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**MODELAGEM TÉCNICA E ECONÔMICA DA
IRRIGAÇÃO DEFICITÁRIA PARA DIFERENTES
MÉTODOS DE APLICAÇÃO DE ÁGUA NA
CULTURA DO MILHO**

TESE DE DOUTORADO

Juliano Dalcin Martins

Santa Maria, RS, Brasil.

2013

**MODELAGEM TÉCNICA E ECONÔMICA DA IRRIGAÇÃO
DEFICITÁRIA PARA DIFERENTES MÉTODOS DE
APLICAÇÃO DE ÁGUA NA CULTURA DO MILHO**

Juliano Dalcin Martins

Tese apresentada ao Curso de Doutorado do Programa de Pós-Graduação em Engenharia Agrícola, Área de Concentração em Engenharia de Água e Solo, da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para a obtenção do grau de **Doutor em Engenharia Agrícola.**

Orientador: Prof. Reimar Carlesso

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**Universidade Federal de Santa Maria
Central de Ciências Rurais
Programa de Pós-Graduação em Engenharia Agrícola**

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DEFICITÁRIA PARA DIFERENTES MÉTODOS DE APLICAÇÃO DE
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elaborada por
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como requisito parcial para obtenção do grau de
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RESUMO

Tese de Doutorado

Programa de Pós-Graduação em Engenharia Agrícola

Universidade Federal de Santa Maria

MODELAGEM TÉCNICA E ECONÔMICA DA IRRIGAÇÃO DEFICITÁRIA PARA DIFERENTES MÉTODOS DE APLICAÇÃO DE ÁGUA NA CULTURA DO MILHO

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ORIENTADOR: REIMAR CARLESSO

Santa Maria, Rio Grande do Sul, Brasil, 13 de Junho de 2013.

A irrigação deficitária é muitas vezes necessária para contornar períodos de secas e com disponibilidade limitada de água. Para reduzir os impactos sobre a produção, os déficits hídricos precisam ser aplicados durante as fases menos sensíveis de desenvolvimento das culturas. No entanto, para selecionar o manejo de irrigação apropriado, é necessário avaliar adequadamente se os impactos econômicos da irrigação deficitária são economicamente viáveis. A compreensão do processo de perda de água dos cultivos agrícolas como a evaporação de água do solo e transpiração da cultura permite uma melhor avaliação das práticas de gestão de irrigação em relação à irrigação deficitária. Este estudo procurou determinar os coeficientes de cultura basais adequados para o milho através da calibração e validação do modelo SIMDualKc, utilizando a metodologia dos coeficientes duais separando assim a transpiração da cultura, e a evaporação na superfície do solo; avaliar a produtividade da cultura e da água, bem como a produtividade econômica da água para o milho, em relação a diferentes níveis de déficit hídrico e sob diferentes sistemas de irrigação, e a sua viabilidade econômica, considerando diferentes alternativas para irrigação por pivô central e gotejamento. Um conjunto de experimentos foi realizado utilizando diferentes estratégias de irrigação plena e irrigação deficitária, pelos métodos de irrigação por aspersão e gotejamento durante os anos de 2011 a 2012. Os resultados da simulação do modelo SIMDualKc apresentaram boa concordância entre o valor simulado de água disponível no solo com o valor observado ao longo do ciclo da cultura. O valor de Kcb inicial e médio calibrados foram, respectivamente, 0,20 e 1,12, e o Kcb final foi de 0,2 para o milho grão e de 0,8 para o milho colhido para silagem. A evaporação foi inferior a 9% da evapotranspiração da cultura tanto nos sistemas de irrigação por aspersão quanto por gotejamento, indicando, assim, a possibilidade de utilizar resíduos culturais para a conservação da água. Os resultados econômicos demonstram que a irrigação deficitária foi altamente dependente dos preços do milho, enquanto mudanças nos custos de água e de mão de obra apresentaram um baixo impacto relacionado aos resultados econômicos. Os resultados também demonstram que, a irrigação deficitária, aplicada em períodos de chuvas são fáceis de serem implementados, ao contrário da irrigação deficitária para períodos de precipitação reduzida, quando apenas um pequeno estresse é economicamente viável. Apesar de melhorar a produtividade da água e do desempenho da irrigação, a adoção de sistemas pivô central pode favorecer a irrigação deficitária para irrigação suplementar quando as chuvas são regulares. A viabilidade econômica da utilização da irrigação deficitária para a cultura do milho, irrigada por gotejamento em superfície, foi dependente do custo de instalação do sistema, principalmente do custo fixo e da vida útil das linhas laterais.

Palavras-chave: Déficit hídrico. Sistemas de irrigação. SIMDualKc. *Zea mais*.

ABSTRACT

Doctoral Dissertation

Programa de Pós-Graduação em Engenharia Agrícola

Universidade Federal de Santa Maria

TECHNICAL AND ECONOMIC MODELING OF DEFICIT IRRIGATION FOR DIFFERENT METHODS OF WATER APPLICATION OF IN CORN

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Santa Maria, Rio Grande do Sul, Brazil, 13th of June, 2013

The deficit irrigation is often required to overcome periods of drought and limited water availability. To reduce the impacts on production, water deficits need to be applied during less sensitive stages of crop development. However, to select the appropriate irrigation management, it is necessary to assess, properly, if the economic impacts of deficit irrigation are economically viable. To understand the process of water loss from crops, such as soil water evaporation and crop transpiration allows a better assessment of irrigation management practices in relation to deficit irrigation. This study sought to determine the basal crop coefficients appropriate for corn through the calibration and validation of SIMDualKc model, using the methodology of dual coefficients, separating crop transpiration and soil surface evaporation; to assess crop and water productivity, as well as water economic productivity for corn in relation to different levels of water deficit and under different irrigation systems and their economic viability, considering different alternatives for center pivot and drip irrigation. A set of experiments was conducted using different strategies of full irrigation and deficit irrigation through the methods of sprinkling and drip irrigation during the years 2011 to 2012. The simulation's results of the SIMDualKc model showed a good agreement between the simulated value of available soil water and the value observed during the crop cycle. The initial and mid Kcb calibrated values were, respectively, 0.20 and 1.12 and the end Kcb was 0.2 for corn grains and 0.8 for corn harvested for silage. Evaporation was lesser than 9% of the crop evapotranspiration in both drip and sprinkling irrigation, indicating, thereby, the possibility of using crop residues for water conservation. The economic results show that deficit irrigation was highly dependent on corn prices, while changes in the costs of water and labor had a low impact in relation to the economic results. The results also show that the deficit irrigation applied in periods of rain is easy to implement, unlike deficit irrigation for periods of reduced precipitation when only a small stress is economically feasible. Although improving water productivity and irrigation performance, the adoption of center pivot systems can favor irrigation deficit for supplementary irrigation when rainfall is frequent. The economic viability of using irrigation deficit in maize by the system of drip irrigation under surface was dependent on the cost of installing the system, mainly the fixed cost and life cycle of the lateral lines.

Key words: Water deficit. Irrigation systems. SIMDualKc. *Zea mais*.

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INTRODUÇÃO

A cultura do milho apresenta grande importância econômica pelas diversas formas de sua utilização, que vão desde a alimentação animal até a indústria de alta tecnologia, como a produção de filmes e embalagens biodegradáveis. O milho é o principal macroingrediente para a produção de rações e devido à competitividade do mercado brasileiro de carnes, a produção do grão tem aumentado gradativamente (CALDARELLI; BACHI, 2012). Segundo estimativas da Conab (2012), a área cultivada com a cultura do milho na safra 2011/12 foi de aproximadamente 15 milhões de hectares e com uma produção de 72 milhões de toneladas.

A variabilidade anual na produtividade de grãos da cultura do milho ocorre devido à ocorrência de déficits hídricos causados pelas variações na distribuição das chuvas (BERGAMASCHI et al., 2007; BERGONCI et al., 2001), pois, frequentemente durante o período de cultivo do milho, devido à maior demanda evaporativa da atmosfera, as chuvas não são suficientes para suprir as necessidades hídricas da cultura (MATZENAUER et al., 2002). Reduções na produtividade de milho são observadas se o déficit hídrico ocorrer entre a antese e o início de enchimento de grãos (BERGONCI et al., 2001; BERGAMASCHI et al., 2004; BERGAMASCHI et al., 2006), pois, se o déficit hídrico ocorrer no período da pré-floração ao início do enchimento de grãos, a recuperação da capacidade produtiva da cultura não poderá ocorrer de forma satisfatória, uma vez que os eventos reprodutivos são muito mais rápidos do que os verificados durante o crescimento vegetativo.

O Brasil apresenta 12% da disponibilidade mundial de recursos hídricos (BRASIL, 2008), e possui um potencial de expansão para agricultura irrigada de cerca de 30 milhões de hectares (CHRISTOFIDIS, 2000), ou seja, um adicional de 29,5 milhões, considerando a área irrigada atual de aproximadamente 4,5 milhões, de acordo com o Censo Agropecuário de 2006 (IBGE, 2009). Sendo assim, o país apresenta um grande potencial de aumento da área irrigada e esta expansão se torna uma questão estratégica, uma vez que implicará em uma maior demanda sobre os recursos hídricos (PAULINO et al., 2011).

Com as crescentes demandas municipais e industriais sobre a água, a sua disponibilidade de distribuição para a agricultura progressivamente está sendo reduzida. O principal uso agrícola da água é para a irrigação, que assim é afetada pela diminuição do seu fornecimento. Portanto, inovações são necessárias para aumentar a eficiência da utilização da água que está disponível para a agricultura. Neste contexto, a irrigação deficitária é uma alternativa para maximizar a eficiência do uso da água e para atingir rendimentos mais

elevados por unidade de água aplicada via irrigação. (FERERES; SORIANO, 2006). A utilização da irrigação deficitária consiste na aplicação de lâminas de irrigação inferiores às necessidades hídricas da cultura, afetando assim, a evapotranspiração e a produtividade da cultura. Entretanto, a redução da produtividade deve ser mínima para manter um retorno econômico satisfatório da cultura irrigada (KANG et al., 2000). Na irrigação deficitária, a cultura é exposta a certos níveis de déficit hídrico, durante um determinado período ou durante todo o período de desenvolvimento, sem a redução significativa na produtividade. Assim, qualquer redução da produção será insignificante em comparação com os benefícios obtidos através da economia de água que poderá ser destinada para irrigar outras culturas (KIRDA, 2002).

Usualmente, o manejo de irrigação é realizado procurando atender plenamente à demanda hídrica dos cultivos, com vista à maximização da produtividade, independente da quantidade de água utilizada (PAZ et al., 2000). Em muitos casos, a quantidade de água aplicada para alcançar a máxima lucratividade é menor do que a necessária para atender totalmente a evapotranspiração da cultura. Assim, pode-se aplicar um déficit hídrico controlado, para reduzir os custos com a irrigação e ao mesmo tempo obter uma maior produtividade econômica da água (ENGLISH; NAVAID, 1996). Em períodos de escassez, quando a água é um fator de produção limitante, o manejo da irrigação deve ser baseado nos resultados econômicos e não na máxima produtividade (BLANCO et al., 2011). Portanto, é importante planejar o manejo da irrigação para manter a produtividade da cultura e aumentar a eficiência do uso da água, mantendo a viabilidade econômica da atividade.

Agricultores irrigantes que possuem quantidade de água limitada para a irrigação, muitas vezes, optam para adequarem-se a essa situação, reduzindo a área irrigada ou utilizando a irrigação deficitária e irrigando parcialmente seus cultivos, mas com a possibilidade de irrigar uma área maior (ENGLISH et al., 2002; MARTIN et al., 1989). A determinação da melhor opção não é uma tarefa fácil, uma vez que, usualmente, a análise econômica é complexa para maximizar os retornos econômicos (ENGLISH et al., 2002; MARTIN et al., 1989). Essa análise depende de uma série de fatores econômicos e biofísicos, entre os quais a produtividade esperada da cultura irrigada com limitações hídricas é uma das mais importantes informações (PAYERO et al., 2009). No entanto, os impactos da irrigação deficitária sobre a produtividade e suas relações com os resultados econômicos podem ser negativos, pois depende do manejo da irrigação adotado, do desempenho do sistema de irrigação e dos custos de produção (LORITE et al., 2007). A redução na produção resultante pode ser compensada em comparação com os benefícios obtidos através da utilização da água

economizada para irrigar outras culturas para as quais a água, normalmente, seria insuficiente sob práticas tradicionais de irrigação (KIRDA, 2002).

A gestão dos recursos hídricos em nível de exploração agrícola engloba a adoção de práticas de irrigação apropriadas que ocasionem a economia de água, requerendo a determinação de um calendário de irrigação otimizado para as condições de aplicação de um limitado volume de água disponível (PEREIRA et al., 2009). Neste contexto, é importante relacionar a produtividade das culturas com o volume de água consumida para esta produção, introduzindo-se assim, o conceito de produtividade da água (PEREIRA et al., 2002), que no caso da irrigação pode ser relacionada diretamente com o total de água utilizado pela cultura (precipitação + irrigação) ou somente a água utilizada na irrigação (RODRIGUES; PEREIRA, 2009). Experimentos conduzidos com o uso de irrigação deficitária têm constatado um aumento da produtividade da água para várias culturas (ZWART; BASTIAANSEN, 2004; FAN et al, 2005), pois a adoção de estratégias neste sentido pode ser capaz de reduzir a quantidade de água aplicada, causando um mínimo impacto na produção das culturas (PEREIRA et al., 2002).

Os benefícios potenciais da irrigação deficitária podem ser atribuídos a três fatores principais: aumento da eficiência da irrigação; redução dos custos de irrigação e redução de riscos associados a impactos ambientais (ENGLISH; NAVAID, 1996). Atualmente, existem modelos de produção/água que permitem estimar a produção da cultura em função da água por ela utilizada, fato que tem despertado grande interesse de pesquisas pela importância que representam na gestão e otimização de recursos hídricos.

O uso de modelos matemáticos permite adequar a gestão da irrigação à demanda climática, levando em consideração a influência de outros fatores, como o solo, na demanda hídrica das culturas. A programação e a condução da irrigação requerem a disponibilidade de ferramentas de cálculo que sejam exatas, fáceis e rápidas. O modelo SIMDualKc (ROSA et al., 2012a; b) foi desenvolvido tendo em vista o cálculo da evapotranspiração cultural (ETc), com a metodologia dos coeficientes de cultivo duais proposta por Allen et al. (1998, 2005), considerando separadamente a transpiração da cultura e a evaporação do solo, permitindo uma melhor avaliação das práticas de gestão de irrigação em relação à irrigação deficitária e culturas que apresentam cobertura parcial do solo (ROSA et al., 2012a), bem como, quando ocorrem chuvas ou irrigações frequentes na presença de resíduos vegetais na superfície do solo que reduzem acentuadamente a evaporação do solo (STAINER, 1989; SCOPEL et al., 2004; ANDRADE, 2008; KLOCKE et al., 2009; ODHIAMBO; IRMAK, 2012), e o dinâmica da evaporação da água no solo entre sistemas de cultivo (DALMAGO, 2004; DALMAGO

et al., 2010). A adoção desta abordagem permite produzir estimativas da ETc mais precisas (TOLK; HOWELL 2001; HOWELL et al., 2004), em particular, permite a análise da estimativa da evaporação da água no solo e transpiração das culturas com maior precisão (FANDIÑO et al., 2012; PAÇO et al., 2012; ROSA et al., 2012b; ZHAO et al., 2012).

A utilização da metodologia do coeficiente de cultivo dual na irrigação deficitária é possível pela consideração do efeito do déficit hídrico na evapotranspiração. O modelo estima separadamente a transpiração diária da cultura e a evaporação do solo, através da aplicação de dois coeficientes (K_c -dual= $K_{cb} + K_e$), o coeficiente de cultivo basal (K_{cb}) e o coeficiente de evaporação de água no solo (K_e), um terceiro coeficiente é utilizado quando a cultura é cultivada em condição de deficiência hídrica (K_s). O resultado é o $K_c = K_{cb} + K_e K_s$. O coeficiente de estresse ou de déficit de umidade do solo (K_s) é utilizado para reduzir o valor de K_{cb} quando o conteúdo de água na zona radicular é insuficiente para manter a plena transpiração das plantas.

As primeiras aplicações da metodologia dos coeficientes culturais duais proposta por Allen et al. (1998), foram relatadas por Allen (2000) e Liu e Pereira (2000). Outras aplicações bem-sucedidas têm sido relatadas, especificamente para as culturas do sorgo (TOLK; HOWELL, 2001); algodão com irrigação deficitária (HOWELL et al., 2004); milho (ZHAO; NAN, 2007; ROSA et al., 2012b); soja (ODHIOMBO; IRMAK, 2012); culturas de cobertura de solo (BODNER et al., 2007); sistemas de forragem (GREENWOOD et al., 2009); e cebola (LÓPEZ-URREA et al., 2009). Em relação a culturas de cobertura parcial, os exemplos de aplicação são para as culturas de lichia (SPOHRER et al., 2006); citros (ER-RAKI et al., 2009); café (FLUMIGNAN et al., 2011) e pêssego (PAÇO et al., 2012).

Tendo em vista o exposto, os objetivos deste estudo foram: (a) calibrar e validar a metodologia K_c -dual usando o modelo SIMDual K_c para a cultura do milho cultivado com resíduos vegetais na superfície do solo e avaliar os impactos de diferentes estratégias de irrigação deficitária com a irrigação por aspersão e gotejamento; (b) avaliar a viabilidade econômica da irrigação deficitária, o desempenho de sistemas de irrigação, preços das commodities agrícolas, custos de produção e preços de água sobre a produtividade física e econômica da água do milho irrigado.

