy.

Table 8 – Water use and productivity indicators relative to the centre-pivot systems described in Table 3 when adopting the management scenarios ILR1 and 3 for irrigation when rainfall is lacking.

System symbol	Super spray emitters					Rotator R3000 sprinklers				
	S1	S2	S3	S4	S5	R1	R2	R3	R4	R5
Irrigated area (ha)	32.13	46.34	65.03	81.27	110.2	32.13	46.34	65.03	81.27	110.2
ILR1										
BWUF	0.724	0.738	0.731	0.739	0.736	0.703	0.730	0.717	0.728	0.721
WP	1.82	1.86	1.84	1.86	1.85	1.77	1.84	1.81	1.83	1.82
EWP	0.73	0.74	0.74	0.74	0.74	0.71	0.73	0.72	0.73	0.73
$EWPR_{irrig\text{-}cost}$	3.02	3.03	3.23	3.99	3.35	2.85	2.94	3.14	3.85	3.24
$EWPR_{full\text{-}cost}$	1.22	1.22	1.25	1.35	1.27	1.19	1.20	1.24	1.33	1.25
ILR3										
BWUF	0.851	0.863	0.856	0.863	0.861	0.834	0.855	0.845	0.854	0.849
WP	1.90	1.93	1.91	1.93	1.92	1.86	1.91	1.89	1.91	1.90
EWP	0.76	0.77	0.77	0.77	0.77	0.75	0.77	0.76	0.76	0.76
$EWPR_{irrig\text{-}cost}$	3.39	3.42	3.78	4.52	3.98	3.19	3.29	3.64	4.34	3.84
$EWPR_{full\text{-}cost}$	1.13	1.13	1.17	1.23	1.19	1.11	1.12	1.16	1.22	1.18

BWUF = beneficial water use fraction; WP = water productivity; EWP = economic water productivity; $EWPR_{irrig\text{-}cost}$ = economic water productivity ratio for irrigation costs; $EWPR_{full\text{-}cost}$ = economic water productivity ratio for total farming costs.

When using well-designed and managed CPs under conditions of scarce rainfall (Table 8), BWUF increases from a range of 0.703–0.739 when adopting ILR1 to the range 0.834–0.863 for ILR3. These results relate to a lower TWU for ILR3, which leads to an increase in the ratio of ET_a to TWU, and thus BWUF. WP and EWP increased similarly to BWUF, reaching higher values for S4 and the lowest for R1, due to highest and lowest DU and CU, respectively (*vide* Table 3). The behaviour of BWUF, WP and EWP indicators is therefore similar to those analysed for the ISR treatments but indicators are slightly higher since less water is used with ILR treatments.

As for BWUF, WP increases from ILR1 to ILR3, ranging from 1.77 to 1.86 kg m^{-3} and from 1.86 to 1.93 kg m^{-3}, respectively. These results are in accordance with those presented by Goyne and McIntyre (2002) for Australian conditions. EWP would slightly improve from the range of 0.71–0.74 BRL m^{-3} to 0.73–0.77 BRL m^{-3} when changing to ILR3 instead of ILR1.

$EWPR_{irrig\text{-}cost}$ increased when an irrigation at a larger deficit was considered (ILR3). Since less water is being used, adopting ILR3 would lead to a decrease of the irrigation costs, which could compensate for the yield losses associated with this treatment. Higher $EWPR_{irrig\text{-}cost}$ values were observed for Spray compared to Rotator equipped systems due to the low energy demand, as referred to above for the ISR cases. However, $EWPR_{full\text{-}cost}$ values followed a different pattern: adopting ILR3 instead of ILR1 treatment leads to lower $EWPR_{full\text{-}cost}$ for all centre-pivot alternatives, decreasing from the range 1.19–1.35 to 1.11–1.23. These results show that, when considering the total production costs, the yield losses due to higher irrigation deficits may not be acceptable when the rainfall contribution is small, unless farmers have not got enough water available for irrigation. However, results do not allow definitive conclusions, particularly taking into account the impacts of changing commodity prices and production costs as analysed in Section 3.2.

When comparing the water productivity indicators resulting from adopting CPs, under abundant (ISR) and scarce (ILR) rainfall, results presented in Tables 7 and 8 show that ILR management leads to higher BWUF, WP and EWP values than ISR1 and 2 due to less water application. However, ISR3, a management strategy with mild deficit irrigation, shows higher values for the same indicators. This results from the fact that abundant rainfall mitigates the impact of deficit irrigation.

By contrast, the $EWPR_{irrig\text{-}cost}$ values are much higher, about double, when comparing results for irrigation to supplement rainfall (ISR treatments) with irrigation when rainfall is scarce (ILR). This indicates that the use of irrigation and rainfall together when the latter is abundant results in higher production values when compared with the applied irrigation water in the case of scarce rainfall. Since farmers search for profit, and considering that ILR1 has a $EWPR_{irrig\text{-}cost}$ higher than ILR3, i.e., $EWPR_{irrig\text{-}cost}$ decreases for heavier deficits, this indicates that farmers would not be likely to choose a deficit irrigation strategy unless reduced water availability would induce them to do so. However, for a use of irrigation and rainfall together, $EWPR_{irrig\text{-}cost}$ are higher for mild deficits ISR2 and 3. In this case, though, the $EWPR_{full\text{-}cost}$ are higher for the management strategies leading to higher yields and having a higher TWU for both ISR and ILR management strategies. Moreover, the $EWPR_{full\text{-}cost}$ values for ISR are higher than those for ILR for more than 50%. These results confirm that adopting deficit irrigation when rainfall is scarce is less attractive than under conditions of irrigation to supplement rainfall, when irrigation controls the risk of crop failure (Dalton et al., 2004). It is likely that mild deficit irrigation and carefully designed irrigation schedules may lead to improved irrigation water use under scarce rainfall conditions (e.g. Grassini et al., 2011), not high deficit irrigation, which would have high impacts on yields and farm returns and could have effects on soil salinity. The adoption of improved irrigation and agronomic factors needs to be given appropriate consideration, which implies adequate support to farmers (Ali & Talukder, 2008; Molden et al., 2010; Pereira et al., 2012).

4. Conclusions

This study shows that economic water use and productivity indicators may be appropriate tools for assessing the impacts of deficit irrigation, particularly the economic water productivity ratio, which represents the yield values per unit of farming costs ($EWPR_{full\text{-}cost}$) This indicator appears to be adequate for assessing the feasibility of deficit irrigation as influenced by commodity prices, and water and labour costs. Results show that the viability of deficit irrigation is extremely dependent upon the commodity prices, while changes in water and labour costs have a low impact on related economic results. This behaviour is due to the price structure prevailing in maize farming in Brazil. However, a increase in the share that irrigation costs represent of total production costs would lead to a significant impact of irrigation costs over $EWPR_{full\text{-}cost}$. These results also support the assumption that deficit irrigation is favoured by the adoption of irrigation to supplement rainfall, especially when facing risks due to a variation in production costs.

The investment in well-designed and managed centre-pivot systems may lead to high irrigation uniformity depending on the irrigation system characteristics. Results show that using centre-pivot systems is appropriate for both rainfall regimes considered and best results refer to mild deficit irrigation. Large deficits lead to reduced economic results. When rainfall is scarce, results confirm that adopting deficit irrigation is less attractive than under conditions of irrigation to supplement rainfall; hence farmers would not be likely to choose a deficit irrigation strategy unless they were facing reduced water availability.

This assessment shows that deficit irrigation requires appropriate support to farmers in order to make better selections and adoptions of improved agronomic practices, better performing irrigation systems and irrigation schedules that avoid stress during critical periods.

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