ARTIGO I- COEFICIENTES DE CULTIVO DUAL PARA A CULTURA DO MILHO NO SUL DO BRASIL: TESTE DO MODELO DE SIMULAÇÃO PARA IRRIGAÇÃO POR ASPERSÃO E GOTEJAMENTO EM SOLO SOB RESÍDUOS CULTURAIS

Dual crop coefficients for maize in southern Brazil: Model testing for sprinkler and drip irrigation and mulched soil¹

Abstract

The study sought to determine the appropriate basal crop coefficients for maize through the calibration and validation of the model SIMDualKc using various treatments of maize irrigated with sprinkler and drip methods under full and deficit irrigation and cropped with organic mulch. The model computes crop evapotranspiration (ET_c) using the dual crop coefficient methodology, thus separating crop transpiration, T_c , and soil evaporation, E_s . Two experiments were carried out and the model was calibrated for one treatment of each experiment and validated with the remaining treatments. The corresponding results show good agreement between the simulated and observed available soil water through the season, with regression coefficients of 0.99 to 1.02, and the root mean square error ranging 2.0 to 3.3% of the total available water. The calibrated K_{cb} for the initial and mid-season are respectively 0.20 and 1.12; the K_{cb} at end season is 0.2 for grain maize and 0.8 for maize harvested for silage. Results show that the evaporation component of evapotranspiration is less than 9% of ET_c for both sprinkler and drip experiments, thus indicating the suitability of using mulch for water conservation.

Keywords: evapotranspiration; soil evaporation; crop transpiration; straw mulch; irrigation scheduling; soil water dynamics; SIMDualKc model.

1. Introduction

Quantifying crop water use and consumption is essential in agriculture, mainly for irrigation management and planning, and hydrologic and water resources applications. Crop evapotranspiration (ET_c) represents the water consumption of agricultural crops by crop transpiration (T_c) and soil evaporation (E_s). ET_c may be calculated by multiplying the

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reference evapotranspiration (ET_o) by a crop coefficient (K_c). ET_o represents the atmospheric evaporative demand and K_c integrates the factors that differentiate the considered crop from the reference crop in terms of ET (Allen, Pereira, Raes & Smith, 1998). There are two approaches to define K_c : one uses the time-averaged single crop coefficient, representing the combined effects of soil evaporation and crop transpiration; the other is the dual crop coefficient approach considering separately T_c and E_s (Allen et al., 1998; Allen, Pereira, Smith, Raes & Wright, 2005). The dual K_c consists of two coefficients: the evaporation coefficient (K_e) and the basal crop coefficient (K_{cb}); a third coefficient is used when the crop is stressed (K_s). It results $K_c = K_s K_{cb} + K_e$.

Most irrigation scheduling/management simulation models use the single K_c approach to compute ET_c , which provides satisfactory results for the estimation of daily evapotranspiration, with adequate precision for most applications. However for high frequency irrigation, for crops that only cover part of the soil, and when the soil is often wetted by rain or irrigation, the dual K_c approach can lead to more accurate estimates of ET_c , e.g., Howell, Evett, Tolk, and Schneider (2004), Liu and Pereira (2000), Tolk and Howell (2001). In particular, it allows analysing T_c and E_s accurately and capturing impacts of wetting frequency and soil management on total water use (Fandiño et al., 2012; Paço et al., 2012; Rosa, Paredes, Rodrigues, Fernando, et al., 2012; Zhang et al., 2013; Zhao et al., 2013).

Properly calibrated crop water simulation models are valuable tools that can be used to compute crop water requirements, supporting upgraded irrigation management practices, to assess impacts of water stress on crop yields. Examples of model applications for maize irrigation scheduling adopting empirical water balance models or water flux and crop growth models are numerous (Huang, 2004; Ko, Piccinni, & Steglich, 2009; Liu, Teixeira, Zhang, & Pereira, 1998; Panda, Behera, & Kashyap, 2004; Popova & Kercheva, 2004; Stulina, Cameira, & Pereira, 2005). Khaledian, Mailhol, Ruelle, and Rosique (2009) modelled soil water and irrigation in presence of mulch.

The performance of both single and dual K_c methods depends upon the appropriate selection of crop coefficient values for each of the four crop growth stages (initial, crop development, mid-season and late season), the adoption of locally adjusted of growth stage lengths, and the accurate estimation of ET_o from climatic data (Piccinni, Ko, Marek, & Howell, 2009; Popova & Pereira, 2011). Allen et al. (1998) present standard crop coefficients and growth stage lengths for various crops, but using them without local adjustment may lead to large errors in the estimation of ET_c . Actual crop coefficients and lengths of growth stages are influenced by many factors including crop varieties, soils and salinity, management

practices (e.g., plant density, row spacing, fertilising, disease and weeds control, irrigation) and climatic conditions, hence they should ideally be derived experimentally for each crop and region under various management practices for more accurate estimation of ET_c (Odhiambo & Irmak, 2012). However, this is not possible due to costs involved, the exigencies in experimental accuracy, and the complexity related with variability in cultivation, soil and water management practices; a different approach is to calibrate models that allow the problems due to such variability to be overcome (Popova & Pereira, 2011; Zhang et al., 2013; Zhao et al., 2013).

E_s is influenced by various factors affecting soil surface conditions, mainly tillage practices, crop residues cover, ground shadow by the crop depending upon crop density and height, and soil surface moisture and wetting frequency. Crop residues and mulch, as well as shadow by the crop, reduce the solar energy available for evaporation at the soil surface (Allen & Pereira 2009; Allen et al., 1998, 2005). Impacts of mulching and crop residues on E_s depend upon the cover pattern and type of mulch and residues, as well as their amount on the soil surface (Acharya, Hati, & Bandyopadhyay, 2005; Hatfield, Sauer, & Prueger, 2001; Hobbs, Sayre, & Gupta, 2008; Ji & Unger, 2001; Klocke, Currie, & Aiken, 2009; Steiner, 1989; Unger & Parker, 1976). Odhiambo and Irmak (2012) concluded that E_s from a soybean field decreased by 5% for each 10% soil covered by residues but that the reduction was only 2.5% during the initial crop stage. In addition, straw mulches may improve yields and water use performance as well as water conservation and saving (Hobbs et al., 2008; Ji & Unger, 2001; Mitchell et al., 2012; Tolk, Howell, & Evett, 1999). However, when water is applied by sprinkler irrigation, evaporation losses due to interception by the mulch limit water savings, as analysed by Scopel, Da Silva, Corbeels, Affholder, and Maraux (2004). Mulching in South America and Brazil is generally associated with no-till direct seeding agricultural systems (Díaz-Zorita, Duarte, & Grove, 2002; Fabrizzi, García, Costa, & Picone, 2005); benefits of these cropping systems led no-tillage systems to enormously expand in the region, with 35 Mha in Brazil, i.e., 70% of the cropped area. Benefits come from reducing soil evaporation, increasing plant available water, improving nutrient cycling, and controlling soil erosion and runoff (Carlesso, Spohr, Eltz, & Flores, 2011; Díaz-Zorita et al., 2002; Fabrizzi et al., 2005; Machado & Silva, 2001). Benefits associated with carbon sequestration are also important (Bayer, Martin-Neto, Mielińczuk, Pavinato, & Dieckow, 2006; Bernoux et al., 2006). Considering the expansion of no-till systems in southern Brazil, related benefits and favourable trends in conservation tillage, deficit irrigation experiments were performed with direct seeding.

Aiming at producing information to parameterise the new dual K_c model used in the Sistema Irriga™, which now is monitoring more than 90.000 ha each year in Brazil (Carlesso, Petry & Trois, 2009), this research was performed using the SIMDualKc software (Rosa, Paredes, Rodrigues, Alves, et al., 2012; Rosa, Paredes, Rodrigues, Fernando, et al., 2012). This software uses the dual crop coefficient approach over a range of cultural practices to provide information for use in irrigation scheduling and hydrologic water balances, including deficit irrigation, and is therefore appropriate to support new developments of the operational model used in Irriga™. SIMDualKc performs a soil water balance at the field level using a daily time step. It estimates T_c and E_s for full and incomplete cover crops, including presence of mulch or crop residues on the soil surface. Separating T_c and E_s allows a better assessment of alternative irrigation management practices relative to deficit irrigation and crop residues. Therefore, the main objectives of this study are: (a) to determine the basal crop coefficients for maize grown in no-tillage conditions in southern Brazil, (b) to calibrate and validate the dual K_c methodology using the model SIMDualKc, and (c) to assess impacts of various deficit irrigation strategies using field data obtained with sprinkler and drip irrigation. Yields, water productivity, and economic issues are analysed in Rodrigues, Martins, Da silva, Carlesso, and Pereira (Submitted for publication).

2. Materials e methods.

2.1. Description of location, climate and soil conditions.

This study was conducted at the experimental station of the Department of Agricultural Engineering, Federal University of Santa Maria (UFSM), Santa Maria, Brazil. The station is located in the central depression of Rio Grande do Sul, at latitude 29°41'24" S, longitude 53°48'42" W, and altitude of 100 m. The climate, according to the classification of Köppen, is a "cfa", i.e., subtropical humid, without dry season and with hot summer (Moreno, 1961). The average monthly climatic data for 1969-2005 at Santa Maria are presented in Table 1.

The soil is a silt-clay loam classified as Paleudalf (Streck et al. 2008; USDA, 1999). Soil texture and soil hydraulic properties are given in Table 2. Methods used in the Sistema Irriga™ soils laboratory are referred to by Michelon et al. (2010). In particular, the water retention at potentials of -100 to -500 was measured with pressure plates and for -500 to -1500 kPa was measured with a WP4 dewpoint potentiometer (Decagon Devices, Inc.).

2.2. Description of the experiments

During the growing season of 2010/2011, two maize experiments were conducted: one irrigated by sprinkler and the other by drip irrigation. The irrigation requirements were determined from the computed crop evapotranspiration estimated through the product $ET_c = K_c \cdot ET_o$. The reference evapotranspiration was estimated with the Penman-Monteith equation (Allen et al., 1998) using meteorological data collected from an automatic weather station located less than 200 m away from the experimental area. Precipitation was also measured there. K_c values were those proposed by Allen et al. (1998). Data relative to maximum and minimum air temperatures ($^{\circ}\text{C}$), maximum and minimum relative humidity (%) and reference evapotranspiration (mm) for the experimental period are presented in Fig. 1. Irrigation was applied following the information automatically provided by the Sistema IrrigaTM (<http://www.sistemairriga.com.br/>) in relation to the intended treatment.

The sprinkler irrigation treatments (STs) were conducted under field conditions with three irrigation treatments and three replications (Fig. 2). The experimental units consisted of plots of $12 \times 12 \text{ m}^2$. The set system consisted of four sectoral sprinklers per plot with pressure head of 196 kPa, discharge of 534 l h^{-1} and throw of 11 m, thus resulting an average application rate of 14.83 mm h^{-1} . The coefficient of uniformity (CU) was measured as proposed by Merriam and Keller (1978); for five observations CU varied from 80 to 96% due to wind effects. Rainfall during the crop season was 414.5 mm. Applied water depths (D) to the three treatments were: A1, D = 328 mm; A2, D = 234 mm; A3, D = 91 mm.

The drip irrigation treatments (DTs) were performed in an area protected by a rainfall shelter consisting of two metallic structures of $16 \times 10 \text{ m}^2$, with an experimental area of 320 m^2 . This structure is moved on rails with an east-west orientation. The mobile cover was moved as rainfall occurred, covering the experimental area and making it possible to apply deficit irrigation treatments accurately without influence of rainfall. The experimental area was surrounded by an irrigated maize crop planted on the same date to avoid any advection from the surroundings. Four irrigation treatments with four replications were adopted (Fig. 3). The experimental units consisted of plots of $3 \times 6 \text{ m}^2$. The irrigation system consisted of pressure compensating in-line drippers at 0.20 m spacings, with operating pressure of 100 kPa and a discharge of 1.3 l h^{-1} . Drip lines were located between rows, and separated by 0.50 m. The application rate was of 13 mm h^{-1} . The coefficient of uniformity CU was measured in 5 plots using the method described by Merriam and Keller (1978) and CU values were greater than 90%. Rainfall (73 mm) was allowed during the initial crop stage to ensure adequate and

uniform establishment of the crop. Water applications to the four treatments were: G1, D = 389 mm; G2, D = 316 mm; G3, D = 218 mm; G4, D = 113 mm.

The planting dates and the dates limiting the crop development stages are presented in Table 3 for both experiments. The STs used direct seeding into oats (*Avena strigosa*) crop residues (5 t ha⁻¹ of dry biomass, a cover fraction of the soil surface $f_{r\text{ mulch}} = 1.0$ and an effective fraction of soil coverage $f_{\text{eff mulch}} = 0.9$). The hybrid AG8011YG was sown with a row spacing of 0.45 m with north-south orientation and a plant density of 6.5 plants per m². This crop was harvested for silage. The DTs experiment used a no-tillage farming system with seeding into bean (*Phaseolus vulgaris L.*) crop residues (3 t ha⁻¹ of dry biomass, $f_{r\text{ mulch}} = 1.0$ and $f_{\text{eff mulch}} = 0.8$). The hybrid P1630H was sown with row spacing of 0.50 m with east-west orientation and plant density of 6.5 plants per m². This crop was harvested for grain at 21% moisture.

2.3. Model SIMDualKc and data requirements

The model SIMDualKc adopts the dual K_c approach as proposed by Allen et al. (1998, 2005) to calculate ET_c considering separately the E and T components. The model is described in detail by Rosa, Paredes, Rodrigues, Alves, et al. (2012) and its test with field data is presented by Rosa, Paredes, Rodrigues, Fernando, et al. (2012). The first approach to adopting a dual K_c was proposed by Wright (1982). The method was subsequently improved by Allen et al. (1998, 2005).

There is a variety of methods to estimate ET from field observations, which include ET from change in soil water (Allen, Pereira, Howell, & Jesen, 2011) and consequent modelling (Jensen & Wright, 1978). Various models for estimating ET have been calibrated/validated or tested using soil water observations, e.g., models presented in Pereira, Van den Broek, Kabat, and Allen (1995). The ISAREG model, which preceded SIMDualKc, has been extensively calibrated/validated for various crops and regions using soil water observations (Cai, Liu, Xu, Paredes, & Pereira, 2009; Cancela, Cuesta, Neira, & Pereira, 2006; Cholpankulov, Inchenkova, Paredes, & Pereira, 2008; Liu et al., 1998; Popova, Eneva, & Pereira, 2006; Popova & Pereira, 2011). Various applications of the dual K_c method to estimate ET using soil water observations have been reported in the literature (Bodner, Loiskandl, & Kaul, 2007; Descheemaeker et al., 2011; Greenwood, Lawson, & Kelly, 2009; Sánchez et al., 2012; Yang et al., 2009; Zhang, Hilton, Greenwood, & Thompson, 2011).

The first dedicated model for estimating ET using the dual crop coefficient approach as proposed by Allen et al. (1998, 2005) is SIMDualKc. Its first published testing was performed with soil water observations (Rosa, Paredes, Rodrigues, Fernando, et al., 2012b). Meanwhile the model has been tested with separately observed T and E in a peach orchard (Paço et al., 2012), for considering the effects of an active ground cover in a vineyard (Fandiño et al., 2012), and for validating the two phases of Ritchie's soil evaporation approach (Ritchie, 1972) in a field cropped with maize and wheat (Zhao et al., 2013). However, SIMDualKc has been also calibrated against ET data obtained from eddy covariance observations (Zhang et al., 2013). It is therefore appropriate to use and test SIMDualKc against soil water changes and consequently derive the basal crop coefficient for maize.

The scheme in Fig. 4 shows the various computational modules and databases used by the model. In this application, the following data were used.

- a) meteorological data as reported in Fig 1 for climatic variables and daily rainfall;
- b) soil data as summarised in Table 2, which allowed the total and readily available soil water (TAW and RAW, mm) to be computed, as well as the initial values for the total evaporable water (TEW, mm), readily evaporable water (REW, mm), and thickness of the evaporation soil layer (Z_e , m). These parameters are defined by Allen et al. (1998, 2005); values were tested as referred in Section 2.5;
- c) crop data referring to dates of crop growth stages (Table 3), root depths (Z_r , m), crop height (h , m), fractions of soil cover by vegetation (f_c), and fractions wetted by rain and irrigation (f_w), which were observed, and data relative to basal crop coefficients (K_{cb}) and soil water depletion fractions for no stress (p) that were the object of calibration, as described below. The values for h and f_c were different for stressed and non-stressed crop conditions. The calibrated K_{cb} values are internally corrected for climate and adjusted for water stress during the computation process;
- d) data to estimate deep percolation, i.e., the parameters a_D and b_D of the decay function by Liu et al. (2006), were also calibrated as in Section 2.5);
- e) observation data on residues mulch consisting of a cover fraction of the soil surface (f_{mulch}), describing the proportion of the surface over which the mulch had been spread, and the effective fraction of soil coverage ($f_{eff\ mulch}$), describing the completeness of coverage achieved within the mulched area. These observations were updated through the crop season, as was the percentage reduction of soil evaporation in relation to the percentage of soil surface covered by the organic mulch, which is described in next section;

- f) curve number runoff data following Allen, Wright, Pruitt, Pereira, and Jensen (2007), which were adjusted using a trial and error procedure;
- g) irrigation data relative to dates and depths of applied irrigation (Table 4).

In this study, SIMDualKc was calibrated for the first time for organic mulches, thus the amount of reduction in the soil surface evaporation due to mulch density and depth as well as the fraction of the soil surface covered by mulch was evaluated. The general rule applied was to reduce the amount of soil water evaporation by 5% for each 10% of soil surface covered by the organic mulch (Allen et al., 1998; Rosa, Paredes, Rodrigues, Alves, et al., 2012), which was based upon the studies by Unger and Parker (1976) and Steiner (1989), and was confirmed by Odhiambo and Irmak (2012). Klocke et al. (2009) stated that E_s was reduced by nearly 50% compared with bare soil E_s when mulch nearly covered the ground under a maize canopy. However, since the SIMDualKc model performs a soil water balance, it cannot assess the mulch interception losses, which require an additional reservoir to represent mulch interception storage (Scopel et al., 2004). Hence, mulch interception evaporation is part of the evaporation component of ET.

Model outputs include: the daily available soil water (ASW, mm); daily ET and respective components E_s and T_c (mm), the daily K_e and K_s , the daily stress adjusted K_{cb} ($K_{cb\ adj}$) and the $K_{c\ act} = K_{cb\ adj} + K_e$. ASW base calculations are described by Liu et al. (1998). The general computational algorithms have been presented by Rosa, Paredes, Rodrigues, Alves, et al. (2012). When the model is used for scheduling irrigations, dates and depths of irrigations are also provided.

2.4. Crop observations and soil moisture measurements

In both experiments, crop height, the fraction of soil covered by the crop (f_c) and the leaf area index (LAI) were observed once or twice a week. LAI was measured on two plants per plot using a non-destructive method with equipment LI-COR 3000. LAI was determined by the ratio of the photosynthetically active leaf area of each plant to the ground area occupied by it. Data for f_c and h are given in Table 5.

The mulch cover fraction was 1.0 during the entire season but the density decreased. For the STs, the density of oats mulch was 0.9 at planting and 0.8 at 40 days before harvesting; for the DTs, with beans mulch, the density was 0.8 at planting, 0.7 by 17 days later and 0.6 after 33 days.

The dates delimiting the crop stages (Table 3) were identified as follows: (a) the initial stage was considered as from sowing to the day when the crop covered approximately 10% of the ground; (b) the development stage was from the end of the initial stage until the crop reached LAI=3; (c) the mid-season was from then until the onset of senescence; and (d) the late season was from the onset of senescence to harvest.

For measuring the soil water content, a set of FDR (Frequency Domain Reflectometry) probes were used, comprising a data logger CR10X, AM16/32 multiplexers and CS626 sensors, all from Campbell Scientific. Readings were taken daily from sowing to harvest. The FDR system was calibrated for soil water contents ranging from near the wilting point up to close to saturation. The sets of sensors were installed in the central point of each sprinkler plot with measurements in the following layer depths 0-0.15, 0.15-0.45, and 0.45-0.90 m. In the DTs experiment there were 2 sets of sensors in each plot and records were made for four layer depths: 0-0.1, 0.1-0.25, 0.25-0.55, and 0.55-0.90 m. FDR sensors were placed between rows and between plants along the row.

The applied water was measured with a flowmeter located upstream of the plots for each treatment. The application depths were obtained by correcting the measured values by 5% in the DT case and for the wind drift evaporation losses and canopy interception storage in the ST case. Various studies on sprinkler interception by a maize canopy show it may vary from 0.4 to 2.7 mm depending on the canopy density, application rate and evaporation power of the atmosphere (Kozak, Ahuja, Green, & Ma, 2007; Lamm & Manges, 2000; Li & Rao, 2000; McLean, Sri Ranjan, & Klassen, 2000; Steiner, Kanemasu, & Clark, 1983; Tolk, Howell, Steiner, Krieg, & Schneider, 1995). Therefore, the measured gross irrigation depths were corrected for 0.3 mm for the wind effect and 1.5 mm for the interception losses when the canopy was fully developed. A linear interpolation was used for the vegetative growth period.

2.5. Model calibration and validation

The calibration procedure sought to adjust the non-observed parameters (K_{cb} and p relative to all crop growth stages, TEW, REW and parameters a_D and b_D of the deep percolation parametric function, and CN of the runoff curve number algorithm) to minimise the differences between observed and simulated daily available soil water ASW values relative to the entire root depth profile. As described by Popova and Pereira (2011) and Rosa, Paredes, Rodrigues, Fernando, et al. (2012), a set of soil and crop parameters was first estimated and then a trial and error procedure was developed for selecting the values for K_{cb}

and p , starting with the standard values (Table 6). When K_{cb} and p values were in an acceptable range and estimation errors were small and showing little variation from one iteration to the next, the trial and error was applied to the soil parameters and the CN value. Finally, a last trial was applied to the crop parameters until differences between observed and simulated soil water values were minimised and approximately stabilised from one iteration to the next. A trial and error procedure relative to the effects of mulch in reducing E_s was also performed.

The calibration and validation of models using independent data sets is often discussed. Sinclair and Seligman (2000) discussed this subject and defined a set of criteria aimed at publishing papers on crop models. These models are defined as dynamic representations of crop processes in a systems context and their generic goal is to simulate and explain crop development and behaviour, yield and quality as a function of environmental and management conditions or of genetic variation. SIMDualKc aims only at representing the water use process considering well defined environmental and management conditions.

The SIMDualKc model was previously presented in terms that agree with recommendations by Sinclair and Seligman (2000), i.e., clearly defined objectives, concept and structure, as well as its background on various aspects of water use and evapotranspiration (Rosa, Paredes, Rodrigues, Alves, et al., 2012). As stated by Monteith (1996), readers may benefit from papers on models where the conceptual basis is clear and the logic behind the mechanistic structure is evident. Hence, relationships and algorithms were presented in a simple manner. In addition, to demonstrate the performance of the model, its testing was also presented and, following Sinclair and Seligman (2000), could be analysed in terms of a few main criteria: soundness of the concept, of the data and methodology; and of the analysis of the results. This testing was performed for maize, wheat and cotton (Rosa, Paredes, Rodrigues, Fernando, et al., 2012; Zhang et al., 2013; Zhao et al., 2013), peaches (Paço et al., 2012) and vineyards (Fandiño et al., 2012). The calibration/validation for maize described by Rosa, Paredes, Rodrigues, Fernando, et al. (2012) referred to only three treatments performed in the same year. This was considered appropriate because the calibration of a simple water balance model refers to only a few parameters that have a well-established physical and biological meaning and relate to the crop and the soil under consideration. In these circumstances, validation is not to prove the validity of the model approaches but to demonstrate that calibrated parameters are well adjusted for soil water and ET simulation in that particular environment. Therefore, since there is no intention of universality for a soil water balance model but of demonstrating the validity for application of

the calibrated parameters in a given environment, the model could be validated for different data sets referring to various treatments applied in the same or in various years depending upon the availability of data (Rosa, Paredes, Rodrigues, Fernando et al., 2012).

The SIMDualKc model has also been calibrated/validated for other crops and environments, including for other sets of maize data in addition to the application dealt with in this study. The transpiration and soil evaporation processes were simulated in a peach orchard and the calibration/validation was performed against measurements of T_c and E_s (Paço et al., 2012). Two years data were used because there was only one treatment. SIMDualKc was calibrated and validated for a vineyard having active ground cover (Fandiño et al., 2012), thus with separation of T_c , E_s and ground cover T. An application to a two year data set of maize on the North China Plain was used to test the model and the algorithm of soil evaporation (Zhao et al., 2013) and another to calibrate/validate the model using ET data observed with an eddy covariance system in maize and wheat (Zhang et al., 2013). Therefore, considering the referred applications and related model behaviour, it was considered appropriate to perform two calibration/validation processes using various treatments of sprinkler irrigation and drip irrigation. As shown in the Results Section, because experiments were conducted at locations 100 m apart, only one calibration could have been performed; thus, results of both calibration processes are shown together.

It is worth noting that various studies have reported on the calibration/validation of soil-water simulation models using various treatments of the same experiment and year. This is the case for various water balance, water flux and drainage models included in a book edited by Pereira et al. (1995); however, crop growth and yield models were generally tested for more than one year. Kleemola, Teittinen, and Karvonen (1996) used a season's set of nitrogen and water treatments for model calibration and the remaining for validation. Justes, Mary and Nicolardot (2009) calibrated the residue decomposition module of STICS model with data for several treatments and used the remainder for validation. Damour, Ozier-Lafontaine, and Dorel (2012) used a single cycle of banana production to calibrate and validate the water use module of a simulation model for banana growth and yield. Relative to the model HYDRUS-1, Tafteh and Sepaskhah (2012) used some treatments for calibration and the remaining treatments of the same season for validation. Singh, Tripathy, and Chopra (2008) also used treatments of the same year for calibration and validation of models in a study aimed at evaluating CERES-Wheat and CropSyst models for water–nitrogen interactions. From these discussions, it may be concluded that it is appropriate to use one treatment of each experiment to calibrate SIMDualKc and the remainder for its validation.

The standard values of K_{cb} and p for the maize crop used in the initial simulations were taken from Allen et al. (1998) and are presented in Table 6 for both experiments. The initial REW, TEW and $Z_e = 0.15$ m for both experiments are also in Table 6. The initial depletion in the evaporable layer for both experiments was 0% of TEW as observed in field. Based on soil water observations, the initial depletion for the entire effective root zone (0.9 m) was set at 5 and 8% of TAW for the ST and DT experiments, respectively. The percentage reduction of the soil evaporation as a function of the fraction covered by mulch was 50% for both experiments (Allen et al. 1998; Rosa, Paredes, Rodrigues, Fernando, et al., 2012). The fraction of the soil wetted by irrigation (f_w), required to calculate K_e together with f_c , was 1.0 for sprinkler irrigation and 0.60 for drip irrigation.

For estimation of deep percolation, the parametric decay equation proposed by Liu et al. (2006) was used. The initial and calibrated parameters a_D and b_D for both treatments are presented in Table 6. Groundwater contribution was not considered in either experiments because a shallow water table was not present.

The model calibration for the STs was performed with data of treatment A2 and validation using the same parameters was performed for treatments A1 and A3. For the DTs, the G3 treatment was used for calibration, and treatments G1, G2, and G4 were used for validation.

The statistical indicators listed below were used to evaluate the goodness of fit of SIMDualKc. They were computed from the pairs of observed and predicted available soil water ASW values O_i and P_i ($i = 1, 2, \dots, n$), whose means are \bar{O} and \bar{P} , respectively. The coefficients of regression slope and determination relating observed and simulated data and forced to the origin, b and R^2 respectively, were computed as:

$$b = \frac{\sum_{i=1}^n O_i P_i}{\sum_{i=1}^n O_i^2} \quad (1)$$

$$R^2 = \left\{ \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\left[\sum_{i=1}^n (O_i - \bar{O})^2 \right]^{0.5} \left[\sum_{i=1}^n (P_i - \bar{P})^2 \right]^{0.5}} \right\}^2 \quad (2)$$

A regression slope coefficient close to 1 indicates that the predicted values are statistically close to the observed ones and a determination coefficient close to 1.0 indicates that most of the variation of the observed values is explained by the model.

The variance of the errors is expressed through the root mean square error (RMSE, mm) (Loague & Green, 1991):

$$RMSE = \left[\frac{\sum_{i=1}^n (P_i - O_i)^2}{n} \right]^{0.5} \quad (3)$$

The average absolute error (AAE, mm) was computed to express the mean size of estimation errors, which is associated with the average relative error (ARE, %):

$$AAE = \frac{1}{n} \sum_{i=1}^n |O_i - P_i| \quad (4)$$

$$ARE = \frac{100}{n} \sum_{i=1}^n \left| \frac{O_i - P_i}{O_i} \right| \quad (5)$$

The modelling efficiency (EF, non-dimensional) proposed by Nash and Sutcliffe (1970), was used to determine the relative magnitude of the residual variance compared to the measured data variance (Moriasi et al., 2007). It is defined by the ratio of the mean square error to the variance in the observed data, subtracted from unity:

$$EF = 1.0 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \quad (6)$$

When EF is close to 0 or negative this means that the mean \bar{O} is as good or better predictor than the model (Legates & McCabe, 1999; Moriasi et al., 2007). The Willmott (1981) index of agreement (d_{IA} , non-dimensional) was used to represent the ratio between the mean square error and the "potential error" (Moriasi et al., 2007). It is defined as

$$d_{IA} = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (7)$$

From this equation, $d_{IA} = 1$ indicates perfect agreement between the observed and predicted values, and $d_{IA} = 0$ indicates no agreement at all (Legates & McCabe, 1999; Moriasi et al., 2007).

3. Results and discussion

3.1. Calibration and validation of the model

The calibrated and the initial parameters relating to the crop (K_{cb} and p), the soil evaporation (Z_e , TEW and REW) and the parameters of the equations used to estimate the deep percolation (a_D and b_D) are presented in Table 6 for both the sprinkler and drip experiments. Since the initial values used were the standard ones proposed by Allen et al. (1998) and Liu et al. (2006), changes from the initial to the calibrated values were relatively small.

The daily dynamics of the observed and simulated available soil water ASW (mm) throughout the crop season relative to the sprinkler silage maize experiments used for calibration and validation are presented in Fig. 5. Results show that model simulations fit the observations of the three ST treatments well; no biases are detected. Results also show that water stress was not induced in treatments A1 and A2, with all observed ASW above the water stress threshold corresponding to ASW when the depletion fraction is 0.5. For treatment A3, there were a few days (22/01/11 and 25/01/11) when a light stress occurred. In fact, the initial ASW was close to the total available water (TAW) and a large amount of rainfall occurred during the crop season which masked the effect of different irrigation strategies since the crop mostly used rainfall and soil water.

The daily dynamics of the observed and simulated ASW relative to the DTs experiment under the rain shelter are presented in Fig. 6. As for the STs, results show a good fit of the observations for all four treatments. Also, results show that treatments G1 and G2 were not water stressed, G3 was stressed for only a few days (29/03/11 – 31/03/11, 10/04/11 – 13/04/11 and 07/05/11 – 14/05/11), and only G4 was stressed for a long period, from day 05/03/11 until harvest. This behaviour was due to the fact that the initial ASW was again close to TAW and 77 mm rainfall occurred during the initial stage of the crop, i.e., soil water and rainfall were enough to provide for the requirements of G2 and G3 crops, however not for G4. Hence, despite a rain shelter being used, ASW and rainfall during the initial stage overcame the impacts of reduced irrigation amounts. Nevertheless, the range of observed ASW was quite wide, from 37 to 197 mm, which allows appropriate calibration and validation of the model.

The regression coefficient (Table 7 and 8) is close to 1.0 for all treatments, thus demonstrating that the estimated ASW values are close to the observed ones. The determination coefficients ranged from 0.75 to 0.96, for the STs (Table 7), and varied from

0.86 to 0.99 for the DTs (Table 8). These high R^2 values indicate a small variance of the residuals, thus a good explanation of the variance through the model. The regressions between simulated and observed ASW for all treatments are presented in Fig. 7a and b, which show that the assumption of homoscedasticity is respected. Results for both experiments show that both regression lines are close to the 1:1 line and that the variance of the residuals is small, with $R^2 = 0.94$ for the STs and $R^2 = 0.99$ for the DTs. For the ST treatments, when rainfall exceeded 60 mm day⁻¹ and ASW values are much above field capacity, estimation errors are larger. These larger errors may result from the fact that the model does not simulate water storage in the mulch and its further release downwards or as evaporation. This is a model limitation already referred to in Section 2.3 and identifies an area requiring further research.

For the STs (Table 7), the RMSE values were smaller than 7.1 mm, averaging 6.5 mm, i.e., representing less than 3.3% of TAW on average. The errors AAE were also small, not exceeding 5.8 mm, which correspond to ARE lower than 3.5%. Errors relative to the DTs experiment (Table 8) were similar, with RMSE < 5.5 mm, corresponding to less than 3.2% of TAW, and AAE not exceeding 4.2 mm, i.e., ARE < 3.9%. EF values ranged from 0.55 to 0.96 and d_{IA} was greater than 0.91 for all STs (Table 7), while EF ranged 0.85 - 0.99 and d_{IA} varied from 0.96 to 1.00 for the DTs (Table 8). These results show a good performance of the model and its ability to simulate ASW for common climatic conditions as previously shown by Rosa, Paredes, Rodrigues, Fernando, et al. (2012) and Zhao et al. (2013).

The possibilities for using the model with standard parameters if soil water or ET observations are not available for calibration were also assessed (results not shown). It was observed that RMSE values for the ST experiment were about 3 times larger than those obtained when using calibrated parameters, and for the DT experiment were nearly double; nevertheless, errors were within 10% of TAW. However, it was observed that results are sensitive to the estimation of percolation and runoff due to the occurrence of large precipitation during the maize crop season. Advice provided by Liu et al. (2006) about the use of the parametric functions for deep percolation need to be followed carefully if errors are to be kept low. For the southern Brazil region, using parameter values close to the ones calibrated in this study is advisable. Moreover, to overcome problems of soil variability that influence soil evaporation and deep percolation, it is also advisable to monitor soil water and therefore check model simulations when high accuracy is required. Results obtained are very useful for further parameterising Sistema Irriga™ and improving its use in practice; however, specific studies on percolation and runoff for tropical soils are being developed to improve related model responses.

3.2. Basal crop coefficients

The values of $K_{cb\ ini}$ generally vary little from one location to another since they represent transpiration from a crop in its initial stage. Values of $K_{cb\ ini} = 0.20$ are common as occurred with this study (Table 6). The variability in wettings are expressed through K_e , including in presence of mulch, which is well evidenced by the K_e peaks in Figs. 8 and 9 during the initial and development crop stages.

The value calibrated for both experiments, $K_{cb\ mid} = 1.12$, is slightly smaller than those presented by Allen et al. (1998, 2007) and Zhao et al. (2013), $K_{cb\ mid} = 1.15$. That $K_{cb\ mid}$ value is slightly larger than those obtained by Liu and Pereira (2000), Hsiao et al. (2009) and Rosa, Paredes, Rodrigues, Fernando, et al. (2012). More often, values for $K_c\ mid$ are reported in literature; thus, assuming $K_c\ mid = K_{cb\ mid} + 0.05$ and $K_c\ end = K_{cb\ end} + 0.05$ as proposed by Allen et al. (1998), it is possible to compare K_c and K_{cb} values. Hence, our calibrated value corresponds to $K_c\ mid = 1.17$, which compares well with the values proposed by Gao et al (2009), with $K_c\ mid$ of 1.18-1.19, and Piccinni et al. (2009), who found $K_c\ mid = 1.20$; it is higher than values reported by Domínguez, Juan, Tarjuelo, Martínez, and Martínez-Romeroa (2012), and Suyker and Verma (2009). Higher values are reported by many, e.g., Popova and Pereira (2011). By contrast, smaller values were proposed by Liu et al. (1998) and Liu and Pereira (2000) for North China, respectively 0.95 and 1.06. The relatively wide range of $K_c\ mid$ values reported in literature is due to the field methods used for its estimation, the ET_o definition and computation adopted, the maize varieties used and their response to the climatic evaporative demand, the definition of the crop stages and their duration, as well as the influence of the climate relative to the adjustment factors proposed by Allen et al. (1998).

Values for $K_{cb\ end}$ essentially depend on crop management prior to harvesting. The STs aimed at early harvesting for silage, thus the adopted $K_{cb\ end} = 0.80$ is above the common values reported in literature, e.g., Rosa, Paredes, Rodrigues, Fernando, et al. (2012). By contrast, $K_{cb\ end} = 0.20$ was found for the drip irrigated grain maize experiment, which is within the range of values proposed by Allen et al. (1998) and Zhao et al. (2013), as well as Gao et al. (2009), who reported $K_c\ end$ ranging from 0.22-0.28.

Fig. 8 shows the K_{cb} curve (with $K_{cb\ mid}$ and $K_{cb\ end}$ values corrected for climate as proposed by Allen et al., 1998), the K_e peaks and the resulting adjusted K_c curve ($K_c\ act$) for the A2 and A3 treatments. $K_c\ act$ results from the daily sum of K_e with the $K_{cb\ adj}$, i.e., the K_{cb} values adjusted for stress ($K_{cb\ adj} = K_s \cdot K_{cb}$). Rainfall and irrigation are also included in Fig. 8

for ease of reading the variation of the parameters. Results show a high frequency of K_e peaks and, consequently of $K_{c\ act}$ too, during the initial period. Then these peaks become smaller when the crop grows and shadows the ground, thus limiting the energy available for soil water evaporation. Those peaks relate well with the precipitation and irrigation events. The $K_{c\ act}$ curve is never below the K_{cb} curve in case A2, hence indicating that no water stress occurred; by contrast, it is below the K_{cb} curve for a few days (22/01/11 and 25/01/11) in case of treatment A3, thus identifying short stress periods.

Similar curves are shown in Fig. 9 for DTs G2 and G4. Because the rain shelter was operating only after the initial period, the evaporative K_e peaks are only clearly visible during that period. Peaks are smoothed and much smaller for the drip irrigation events after the shelter was operating. The water stress imposed to G4 is clearly visible in Fig. 9b, where the $K_{c\ act}$ curve is below the K_{cb} curve from April 30 until harvest. It should be noted that this curve reacted well to the irrigation events applied during midseason.

The water balance components, precipitation, irrigation, deep percolation, runoff and ET, are presented in Table 9. For the ST treatments, despite large differences in irrigation, differences in ET are small or very small as for A1 and A2. In fact, when less water was applied the crop made better use of the available water. Thus deep percolation decreased when less irrigation was applied; conversely, the seasonal use of soil water increased from 7 mm in A1 to 80 mm in A3. For the DT experiment the increase in soil water use as the applied irrigation decreased is more evident. Deep percolation also decreased; however, these values are much less than for ST because less water was applied. Anyway, percolation occurred only during the initial period when the crop received precipitation. Because the mulch substantially controlled runoff, this was limited to 15 mm for ST and was negligible for DT due to the shelter effect. These results are definitely usable in practice with Sistema IrrigaTM.

3.3. Evaporation and transpiration components

The SIMDualKc model provides both components of ET_c , soil evaporation (E_s , mm) and plant transpiration (T_c , mm). Results for the respective daily values are shown in Fig. 10 for the STs A2 and A3, and in Fig. 11 for the DTs G2 and G4. Fig. 10 shows that E_s , started larger than T_c for the first days and, due to the effects of mulch, nearly equalled T_c for the initial crop stage. After this phase, E_s , became progressively much smaller than T_c , which steadily increased with crop development. The reduction of E_s was also due to increased

ground shading by the crop. After full cover, E_s remained very small. The effect of mulch is clearly visible, limiting the K_e peaks during the initial period to half of maximum K_c (Fig. 8). Mulch effect is also visible since E_s remains very low during late season, contrasting with the observations of Zhao et al. (2013) who noticed an increase of E_s under maize without mulch. Results so far are adequate but further experiments need to be developed to prove that soil evaporation reduces by 5% for each 10% fraction of soil covered by mulch as assumed by Allen et al. (1998).

Results in Fig. 11 for drip irrigation during the initial period, when the shelter was not active, show a smaller reduction of E_s , which is greater than T_c during this period. The general pattern of E_s dynamics is similar to ST treatments, E_s becomes much lower after the initial crop stage because there was no rainfall after the initial period, there were less irrigation events and the soil was only partially wetted by irrigation.

Results for E_s and T_c are presented in Table 10 for the crop development stages and the season. Estimates for E_s/ET_c for the STs were 8, 7 and 6%, respectively for treatments A1, A2 and A3. For the DTs experiment, E_s/ET_c was 9, 9, 8 and 9% respectively for the treatments G1, G2, G3 and G4. E_s was proportionally larger for the DTs for various reasons, mainly because different mulches were used: in the STs, 5 t ha^{-1} of dry oats mulch with effective fraction of soil coverage of 0.9 were applied while mulching for the DTs consisted of 3 t ha^{-1} of dry beans mulch with effective fraction of soil coverage of 0.8 at planting. It can also be observed that larger values of E_s/ET_c occurred in treatments that received more water and more frequent irrigations: for the sprinkling experiment, treatments A1, A2 and A3 received respectively 21, 15 and 7 irrigations; for DTs the number of irrigations was 15, 11, 6 and 3 respectively for treatments G1, G2, G3 and G4. The latter had a higher E_s/ET_c because the T_c amount was much lower than for the other three.

Evaporation averaged 47% of ET_c for the STs and 53% for the DTs during the initial period (Table 10). This is probably due to the high soil water content in the evaporative layer, the high frequency of wettings, the very limited crop development and very low f_c at this stage. During the crop development phase, E_s was higher in treatments with a larger number of irrigation events. By contrast, during this stage E_s was practically nil in the treatment G4 because the surface layer was dry and did not receive any irrigation by this time. During the midseason, the fraction of wet soil exposed to solar radiation was further reduced due to high ground surface cover f_c , hence evaporation reduced to near zero. During the late season, in addition to mulch effects, f_c values decreased but, for STs, harvested for silage, the wetted fraction remained small and evaporation was minimal. In the DTs, despite f_c being reduced, f_w

was kept low, hence E_s was very small. As expected, E_s was smaller for treatments with less water application since the evaporative soil layer remained dry for long periods. However, further experimental analysis is required because, as referred before, a fraction of E_s originates in the wetted mulch and this was not modelled separately.

The seasonal E_s/ET_c ranged from 6 to 9% (Table 10), which is much lower than for conditions without mulch as in the following examples: Zhao et al. (2013) reported values of 37% or larger, Liu, Zhang, and Zhang (2002) and Zhang, Pei, and Hu (2003) obtained E/ET of 30%; Kang, Gu, Du, and Zhang. (2003) found a seasonal value of 33%; Xu and Mermoud (2003) found 25 to 36%; and Tahiri, Anyoji, and Yasuda (2006) found a maximum E/ET of 38%. Klocke et al. (2009) observed E_s/ET_c of 14 to 18% for a maize crop with wheat mulches, and these results are somewhat larger than those obtained in this study. Scopel et al. (2004) found a decrease of 50% on E/ET ratio when using a crop residues mulch with 6 t ha⁻¹ and 10% decrease when the mulch amount was 1 t ha⁻¹. Chen, Zhang, Pei, and Sun (2004) reported a decrease of 58% in E/ET when using wheat straw mulch compared to the non-mulched treatment. These results also agree with those reported by Odhiambo and Irmak (2012) for soybeans. However, literature data do not refer to drip irrigation of maize and comparison of the mulches used is difficult. Despite our results relating well to the literature, there is the need to better assess the impacts of mulches on soil evaporation from further field experiments considering the environmental conditions prevailing in southern Brazil.

4. Conclusions

The SIMDualKc model was calibrated and validated for sprinkler and drip irrigated maize with soil surface mulches of oats and beans, respectively. Results were similar for all treatments, and it was probably best to use just one sprinkler and one drip treatment for a common calibration and use the remaining treatments for validation. The statistical indicators used to assess the model's ability to simulate the ASW showed that the model does not present any trend to over or underestimate the soil water content during the different crop growth stages. Indicators relating to errors have shown that these are small, less than 4% of the total ASW.

The model allowed K_{cb} to be determined and it was observed that these parameters are common for sprinkler and drip irrigation. Therefore, crop parameters determined here may be used elsewhere in Southern Brazil unless environmental conditions greatly change. Other

soil parameters may be well adapted to other locations using approaches compatible with those in this study.

Results showed that E_s is an important component of ET_c during the initial crop growth stage. However, its relative value is highly influenced by mulch. After this stage, E_s/ET_c progressively decreases until becoming almost negligible due to the combined effects of mulch, crop development and low energy available on the ground. As expected, E_s was smaller for treatments with less water application since the evaporative soil layer remained dry for large periods. There is a need to better assess the impacts of mulches on soil evaporation from further field experiments considering the environmental conditions prevailing in southern Brazil. In addition, the SIMDualKc model should be improved to include an additional reservoir representing water storage in the mulch to assess interception losses. Results achieved suggest that corrections used were adequate but their appropriateness may change considerably as pointed out in the literature.

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Table 1 - Monthly climatic data relative for the period 1969-2005 in Santa Maria, Brazil.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max air temperature, °C	30.7	29.9	28.6	25.0	21.9	19.4	19.4	20.8	22.0	24.9	27.4	29.8
Min air temperature, °C	19.7	19.6	18.2	14.9	11.8	9.9	9.8	10.6	11.8	14.3	16.1	18.4
Average Relative Humidity, %	72.1	77.0	79.0	81.7	82.9	83.3	81.2	78.8	77.6	74.7	70.2	68.4
Wind Speed, m s ⁻¹	1.7	1.7	1.5	1.5	1.5	2.3	2.3	2.3	2.1	2.1	2.1	1.7
ET _o , mm d ⁻¹	4.0	3.5	2.8	1.7	1.1	0.8	0.9	1.3	1.98	2.7	3.5	4.1
Precipitation, mm	148.0	134.9	137.3	143.4	150.5	155.4	143.0	126.8	159.8	159.1	120.1	133.7

ET_o is reference evapotranspiration.

Table 2 - Soil texture and soil hydraulic properties for both experimental sites, in Santa Maria, Brazil.

Irrigation systems	Layer	Texture (%)			θ ($\text{cm}^3 \text{cm}^{-3}$)		
		Sand	Silt	Clay	θ_{FC}	θ_{WP}	θ_{Sat}
Drip irrigation	0.0 - 0.10	36.0	44.7	19.4	0.385	0.119	0.519
	0.10- 0.25	35.5	40.4	24.2	0.357	0.112	0.491
	0.25- 0.55	32.1	35.4	32.5	0.307	0.117	0.477
	0.55- 0.90	24.2	31.7	44.1	0.329	0.191	0.476
Sprinkler irrigation	0.0 - 0.15	32.3	42.5	25.2	0.380	0.090	0.492
	0.15- 0.45	30.4	38.2	31.4	0.360	0.090	0.494
	0.45- 0.90	23.5	29.0	47.5	0.395	0.201	0.506

θ_{FC} , θ_{WP} and θ_{Sat} represent the soil water content at field capacity, the wilting point and at saturation.

Table 3 - Crop stage dates for both experiments of ways irrigation systems, in Santa Maria, Brazil.

Crop Growth stages	Sprinkler irrigation	Drip irrigation
	Dates	
Planting	06/10/2010	13/01/2011
End of initial stage	31/10/2010	31/01/2011
Start mid-season	23/11/2010	20/02/2011
Start senescence	15/01/2011	23/04/2011 ^(G1) 23/04/2011 ^(G2) 12/04/2011 ^(G3) 06/04/2011 ^(G4)
Harvesting	02/02/2011	14/05/2011

The dates delimiting the crop stages: The initial stage was considered as from sowing (Planting) to the day when the crop covered approximately 10% of the ground (End of initial stage). The development stage was from the end of the initial stage until the crop reached LAI=3 (Start mid-season). The mid-season was from then until the onset of senescence (Start senescence), and the late season was from the onset of senescence to harvest (Harvesting). G1, G2, G3 and G4 refer to the drip treatments.

Table 4 - Irrigation dates and depths for both treatments of ways irrigation systems, in Santa Maria, Brazil.

Sprinkler Treatments				Drip treatments, under rain shelter							
A1	A2	A3		G1	G2	G3	G4				
Dates	Depths (mm)	Dates	Depths (mm)	Dates	Depths (mm)	Dates	Depths (mm)	Dates	Depths (mm)	Dates	Depths (mm)
14/10	11.6	14/10	11.6	14/10	11.6	30/01	10.4	01/02	11.2	11/02	30.3
18/10	11.6	18/10	11.6	18/10	11.6	02/02	10.4	08/02	24.7	24/02	30.3
21/10	11.6	21/10	11.6	21/10	11.6	08/02	23.4	18/02	30.3	07/03	30.3
26/10	11.6	26/10	11.6	26/10	11.6	16/02	28.7	27/02	30.3	17/03	39.3
03/11	13.0	04/11	11.6	09/11	13.0	21/02	28.7	05/03	30.3	01/04	43.8
07/11	13.0	09/11	11.1	31/12	15.6	01/03	28.7	12/03	30.3	14/04	43.8
15/11	19.8	14/11	16.3	25/01	15.6	05/03	28.7	19/03	30.3		
20/11	14.5	22/11	19.8			10/03	28.7	27/03	32.6		
02/12	15.6	16/12	15.6			15/03	28.7	07/04	32.6		
09/12	15.6	18/12	19.5			21/03	28.7	19/04	32.6		
15/12	15.6	27/12	19.5			27/03	28.7	06/05	30.3		
17/12	19.5	31/12	19.5			04/04	28.7				
19/12	15.6	15/01	19.5			12/04	28.7				
24/12	15.6	19/01	19.5			22/04	28.7				
27/12	15.6	25/01	15.6			06/04	28.7				
29/12	15.6										
31/12	15.6										
09/01	15.6										
14/01	15.6										
19/01	29.9										
24/01	15.6										

A1= Sprinkler irrigation with 328 mm; A2= Sprinkler irrigation with 234 mm; A3= Sprinkler irrigation with 91 mm; G1= Drip irrigation with 389 mm; G2= Drip irrigation with 316 mm; G3= Drip irrigation with 218 mm; G4= Drip irrigation with 113 mm.

Table 5 - Crop height (h) and fraction of ground covered by the crop (f_c) during the crop growing season.

	Treatment	Initial	Crop development	Mid season	End season
h (m)	A1	0.10	0.22	2.40	2.40
	A2	0.10	0.22	2.40	2.40
	A3	0.10	0.22	2.20	2.20
	G1	0.10	0.38	2.30	2.30
	G2	0.10	0.38	2.20	2.20
	G3	0.10	0.38	2.10	2.10
	G4	0.10	0.38	2.00	2.00
f_c	A1	0.01	0.20	0.85	0.85
	A2	0.01	0.20	0.90	0.90
	A3	0.01	0.20	0.80	0.80
	G1	0.01	0.20	0.90	0.70
	G2	0.01	0.20	0.90	0.70
	G3	0.01	0.20	0.80	0.65
	G4	0.01	0.20	0.85	0.60

A1= Sprinkler irrigation with 328 mm; A2= Sprinkler irrigation with 234 mm; A3= Sprinkler irrigation with 91 mm; G1= Drip irrigation with 389 mm; G2= Drip irrigation with 316 mm; G3= Drip irrigation with 218 mm; G4= Drip irrigation with 113 mm.

Table 6 - Standard and calibrated basal crop coefficients (K_{cb}), depletion fractions for no stress (p), soil evaporation, runoff and deep percolation parameters.

	Sprinkler irrigation		Drip irrigation	
	Standard	Calibrated	Standard	Calibrated
K_{cb} ini	0.15	0.20	0.15	0.20
K_{cb} mid	1.15	1.12	1.15	1.12
K_{cb} end	0.50	0.80	0.15	0.20
p ini	0.55	0.50	0.55	0.50
p dev	0.55	0.50	0.55	0.50
p mid	0.55	0.50	0.55	0.50
p end	0.55	0.50	0.55	0.50
REW (mm)	12.00	12.00	12.00	12.00
TEW (mm)	49.00	49.00	49.00	49.00
Z_e (m)	0.15	0.15	0.15	0.15
CN	75	75	75	75
a_D	440	390	408	353
b_D	-0.017	-0.022	-0.017	-0.022

K_{cb} ini is K_{cb} value for the initial growth phase; K_{cb} mid is K_{cb} value for the mid-season phase; K_{cb} end is K_{cb} value for the end season growth phase; p ini is depletion fractions for no stress initial; p dev is depletion fractions for no stress crop development; p mid is depletion fractions for no stress mid-season; p end is depletion fractions for no stress late season; REW and TEW are the readily and total evaporable water; Z_e is the depth of the soil evaporation layer; CN is the curve number; a_D and b_D are the parameters of the deep percolation equation (Liu et al., 2006).

Table 7 - Indicators of goodness of fit relative to the model simulation of soil water content for the sprinkler irrigation treatments using the calibrated parameters.

Goodness of fit indicators	b	R ²	RMSE (mm)	RMSE/TAW (%)	AAE (mm)	ARE (%)	EF	d _{IA}
A1 (validation)	1.01	0.75	6.4	3.0	4.5	2.2	0.55	0.91
A2 (calibration)	1.02	0.88	6.0	2.8	4.2	2.2	0.84	0.96
A3 (validation)	0.99	0.96	7.1	3.3	5.8	3.5	0.96	0.99
All treatments	1.01	0.94	6.5	3.1	4.8	2.6	0.93	0.98

b and R² are the coefficients of regression and determination; RMSE is the root mean square error; TAW is the total available water; AAE and ARE are the average absolute and relative errors; EF is the modelling efficiency; d_{IA} is the index of agreement; A1= Sprinkler irrigation with 328 mm; A2= Sprinkler irrigation with 234 mm; A3= Sprinkler irrigation with 91 mm.

Table 8 - Indicators of goodness of fit relative to the model simulation of soil water content for the drip irrigation treatments using the calibrated parameters.

Goodness of fit indicators	b	R ²	RMSE (mm)	RMSE/TAW (%)	AAE (mm)	ARE (%)	EF	d _{IA}
G1 (validation)	1.00	0.86	3.4	2.0	2.9	1.7	0.85	0.96
G2 (validation)	1.00	0.93	3.6	2.1	3.0	2.0	0.93	0.98
G3 (calibration)	1.00	0.97	5.5	3.2	4.2	3.4	0.97	0.99
G4 (validation)	1.02	0.99	5.0	2.9	3.6	3.9	0.99	1.00
All treatments	1.00	0.99	4.5	2.6	3.4	2.8	0.99	1.00

b and R² are the coefficients of regression and determination; RMSE is the root mean square error; TAW is the total available water; AAE and ARE are the average absolute and relative errors; EF is the modelling efficiency; d_{IA} is the index of agreement; G1= Drip irrigation with 389 mm; G2= Drip irrigation with 316 mm; G3= Drip irrigation with 218 mm; G4= Drip irrigation with 113 mm.

Table 9 - Season water balance components for sprinkler and drip irrigation treatments, maize cropped with straw mulch in Santa Maria, Brazil.

Irrigation systems	Precipitation (mm)	Irrigation (mm)	Deep percolation (mm)	Runoff (mm)	ΔASW (mm)	ET_c (mm)
Sprinkler irrigation						
A1	415	328	234	15	7	502
A2	415	234	148	15	10	497
A3	415	91	93	15	80	479
Drip irrigation						
G1	73	389	86	1	3	365
G2	73	316	33	1	19	361
G3	73	218	24	1	89	342
G4	73	113	23	1	122	272

ΔASW is variation of available soil water between planting and harvesting; ET_c is crop evapotranspiration; A1= Sprinkler irrigation with 328 mm; A2= Sprinkler irrigation with 234 mm; A3= Sprinkler irrigation with 91 mm; G1= Drip irrigation with 389 mm; G2= Drip irrigation with 316 mm; G3= Drip irrigation with 218 mm; G4= Drip irrigation with 113 mm.

Table 10 - Evaporation (E_s , mm) and transpiration (T_c , mm) for each crop growth stage of the maize crop in Santa Maria.

	Initial stage		Vegetative growth		Mid season		Late crop Season		Full Crop Season		E_s/ET_c (%)
	E_s	T_c	E_s	T_c	E_s	T_c	E_s	T_c	E_s	T_c	
A1	16	18	10	68	10	287	3	90	39	463	8
A2	16	18	7	68	8	287	3	90	34	463	7
A3	16	18	2	67	7	278	4	87	29	450	6
G1	22	19	8	56	3	228	1	28	34	331	9
G2	20	19	7	56	3	227	1	28	31	330	9
G3	20	19	4	55	5	218	0	21	29	313	8
G4	20	19	1	55	4	161	0	12	25	247	9

A1= Sprinkler irrigation with 328 mm; A2= Sprinkler irrigation with 234 mm; A3= Sprinkler irrigation with 91 mm; G1= Drip irrigation with 389 mm; G2= Drip irrigation with 316 mm; G3= Drip irrigation with 218 mm; G4= Drip irrigation with 113 mm; ET_c = crop evapotranspiration.

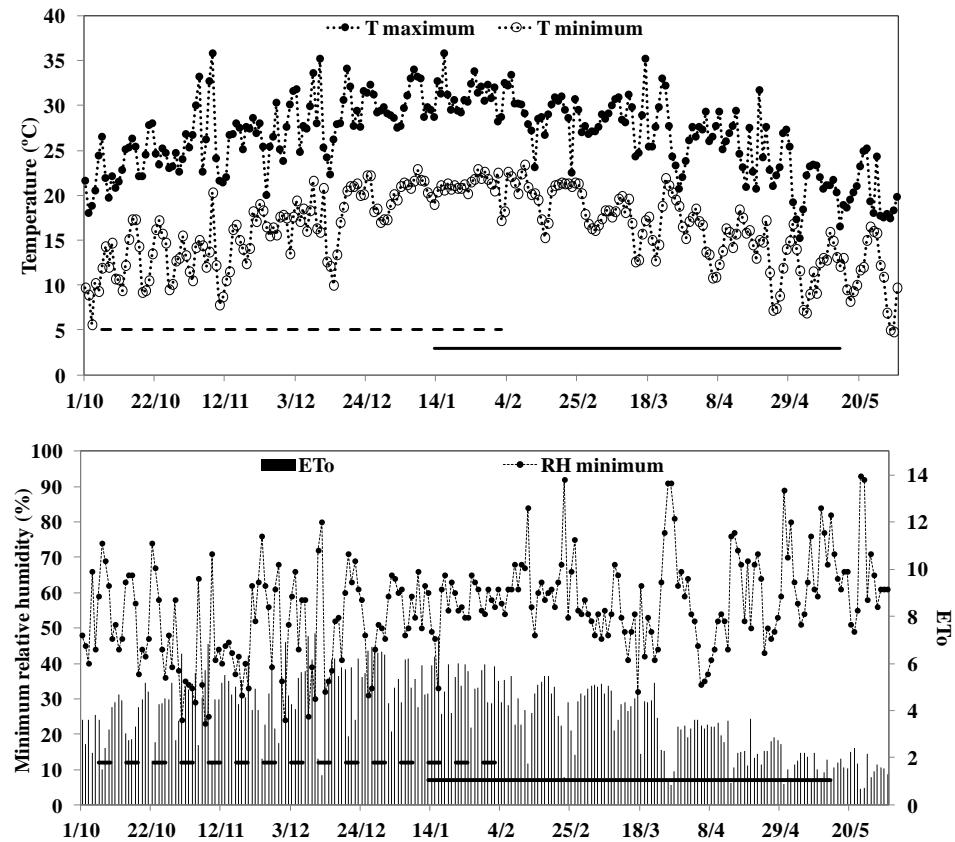


Fig. 1- Daily maximum and minimum temperature (T), minimum relative humidity (RH) and reference evapotranspiration (ET_0) during the experimental periods (sprinkler experiment - -) and (drip experiment —), 2010/11.

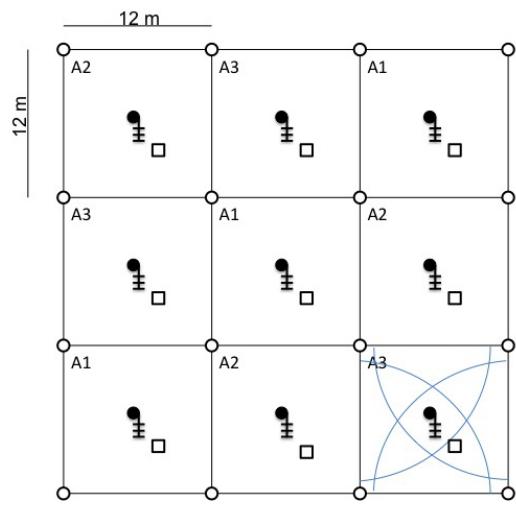


Fig. 2 - Experimental layout on the sprinkler irrigation treatments,  locations of soil water, crop cover and plant measurements;  soil sampling for hydraulic properties determination;  sectoral sprinklers (90°).

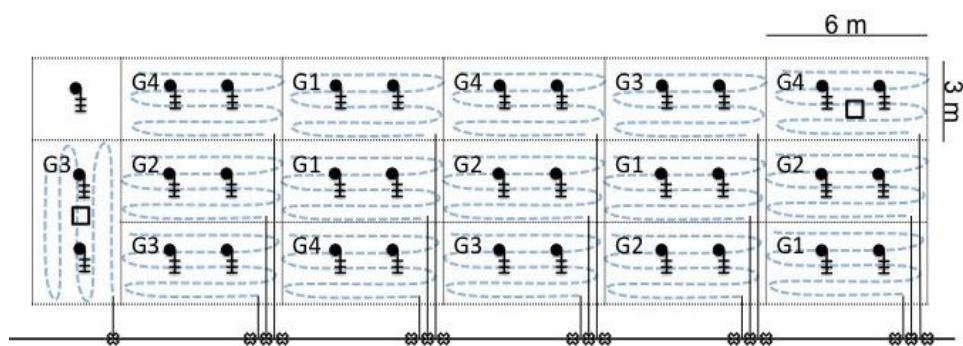


Fig. 3 - Experimental layout on the drip irrigation treatments, **locations of soil water, crop cover and plant measurements;** **soil sampling for hydraulic properties determination;** **drip pipes,** **valves for controlling irrigation water applications.**

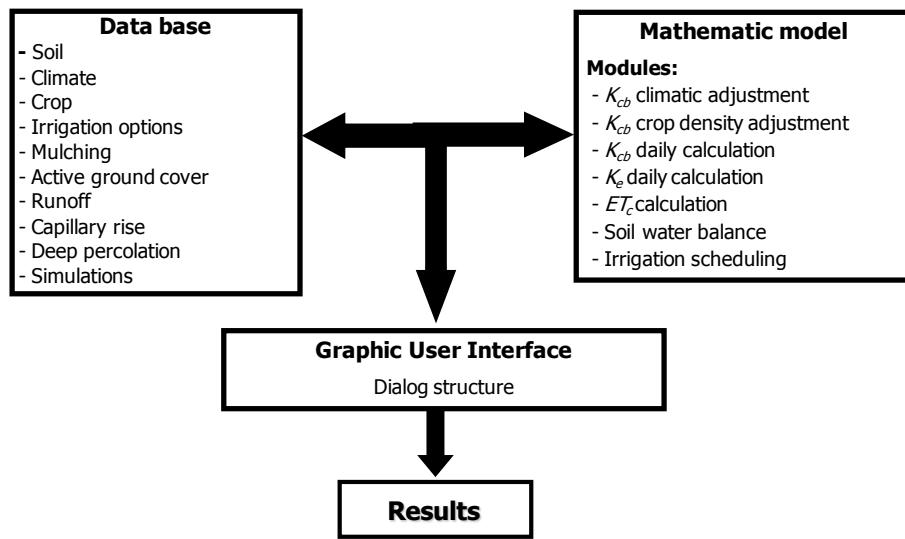


Fig. 4 - Conceptual structure of the SIMDualKc model (from Rosa, Paredes, Rodrigues, Alvez, et al., 2012a).

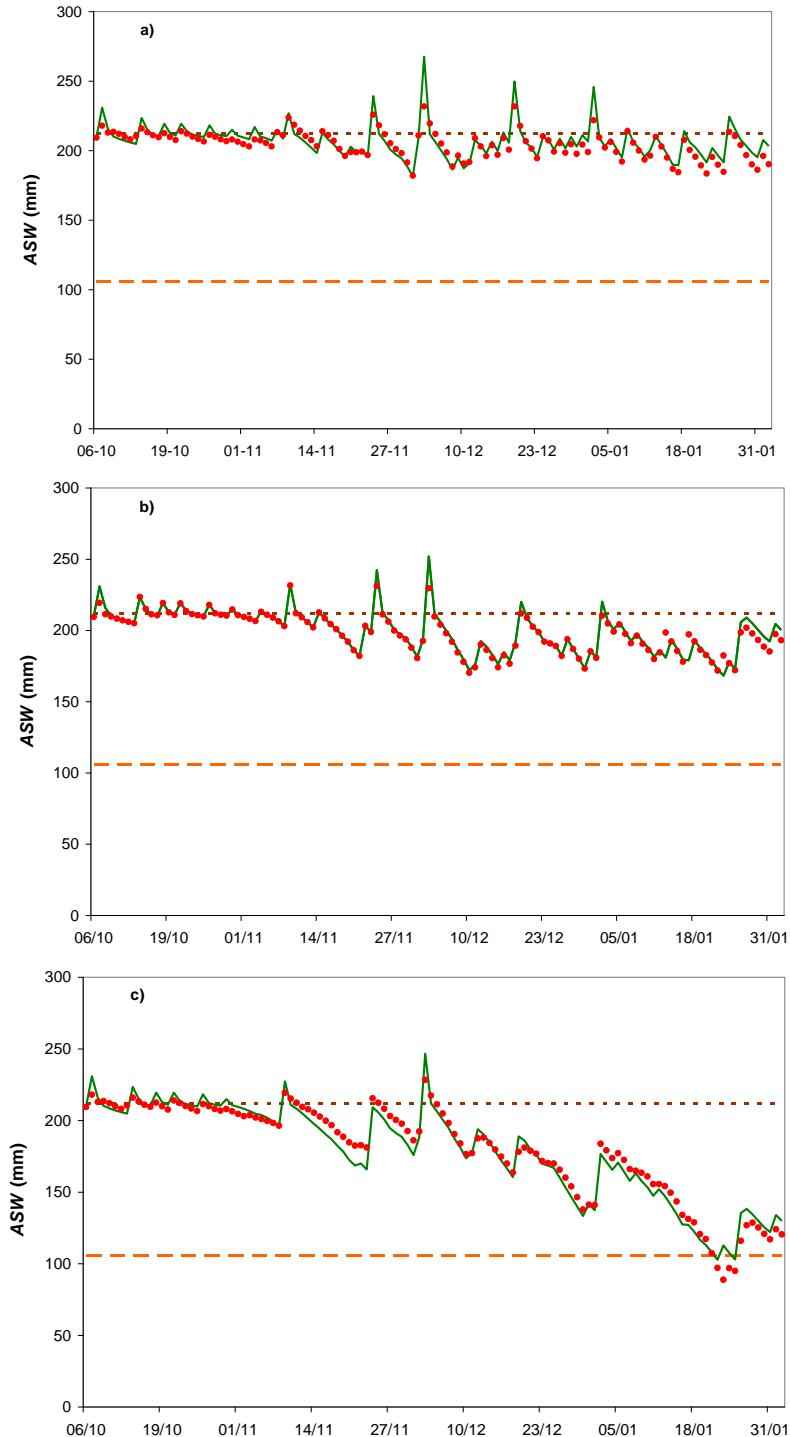


Fig. 5 - Daily comparison between observed (●) and simulated (—) available soil water (ASW) for the sprinkler irrigation experiment with maize treatments: a) A1 (validation), b) A2 (calibration) and c) A3 (validation). The horizontal lines refer to TAW (- - -) and RAW (— — —), respectively the total and readily available soil water.

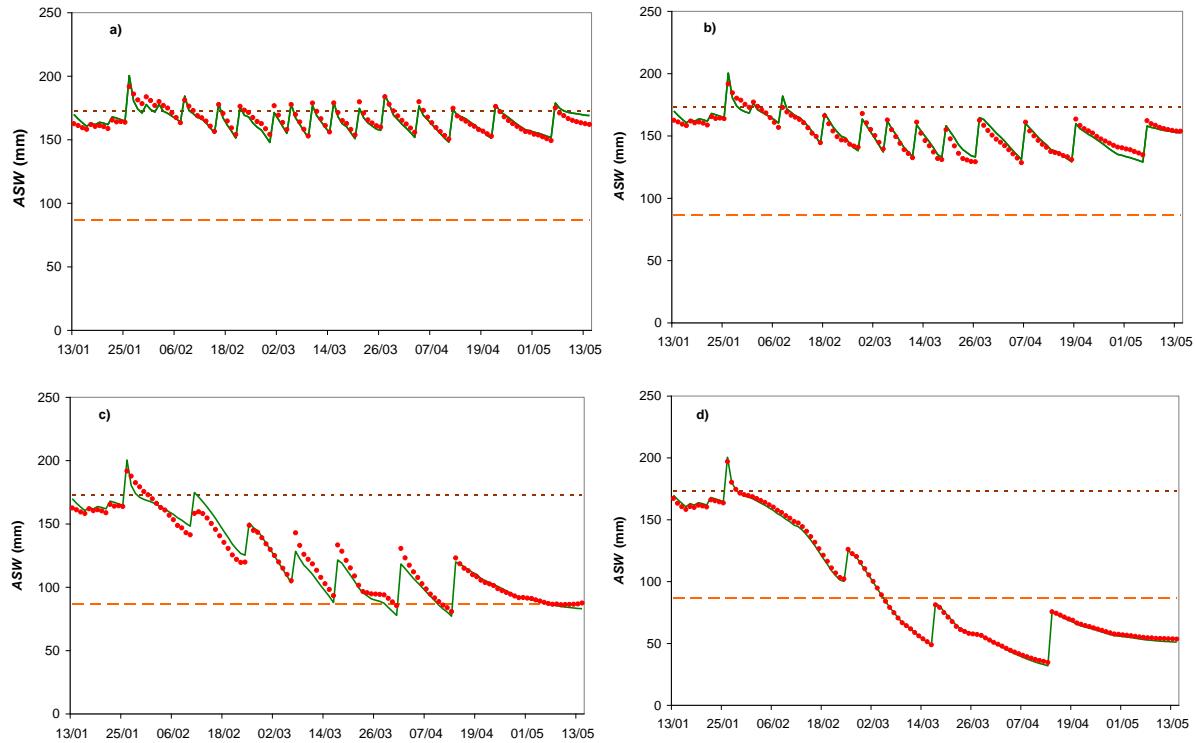


Fig. 6 - Daily comparison between observed (●) and simulated (—) available soil water (ASW) for the drip irrigation experiment with maize treatments: a) G1 (validation), b) G2 (validation), c) G3 (calibration) and d) G4 (validation). The horizontal lines refer to TAW (---) and RAW (—), respectively the total and readily available soil water.

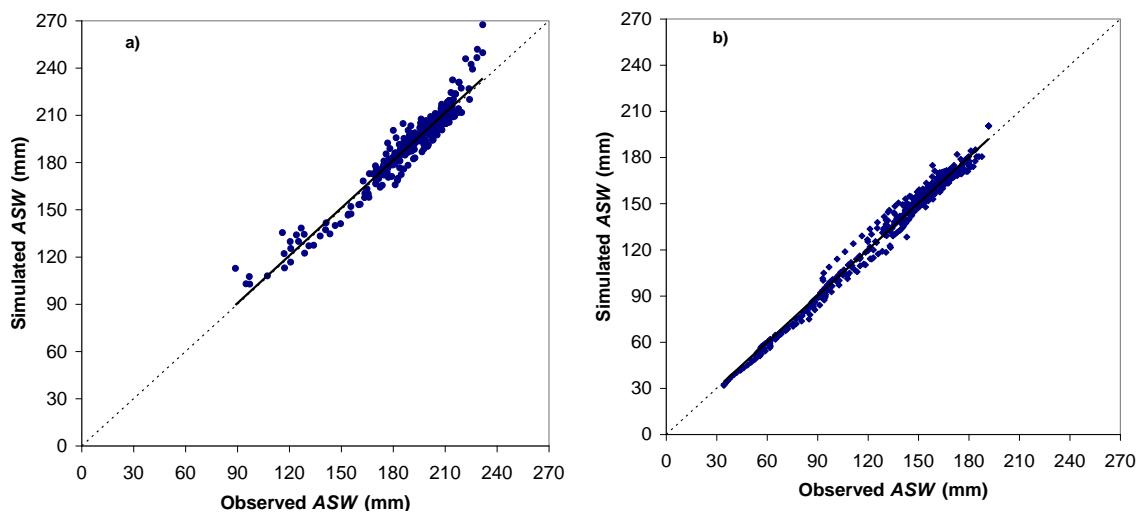


Fig. 7 - Comparison between the observed and simulated available soil water (ASW): a) sprinkler irrigation treatments ($n=360$) and $R^2=0,94$, and b) drip irrigation treatments ($n=488$) and $R^2=0,99$.

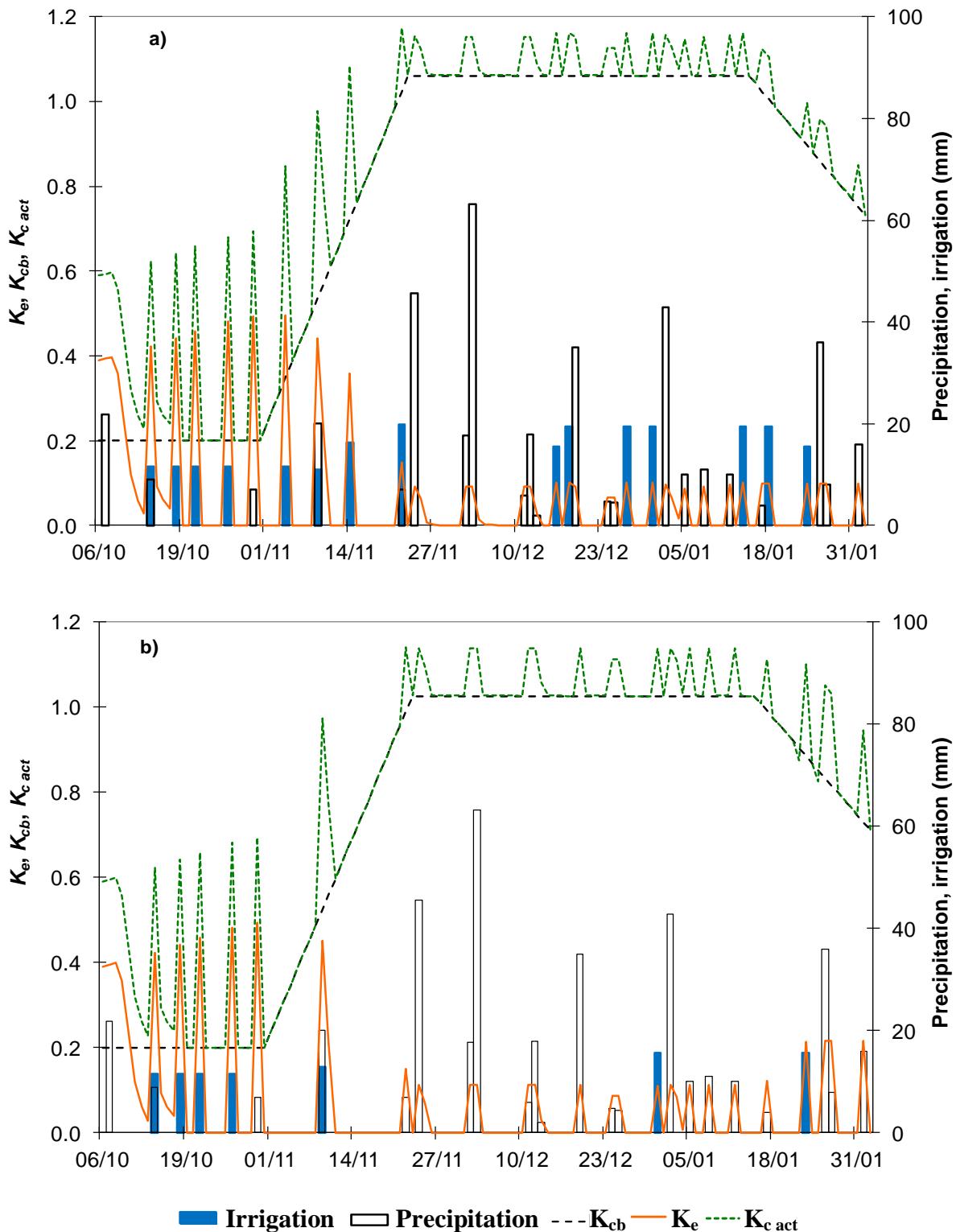


Fig. 8 - Daily variation of the basal crop coefficient (K_{cb}), the evaporation coefficient (K_e), and the adjusted crop coefficient ($K_{c\text{act}}$) along with precipitation and irrigation for the sprinkler irrigation treatments A2 (a) and A3 (b).

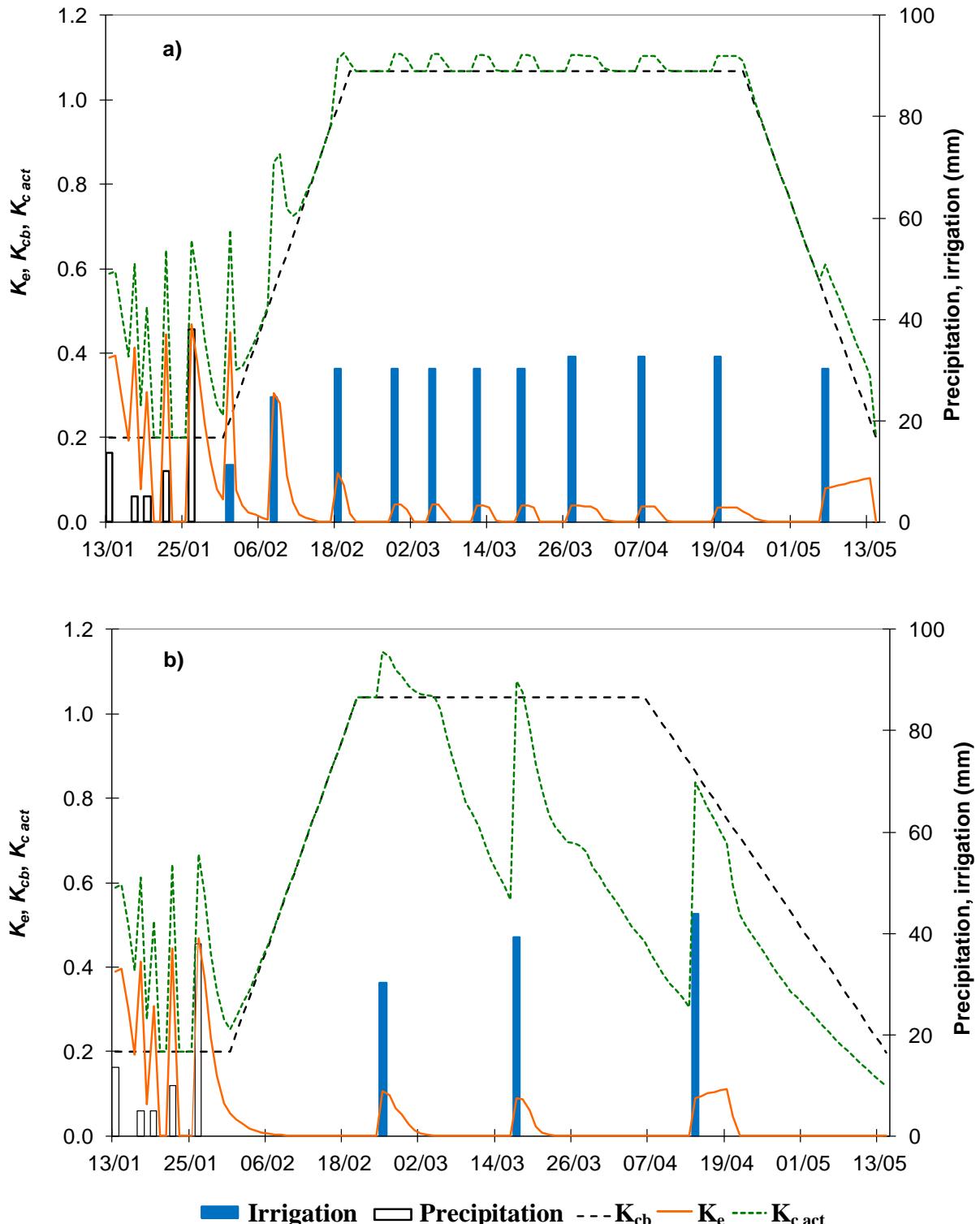


Fig. 9 - Daily variation of the basal crop coefficient (K_{cb}), the evaporation coefficient (K_e), and the adjusted crop coefficient ($K_{c\text{ act}}$) along with precipitation and irrigation, for the drip irrigation treatments G2 (a) and G4 (b).

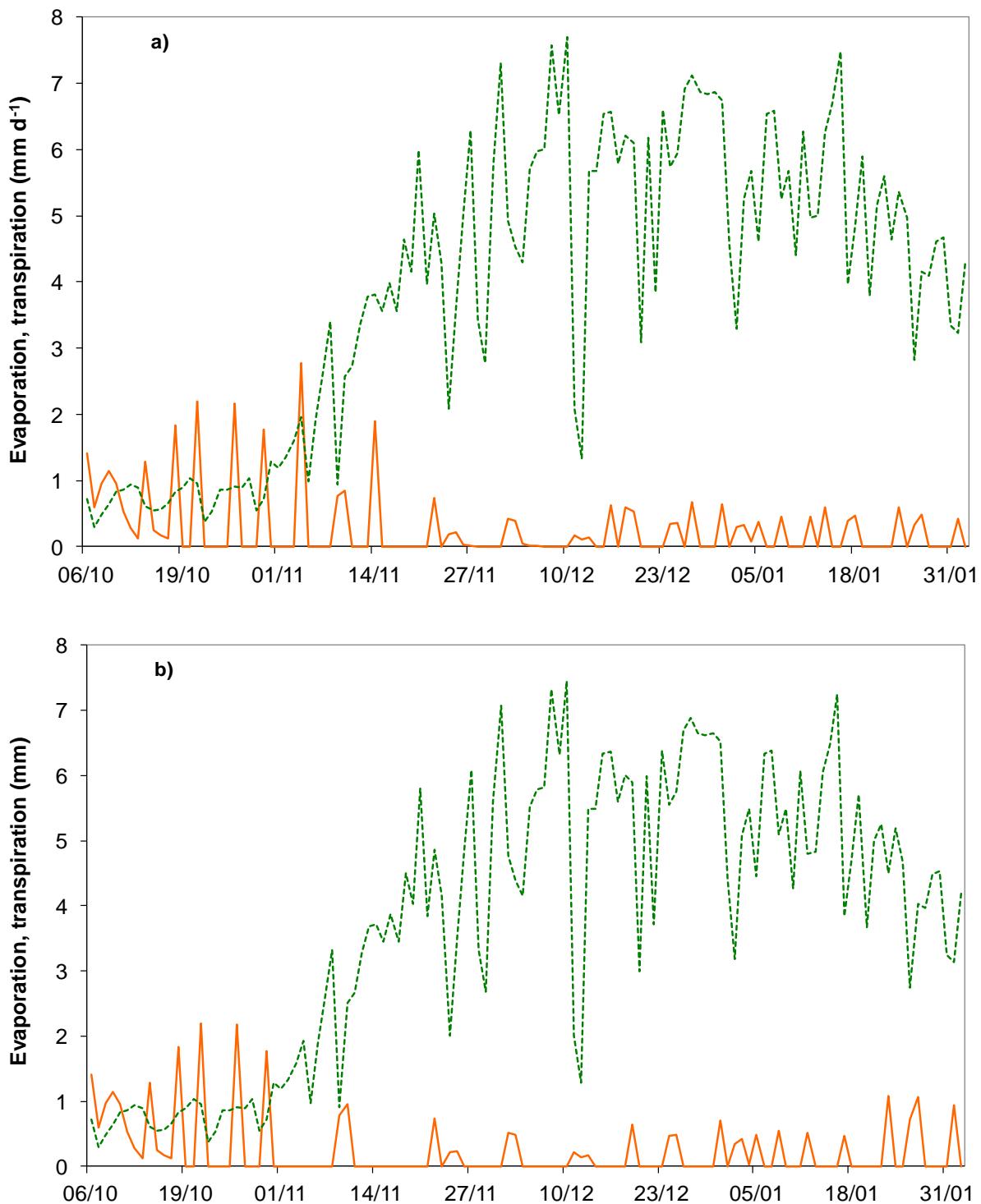


Fig. 10 - Daily variation of soil evaporation (E_s , —) and plants transpiration (T_c ,) simulated for the sprinkler irrigation treatments A2 (a) and A3 (b).

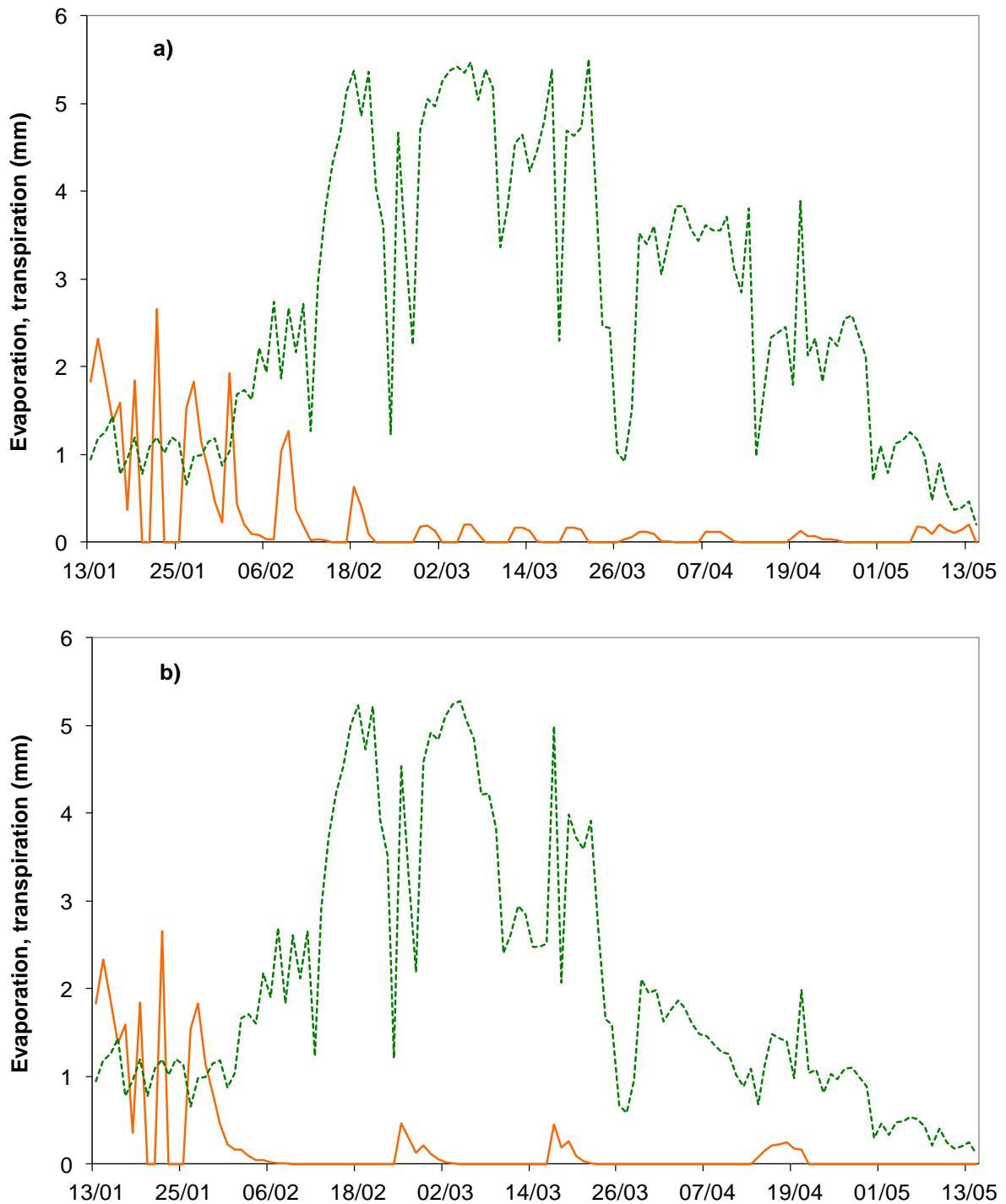


Fig. 11 - Daily variation of soil evaporation (E_s , —) and plants transpiration (T_c ,) simulated for the drip irrigation treatments G2 (a) and G4 (b).

ARTIGO II: MODELAGEM ECONÔMICA DA IRRIGAÇÃO DEFICITÁRIA EM MILHO NO BRASIL CONSIDERANDO DOIS REGIMES DE PRECIPITAÇÃO

Economic modelling of deficit irrigated maize in Brazil with consideration of two rainfall regimes²

Abstract

Deficit irrigation is often required to cope with droughts and limited water availability. However, to select an appropriate irrigation management, it is required 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, another using drip irrigation with exclusion of precipitation 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 data; and b) a sensitivity analysis to commodity prices and production costs. Alternative center-pivot irrigation scenarios were also developed to assess their feasibility in terms of water use and productivity when irrigation is used in supplement of rainfall or when rainfall is lacking. Results show that the feasibility of deficit irrigation is highly influenced by commodity prices and by the irrigation (and water) costs when the share of irrigation costs in the production costs would be high. Results also show that deficit irrigation applied when rainfall is abundant is easy to implement contrarily to deficit irrigation where rainfall is very scarce, when only a mild stress is economically viable. When adopting well designed and managed center-pivot systems, results confirm that adopting deficit irrigation when rainfall is scarce is less attractive than under conditions of irrigation in supplement of rainfall. It could be concluded that farmers would not likely choose a deficit irrigation strategy unless when facing a reduced water availability for irrigation.

Key words: beneficial water use, center-pivot irrigation, economic water productivity, irrigation and production costs, irrigation under low rainfall, supplemental irrigation, water productivity

² Artigo elaborado de acordo com normas da revista Biosystems Enginnering

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, the agricultural water withdrawal represents 70% of that relative to all water uses. Thus, and because water scarcity is increasing, the need to optimize water withdrawal is also increasing, mainly for irrigation purposes (Pereira, Cordery & Iacovides, 2009). Consequently, farmers are forced to adopt an optimized 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 (DI). This approach consists in 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 maximize water productivity (Kang, Shi, & Zhang, 2000; Geerts & Raes, 2009). However, depending upon water management and available rainfall during the crop season, the impacts of deficit irrigation on yields and related farmer incomes may or 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 Cheric (2010) have shown that maize water productivity (WP) varies with total available soil water (TAW), with a high TAW favouring crop responses to DI. Various studies have been developed to assess impacts of deficit irrigation on maize yields and economic returns (Dominguez et al., 2012; Farré & Faci, 2009; Payero, Melvin, Irmak & Tarkalson, 2006; Popova, Eneva, & Pereira, 2006). These studies clearly demonstrate that the feasibility of deficit irrigation strategies highly depends 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 the possibility to reduce irrigation depths by 25% throughout the crop cycle except for a -14 to +7 days window around silking in 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 at 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 respective 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), emphasized 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 a few indicators relative 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 maximize 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 the natural resources. In order to achieve improved WP, farmers may upgrade/modernize their irrigation systems since the improvement of irrigation performance, mainly the distribution uniformity, is essential to reduce the 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), relative to modernizing surface irrigation systems; hence, efforts are required to help farmers investing to achieve better irrigation performance.

Currently, farmers are investing on irrigation modernization by switching from labour demanding and less performing systems into 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 assure the best possible distribution uniformity. Several studies assessed impacts of irrigation non-uniformity on crop yields and evidenced its importance (Brennan, 2007; Dechmi et al., 2003; López-

Mata et al., 2010; Mantovani, Villalobos, Orgaz & Fereres, 1995; Salmerón, Urrego, Isla & Cavero, 2012; Sanchez, Zapata, & Faci, 2010).

Many sprinkler systems have neither been properly designed nor operated according to the design rules, or their operation is hampered by poor maintenance. It 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 waste water and energy as well as to yield losses (Dechmi et al., 2003; Salmerón et al., 2012; Salvador, Martínez-Cob, Cavero & Playán, 2011). Contrarily, well-designed and managed center pivot systems may provide highly uniform water application (Valín, Cameira, Teodoro & Pereira, 2012).

Drip irrigation systems proved to be an effective alternative to other systems in terms of distribution uniformity and water saving. However, the performance of these systems highly depends on the quality of design and equipment selected (Keller & Bliesner, 1990; Pereira, 1999; Evans, Wu, & Smajstrala, 2007; Pedras, Pereira, & Gonçalves, 2009). Although drip irrigation can provide highly uniform water application when a good design is adopted, related objectives must combine with appropriate irrigation scheduling in the irrigation practice (Barragan et al., 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 represent an additional 25.5 million ha considering the current irrigated area of approximately 4.5 million ha. Despite the large soils potential for sustainable irrigation development, only a small fraction is explored. This results that Brazil is a country where the ratio irrigated area/irrigable area is small (about 10%), thus resulting the very low rate of 0.018 irrigated ha per capita, the lowest in South America (ANA, 2009). About 90% of the irrigated areas were developed by private enterprises, and less than 10% through public projects. According to the last agricultural census (IBGE, 2009), the irrigation methods used in Brazil distribute as follows: 24.35% by flooding, 5.76% by furrow, 18.86% by center-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 was an increase of 39% in the number of farmers using irrigation and 42% in the total irrigated area, thus resulting an average growth rate of 150.000 ha per year.

Center-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 et al., 2012; Valín et al., 2012). In Brazil, center-pivot systems irrigate an estimated area of

840000 ha, mainly in the Central West region of the country, due to the referred advantages and potential for achieving high water distribution uniformity (Sandri & Cortez, 2009). The irrigated area by center pivots is rapidly increasing, with 300 new systems (about 20000 ha) installed this year in Rio Grande do Sul State, where this study was developed.

Recent studies have been developed to assess the impacts of center-pivot systems in terms of distribution uniformity, energy costs and crop profitability. López-Mata et al. (2010) concluded that improving a center-pivot to increase the water application uniformity from 75 to 95% may lead to increase the crop gross margin up to 27%. Ortiz, Juan, and Tarjuelo (2010) analysed the effect of water application uniformity on the uniformity of soil water content and of crop yields for a center-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 el al. (2012) analysed the main factors influencing annual water application costs in center-pivot systems and determined the most cost-effective center-pivot design. They concluded that the cost of water application with center-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 center-pivot systems with hydraulic factors, mainly relative to the pump and the pipe system, which mainly relate with energy costs. However, the approach did not lead to a clear assessment of the relationships among water saving, investments and yield incomes. Nevertheless, results agree with former analysis relative to sprinkler systems (Mantovani et al., 1995; Pereira et al., 2002; Tarjuelo et al., 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 in supplement of rainfall, the other by a drip system but where rainfall was avoided through using 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 is lacking. Data were used to develop

several alternative center-pivot irrigation scenarios referring to different irrigation management options in order to better 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 in supplement of rainfall (ISR) using a set sprinkler system, the other with very low rainfall (ILR) by using a drip irrigation system under a rainfall shelter. ISR represented rainfall conditions of Southern Brazil, and ILR simulated conditions from the dry central Brazil. Conducting the experiments under different rainfall conditions allows to better base the use of the Sistema IrrigaTM (Carlesso, Petry & Trois, 2009) under different climatic conditions and for various irrigation strategies throughout Brazil. Sistema IrrigaTM is presently monitoring more than 90000 ha each year in Brazil, including southern areas with high rainfall and areas in Central Brazil with very low rainfall in the dry season. These 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 lacking is preferable relative to just perform simulations with actual weather data because it allows capturing the crop responses to those different strategies. 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 was already observed for the irrigated areas monitored with the Sistema IrrigaTM; a better model parameterization 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, a cover fraction of the soil surface f_r _{mulch} = 1.0 and 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 per m². 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 by plants and yields. Detailed information on the experiments and results is published in this Journal (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 a mild water deficit while the ILR treatments were all with 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, fertilizers and irrigation were obtained from the experimental data.

2.2. Water productivity and water use indicators

Water productivity (WP) concepts may apply to various water uses and scales. Therefore, it is of great importance to properly define the related concepts used in this study. Herein, 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, m³), thus:

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

When considering only the irrigation water use (IWU, m³), it results 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 recognize both the beneficial and non-beneficial water uses. 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 controlling ET from weeds, the beneficial water use corresponds to the actual ET. Thus, in alternative to Eqs. 1 and 2, WP may be computed in relation to the beneficial water use (BWU, m³), 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 equation 1 by the monetary value of the achieved yield, the economic water productivity (EWP, BRL m⁻³) is defined by:

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

The monetary value refers to the Brazilian Real (BRL), which exchange rate is 1 BRL = 0.48 USD. When considering IWU or BWU only, it results:

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

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

It is important to consider the economic issues relative 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 equation 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-cost}):

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

EWPR_{full-cost} allows to assess if a given management option leads to positive (EWPR ≥ 1) or negative (EWPR < 1) income since it compares the value of production with the farming costs. If in alternative one considers the irrigation costs only, it results:

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

As referred above, data on Y_a , IWU, TWU and BWUF (Table 1) were obtained from computing the soil water balance (Martins et al., 2013). The yields monetary values were computed with the grain price of 0.40 BRL kg⁻¹. The irrigation and production costs are summarized in Table 2.

2.3. Alternative irrigation system scenarios

In order to access the impacts of adopting center-pivot systems, the most used for maize in the present conditions of Brazil, several scenarios were developed that allow to assess the economic results of the corresponding investment. Simulation scenarios were created with irrigated areas, land slopes, pivot point pressures and sprinkler packages corresponding to five different center-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) by considering the actual system characteristics.

The model DEPIVOT consists of a simulation package developed in Visual Basic and database in Access. It allows developing alternative sprinkler packages and comparing them 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 sprinklers package with computation of pressure and discharge at each outlet and including the consideration of pressure regulators; (d) verification of the sprinklers 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 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 sprinklers packages and to compare various working conditions, mainly relative 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 center-pivot costs, including the selected sprinkler package. The investment annuity A_{inv} (BRL year⁻¹) relative to the investment cost C_{inv} is:

$$A_{inv} = CRF C_{inv} \quad (9)$$

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 center-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 n and the interest rate i as:

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

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

$$C_{en} = P E_r T_i \quad (11)$$

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 observed 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 the difference for all water productivity indicators between different treatments 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, Kusli 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 Roushaphel (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 as O'Neill, Humphreys, Louis and Katupitiya (2008), with 1.7 kg m⁻³ for full irrigation, and Sampathkumar, Pandian, Ranghaswamy and Manickasundaran (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} in case of 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, Salin, Tarino & Mahoo, 2003), 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).

EW_P 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. EW_P_{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 sprinkler system (ISR1) had the lowest EW_P value among all treatments and systems. As for WP_{Irrig} , EW_P_{Irrig} increased at a smaller rate for ILR comparatively to ISR due to the lack of rainfall contribution to ET. However, this indicator has shown a similar behaviour for both ISR and ILR, which reflects the effect of a smaller denominator when deficit irrigation is considered. EW_P values were also in accordance to the ones presented by Rodrigues and Pereira (2009) for Portugal. As for WP_{BWU} , the behaviour of EW_P_{BWU} is contrasting, i.e., because BWU corresponds to the water used for achieving the desired yield EW_P_{BWU} decreases when water deficits increase.

To assess the feasibility of different irrigation strategies in terms of defining the economical return threshold from which farming becomes profitable, the economic water productivity ratio (EWPR) was used, particularly the indicators EWPR_{Irrig-cost} and EWPR_{full-cost} that compare the yield values per unit of irrigation and farming costs respectively. Table 5 shows the variation of both indicators for all the irrigation experiments. When considering the irrigation costs only, EWPR_{Irrig-cost} was larger when adopting moderate deficit irrigation for the ISR treatments (ISR3 in Table 5); however, differences between treatments are small. For the ILR deficit irrigation treatments EWPR_{Irrig-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 the mild ones. Apparently, results are in accordance to those attained by Abd El-Wahed and Ali (2013). The difference in behaviour between ISR and ILR indicates that EWPR_{Irrig-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 likely that this indicator should not be used to compare situations referring to supplemental irrigation with those where irrigation largely is the main source for evapotranspiration.

Results for EWPR_{full-cost} (Table 5) show a different behaviour relative to EWPR_{Irrig-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 likely due to the fact that

irrigation costs in southern Brazil play a minor role in the total farming costs. The EWPR_{full-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 heavier DI. These lower values for ILR are due to less water availability, thus smaller ET_a and smaller yields (Table 1). The adoption of heavy deficit irrigation 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 their 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-cost} due to increasing by 20, 50 and 100% and decreasing by 20 and 50% the present commodity prices and production costs (Table 6).

As shown in Table 5, the EWPR_{full-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 to half the commodity prices, EWPR_{full-cost} decreased to values not exceeding 0.93 for treatment ISR1 (Table 6). A further reduction would occur if the production costs would 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. Differently, considering a decrease of only 20% on the commodity prices, all ISR treatments would have positive but low incomes (Table 6). ILR1 had then EWPR_{full-cost} slightly above 1.0, thus showing to be somewhat sensitive to commodity price changes. However, because referring to low water availability and high ET deficits, ILR1 shows to be 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 but not opposed to those by Cortignani and Severini (2009) relative to Italy, where the adoption of DI 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 increase 100%, $EWPR_{full-cost}$ would decrease 3.1 to 4.6% only; similarly, if the water and labour costs decrease to half of the actual values $EWPR_{full-cost}$ would increase by 1.6 to 1.9%.

If the commodity price would increase 20%, all treatments, except ILR4, would lead to positive incomes, even for increased production costs (Table 6). Nevertheless, the treatment ILR4 has shown $EWPR_{full-cost}$ values close to 1. An increase of commodity prices of 50% would lead to $EWPR_{full-cost}$ 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 would decrease to half of the present value. If the production costs would double their current value, $EWPR_{full-cost}$ would be improved from 44.5 to 45.2% when commodity prices would increase by 50%. Summarizing, results show that the viability of deficit irrigation is extremely dependent of 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 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 relative to 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 however depending 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 et al. (2007) suggest that a water price increment has a lower effect than a production cost increase; however, the water costs considered were quite low. Differently, Huffaker and Whittlesey (2003) concluded that increasing the cost of applied water may be an effectual water 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.

Figure 1 show that ISR treatments would lead to a positive farm income even if the irrigation costs would represent half of the total production costs, with $EWPR_{full-cost}$ decreasing by 32.3 to 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 higher than 2, representing an increase ranging from 18.2 to 21.8% when compared to the current price/costs scenario.

Differently, 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 attains 40%. ILR 4 is already below that threshold. Contrarily, if the irrigation costs would only 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 DI 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 of costs change as referred before for a few reported research results (Huffaker and Whittlesey, 2003; Gómez-Limón & Riesgo, 2004; Bazzani et al., 2005; Bartolini et al., 2007; 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 a more efficient use of rainfall, as for irrigation in supplement of rainfall, favours the adoption of deficit irrigation when facing risks due to a variation in production costs.

3.3. Impacts of deficit irrigation with center pivot sprinkler systems

Potential water savings due to adopting center 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 that those CPs are well designed and managed as described in Section 2.3 and Table 3, it is possible to assess DI and water saving assuming two different scenarios, one for irrigation in supplement of rainfall as it happens in Southern Brazil, and the other for irrigation in conditions where rainfall is lacking, as it occurs in Central and North-eastern 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 (*vd.* Table 3).

As for BWUF, WP would increase from ISR1 to ISR3 due to the water savings attained during crop season that are sufficient to overcome the effects of correspondent yield losses. WP would vary between 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 center pivot equipment and emitters characteristics. Results are similar to those presented by Schneider and Howell (1999) for center-pivot systems in U.S.A., with WP = 1.70 kg m⁻³ for full irrigation. As for WP, EWP 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 center-pivot system. The analysis by Dalton, Porter, and Winslow (2004), shows 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 when less water was used decreasing the irrigation costs since yields were not highly affected by the mild DI considered. Better values were observed for the S equipped CPs because they require less pressure, 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, which aspects are not considered herein. EWPR_{full-cost} showed a behaviour very similar among all CPs, with only very small differences between S and R equipped systems (Table 7), with all values largely above 1.0, thus indicating that farm returns would be always positive. The very small differences in EWPR_{full-cost} among all systems are due to the fact that irrigation costs consist of only a small share in the production costs and differ little among them (Table 3). Results allow identifying the ISR3 management (mild deficit) as the scenario that would lead to higher economic results when compared with ISR1 and 2. However differences are small and farmers probably would select this management if water availability for irrigation is limited as referred by Cortignani and Severini (2009) relative to Italy.

When using well designed and managed CPs under conditions of scarce rainfall (Table 8) BWUF increases from the range of values from 0.703 to 0.739, when adopting ILR1 to the range of 0.834 to 0.863 for ILR3. These results relate to a lower TWU for ILR3, that lead to increase the ratio of ET_a to TWU, thus BWUF. WP and EWP increased similarly to BWUF, reaching its higher value for alternative S4 and the lowest for R1, due to highest and lowest DU and CU, respectively (*vd.* Table 3). The behaviour of BWUF, WP and EWP indicators are 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 as of those presented by Goyne and McIntyre (2002) for Australian conditions. EWP would slightly improve from the range of 0.71 to 0.74 BRL m⁻³ to 0.73 to 0.77 BRL m⁻³ when changing to ILR3 instead of ILR1.

EWPR_{irrig-cost} increased when a heavier deficit irrigation 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-cost} values were observed for Spray relative to Rotator equipped systems due to low energy demand as referred for the ISR cases analysed before. However, EWPR_{full-cost} have a different behaviour: adopting ILR3 instead of ILR1 treatment leads to lower EWPR_{full-cost} for all center-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 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 lacking (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 DI, shows higher values for the same indicators. This results from the fact that abundant rainfall mitigates then the impact of deficit irrigation.

Differently, the $EWPR_{irrig-cost}$ are much higher, about the double, when comparing results for irrigation in supplement of rainfall (ISR treatments) with irrigation when rainfall is scarce (ILR). This indicates that the conjunctive use of irrigation and rainfall with the latter is abundant results in higher production value when compared with the applied irrigation water in case of scarce rainfall. Since farmers search for profit, and considering that ILR1 has a $EWPR_{irrig-cost}$ higher than ILR3, i.e., $EWPR_{irrig-cost}$ decreases for heavier deficits, this indicates that farmers would not likely choose a deficit irrigation strategy unless a reduced water availability would induce them to do so. Contrarily, for a conjunctive use of irrigation and rainfall, $EWPR_{irrig-cost}$ is higher for mild deficits ISR2 and 3. However, the $EWPR_{full-cost}$ are higher for the management strategies leading to higher yields and having a higher TWU for both ISR and ILR management strategies. Moreover, the $EWPR_{full-cost}$ 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 in supplement of rainfall when irrigation controls the risk of crop failure (Dalton, Porter, & Winslow, 2004). It is likely that mild DI and carefully designed irrigation schedules may lead to improved irrigation water use under scarce rainfall conditions (e.g. Grassini et al., 2011), not heavier DI that would produce high impacts on yields and farm returns. The adoption of improved irrigation and agronomic factors needs 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-cost}), that shows to be adequate for assessing the feasibility of deficit irrigation as influenced by commodity prices, and water and labour costs. Results show that 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 change of the share fraction of irrigation costs in the total production costs would lead to a significant impact of irrigation costs over EWPR_{full-cost}. These results also support the assumption that deficit irrigation is favoured by the adoption of irrigation in supplement of rainfall, especially when facing risks due to a variation in production costs.

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

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

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Table 1 - Irrigation water use and grain yield relative to each treatment (adapted from Martins et al., 2013).

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	9,190	8,340	7,650	5,312

ISR1= irrigation in supplement of rainfall 328 mm; ISR2= irrigation in supplement of rainfall 234 mm; ISR3= irrigation in supplement of rainfall 91 mm; ILR1= irrigation in supplement with very low rainfall 389 mm; ILR2= irrigation in supplement with very low rainfall 316 mm; ILR3= irrigation in supplement with very low rainfall 218 mm; ILR4= irrigation in supplement with very low rainfall 113 mm.

Table 2 - Operating costs and irrigation for corn for both irrigation systems used in simulations.

Items	Costs
Operation Costs	
Machinery (BRL ha ⁻¹)	204.00
Labour (BRL ha ⁻¹)	47.00
Seeds (BRL ha ⁻¹)	
Set Sprinkler	233.00
Drip	208.00
Fertilizers (BRL ha ⁻¹)	
Set Sprinkler	1,108.00
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

* 1 BRL = 0.48 USD

Table 3 - Scenarios for different irrigation system center pivot for the corn crop, using the super spray emitter and rotator R3000 sprinkler.

Sprinkler Package	System Scenario	Irrigated Area	Average Land Slope (%)	Pivot Point Pressure (kPa)	CU (%)	DU (%)	C_a (BRL ha ⁻¹ year ⁻¹)*	C_m
Senninger™	S1	32.13	1.46	290	95.2	90.7	385	53
	S2	46.34	1.52	385	96.5	93.0	369	51
	S3	65.03	2.47	455	95.9	91.8	291	40
	S4	81.27	0.65	410	96.6	93.0	269	37
	S5	110.22	1.47	430	96.3	92.6	254	35
Nelson™	R1	32.13	1.46	330	92.1	87.8	417	56
	R2	46.34	1.52	410	95.8	91.6	395	53
	R3	65.03	2.47	480	93.7	89.8	314	42
	R4	81.27	0.65	440	95.2	91.4	289	39
	R5	110.22	1.47	470	94.1	90.4	272	37

* 1 BRL = 0.48 USD

CU = Christiansen coefficient of uniformity; DU = distribution uniformity; C_a = investment annuity per unit of irrigated area; C_m = annual maintenance costs; S1= center pivot 1 with super spray; S2= center pivot 2 with super spray; S3= center pivot 3 with super spray; S4= center pivot 4 with super spray; S5= center pivot 5 with super spray; R1= center pivot 1 with rotator R3000; R2= center pivot 2 with rotator R3000; R3= center pivot 3 with rotator R3000; R4= center pivot 4 with rotator R3000; R5= center pivot 5 with rotator R3000.

Table 4 - Physical and economic water productivity (WP and EWP) for all treatments of deficit irrigated maize in Brazil with consideration of two different rainfall regimes.

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	1.71ab	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	2.33ab	0.69a	0.72a	1.63a	0.89a	1.01a	0.93ab
3	1.95b	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= water productivity; WP_{Irrig} = irrigation water productivity; WP_{BWU} = water productivity relative to the beneficial water use; EWP economic water productivity; EWP_{Irrig} irrigation economic water productivity; EWP_{BWU} = economic water productivity relative to the beneficial water use; ISR= irrigation in supplement of rainfall; ILR= irrigation in supplement with very low rainfall.

Table 5 - Comparison between economic water productivity ratio for irrigation costs (EWPR_{Irrig-cost}) and total farming costs (EWPR_{full-cost}) for all the irrigation experiments of deficit irrigated maize in Brazil with consideration of two different rainfall regimes.

Treatment	EWPR _{full-cost}	EWPR _{Irrig-cost}	Treatment	EWPR _{full-cost}	EWPR _{Irrig-cost}
ISR1	1.83 a	7.00 a	ILR1	1.27 a	3.36 a
ISR2	1.75 b	6.95 a	ILR2	1.16 ab	3.09 ab
ISR3	1.71 b	7.16 a	ILR3	1.06 b	2.84 b
			ILR4	0.74 c	1.99 c

Within column, values with the same letter are not significantly different at $p < 0.05$. ISR1= irrigation in supplement of rainfall 328 mm; ISR2= irrigation in supplement of rainfall 234 mm; ISR3= irrigation in supplement of rainfall 91 mm; ILR1= irrigation in supplement with very low rainfall 389 mm; ILR2= irrigation in supplement with very low rainfall 316 mm; ILR3= irrigation in supplement with very low rainfall 218 mm; ILR4= irrigation in supplement with very low rainfall 113 mm.

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

ISR1= irrigation in supplement of rainfall 328 mm; ISR2= irrigation in supplement of rainfall 234 mm; ISR3= irrigation in supplement of rainfall 91 mm; ILR1= irrigation in supplement with very low rainfall 389 mm; ILR2= irrigation in supplement with very low rainfall 316 mm; ILR3= irrigation in supplement with very low rainfall 218 mm ; ILR4= irrigation in supplement with very low rainfall 113 mm.

Table 7 - Water use and productivity indicators relative to the center-pivot systems described in Table 3 when adopting the management scenarios ISR1, ISR2 and ISR3 for irrigation in supplement of rainfall.

<u>System symbol</u>	Super Spray emitters					Rotator R3000 sprinklers				
	S1	S2	S3	S4	S5	R1	R2	R3	R4	R5
<u>Irrigated area (ha)</u>	32.13	46.34	65.03	81.27	110.2	32.13	46.34	65.03	81.27	110.2
<u>ISR1</u>										
BWUF	0.64	0.65	0.64	0.65	0.65	0.63	0.64	0.64	0.64	0.64
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-cost}	4.78	4.81	5.18	6.33	5.40	4.51	4.65	5.02	6.10	5.21
EWPR _{full-cost}	1.63	1.63	1.67	1.78	1.70	1.60	1.61	1.66	1.76	1.68
<u>ISR2</u>										
BWUF	0.73	0.74	0.73	0.74	0.73	0.72	0.73	0.73	0.73	0.73
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-cost}	5.39	5.43	5.97	7.18	6.29	5.07	5.23	5.77	6.89	6.06
EWPR _{full-cost}	1.63	1.64	1.68	1.77	1.71	1.60	1.62	1.67	1.75	1.69
<u>ISR3</u>										
BWUF	0.81	0.81	0.81	0.81	0.81	0.80	0.81	0.80	0.81	0.80
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-cost}	7.19	7.29	8.48	9.73	9.17	6.75	6.96	8.09	9.26	8.77
EWPR _{full-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-cost} = economic water productivity ratio for irrigation costs; EWPR_{full-cost} economic water productivity ratio for total farming costs; S1= center pivot 1 with super spray; S2= center pivot 2 with super spray; S3= center pivot 3 with super spray; S4= center pivot 4 with super spray; S5= center pivot 5 with super spray; R1= center pivot 1 with rotator R3000; R2= center pivot 2 with rotator R3000; R3= center pivot 3 with rotator R3000; R4= center pivot 4 with rotator R3000; R5= center pivot 5 with rotator R3000; ISR1= irrigation in supplement of rainfall 328 mm; ISR2= irrigation in supplement of rainfall 234 mm; ISR3= irrigation in supplement of rainfall 91 mm.

Table 8 - Water use and productivity indicators relative to the center-pivot systems described in Table 3 when adopting the management scenarios ILR1 and ILR3 for irrigation when rainfall is lacking.

<u>System symbol</u>	Super Spray emitters					Rotator R3000 sprinklers				
	S1	S2	S3	S4	S5	R1	R2	R3	R4	R5
<u>Irrigated area (ha)</u>	32.13	46.34	65.03	81.27	110.2	32.13	46.34	65.03	81.27	110.2
<u>ILR1</u>										
BWUF	0.72	0.74	0.73	0.74	0.74	0.70	0.73	0.72	0.73	0.72
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-cost}	3.02	3.03	3.23	3.99	3.35	2.85	2.94	3.14	3.85	3.24
EWPR _{full-cost}	1.22	1.22	1.25	1.35	1.27	1.19	1.20	1.24	1.33	1.25
<u>ILR3</u>										
BWUF	0.85	0.86	0.86	0.86	0.86	0.83	0.86	0.85	0.85	0.85
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-cost}	3.39	3.42	3.78	4.52	3.98	3.19	3.29	3.64	4.34	3.84
EWPR _{full-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-cost} = economic water productivity ratio for irrigation costs; EWPR_{full-cost} economic water productivity ratio for total farming costs; S1= center pivot 1 with super spray; S2= center pivot 2 with super spray; S3= center pivot 3 with super spray; S4= center pivot 4 with super spray; S5= center pivot 5 with super spray; R1= center pivot 1 with rotator R3000; R2= center pivot 2 with rotator R3000; R3= center pivot 3 with rotator R3000; R4= center pivot 4 with rotator R3000; R5= center pivot 5 with rotator R3000; ILR1= irrigation in supplement with very low rainfall 389 mm; ILR3= irrigation in supplement with very low rainfall 218 mm.

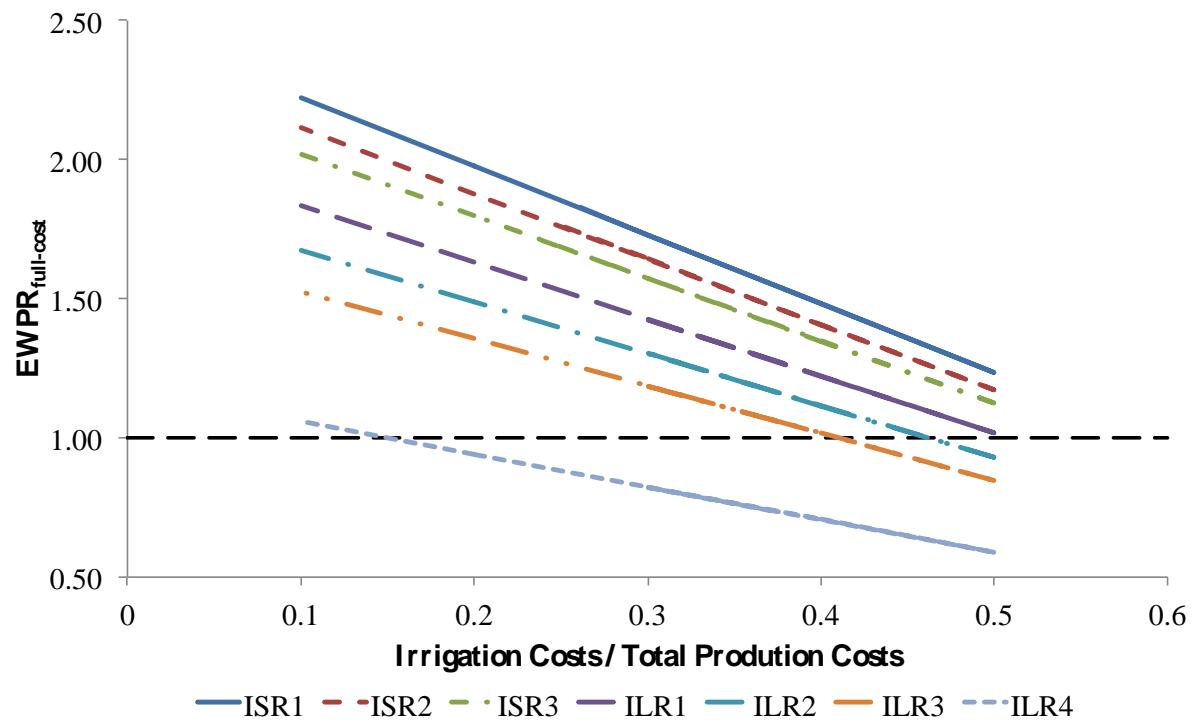


Fig. 1 - Impacts of a variation of the fraction of irrigation costs over the total production costs on the full costs economic water productivity ratio (EWPR_{full-cost}) for all treatments.

ARTIGO III- VIABILIDADE ECONÔMICA DA IRRIGAÇÃO DEFICITÁRIA EM MILHO IRRIGADO POR GOTEJAMENTO³

Viabilidade econômica da irrigação deficitária em milho irrigado por gotejamento

Resumo- A irrigação por gotejamento apresenta usualmente maior eficiência de uso da água, sendo assim, a utilização deste sistema de irrigação pode ser uma alternativa para pequenas áreas irrigadas, e onde há escassez hídrica, mas sua adoção para a cultura do milho dependerá da viabilidade econômica e da relação custo e benefício. Objetivou-se, com este estudo, avaliar a viabilidade econômica do uso da irrigação deficitária por gotejamento na cultura do milho. Foram conduzidos dois experimentos sob uma cobertura móvel, nos anos agrícolas de 2010/11 e 2011/12. Os tratamentos foram constituídos de irrigação plena com reposição de 100% da evapotranspiração da cultura e irrigação deficitária com reposição da evapotranspiração da cultura de (80, 55 e 30% da ETc) durante o ano agrícola de 2010/11 e reposição de (100, 80, 65, 45 e 40% da ETc) durante o ano agrícola 2011/12. A produtividade obtida apresentou uma relação linear com o aumento da quantidade de lâmina irrigada. De acordo com a análise econômica, conclui-se que as despesas com os custos fixos relacionados às linhas laterais do sistema de irrigação foram as que mais oneraram o custo final de produção em todos os tratamentos e condições estudados. A análise de sensibilidade demonstra que a lucratividade da irrigação por gotejamento na cultura do milho foi associada ao custo fixo anual do sistema de irrigação e do preço de comercialização do milho.

Termos para indexação: Déficit hídrico, Irrigação localizada, Manejo de irrigação, Custo de produção, *Zea mays*.

³ Artigo elaborado de acordo com normas da revista Pesquisa Agropecuária Brasileira

Economic Viability of deficit irrigation in drip irrigated corn

Abstract- Drip irrigation usually presents more efficiency in the use of water, so the use of this irrigation system can be an alternative for small irrigated areas and where there is water scarcity, but its adoption in the corn crop will depend on the economic viability and the cost-benefit relationship. The objective of this study was to evaluate the economic viability of using deficit drip irrigation in maize. Two experiments were conducted under a movable covering, in the agricultural years of 2010/11 and 2011/12. The treatments consisted of full irrigation with replacement of 100% of crop evapotranspiration and deficit irrigation with replacement of the crop evapotranspiration (80, 55 and 30% of ETc) in 2010/11 and (100, 80, 65, 45 and 40% of ETc) in 2011/12. The obtained yield showed a linear relationship with the increasing amount of irrigated blade. According to the economic analysis, it was concluded that expenses with fixed costs related to the lateral lines of the irrigation system were the most burdened final cost of production in all treatments. The sensibility analysis shows that the profitability of drip irrigation in maize was associated with the annual fixed cost of the irrigation system and the price of corn in the trade.

Index terms: Water deficit, Localized irrigation, Irrigation management, Production cost, *Zea mays*.

Introdução

A recomendação convencional da quantidade de água aplicada via irrigação é realizada para suprir a demanda hídrica plena de água dos cultivos e maximizar a produtividade. Contudo, nos próximos anos mudanças deverão ocorrer na prática da irrigação,

em decorrência das pressões econômicas sobre os sistemas de produção agrícola, da crescente competição pelo uso da água e dos impactos ambientais causados pelo uso da irrigação (Frizzone, 2004). Estes fatores deverão motivar mudanças nas práticas de irrigação, com maior enfoque na eficiência econômica do que apenas no suprimento da demanda hídrica dos cultivos agrícolas (Ramos et al., 2012).

A eficiência econômica objetivando a otimização dos recursos investidos não é normalmente considerada no manejo tradicional de irrigação em sistemas já implantados, prática esta, que procura maximizar a produtividade da terra. No entanto, irrigar com o objetivo de maximizar o lucro é um problema mais complexo e desafiador que irrigar apenas para obter a máxima produtividade da cultura (Figueiredo et al., 2008). A otimização da irrigação passa pelo aumento da eficiência do uso da água pelas culturas, que pode ser atingida com a utilização da irrigação deficitária (Fereres & Soriano, 2007).

A irrigação deficitária consiste na aplicação de água abaixo dos requesitos necessários para atender plenamente a evapotranspiração máxima das culturas. Assim, são aplicadas lâminas inferiores às necessárias para satisfazer às necessidades hídricas da cultura, afetando assim, a evapotranspiração e a produtividade, entretanto, a redução da produtividade deve ser mínima ao ponto de manter o retorno econômico da cultura irrigada (Englisch et al., 2002). No entanto, os impactos da irrigação deficitária sobre a produtividade e suas relações com os resultados econômicos podem ou não ser negativos, dependendo do manejo da irrigação adotado, do desempenho do sistema de irrigação e dos custos de produção (Lorite et al., 2007).

O sistema de irrigação por gotejamento apresenta vantagens como reduzir a quantidade de água aplicada e do uso de fertilizantes, economia de mão de obra, redução dos gastos com energia, e possibilidade de automação (Boas et al., 2011). Na irrigação por gotejamento é possível aplicar pequenas quantidades de água com um alto grau de

uniformidade e frequência, torna-se potencialmente muito mais eficiente do que outros métodos de irrigação (Boskurt et al., 2006). Apesar das inúmeras vantagens que o sistema oferece, o gotejamento tem sido pouco utilizado para a irrigação da cultura do milho no Brasil. Uma das principais limitações é seu alto custo de implantação. Por ser um sistema fixo, a irrigação por gotejamento exige alto investimento em obras e aquisição de equipamentos para captação, condução, controle e distribuição da água, devendo ser considerados gastos como energia e mão de obra para operação e manejo do sistema, que representam importantes custos adicionais à produção (Boas et al., 2011).

Entre os vários componentes de um sistema de irrigação por gotejamento, o custo das linhas laterais é o fator mais importante e o que mais onera o custo total do sistema (El-Hendawy et al., 2008). Como o espaçamento entre as linhas laterais do sistema de gotejamento para a cultura do milho é definida em função do espaçamento entre linhas de cultivo, que comumente para a cultura do milho varia de 0,45 a 0,90 metros, a quantidade de gotejadores utilizada é elevada, mesmo com a utilização de gotejadores em linhas alternadas. Em alguns casos, o alto custo inicial da instalação tem feito com que este sistema seja considerado uma opção economicamente inviável para culturas com espaçamento entre linhas reduzidos, dependendo também do valor comercial do produto (El-Hendawy et al., 2008).

O objetivo deste trabalho foi determinar a viabilidade econômica da adoção de estratégias de irrigação deficitária, seu impacto no custo de produção e a viabilidade técnica e econômica da irrigação por gotejamento na cultura do milho, quando comparada a diferentes alternativas de sistemas de gotejamento usualmente projetadas.

Material e Métodos

Dois experimentos foram conduzidos na estação experimental do Departamento de Engenharia Rural da Universidade Federal de Santa Maria, nos anos agrícolas de 2010/11 e

2011/12. A área experimental está situada na Depressão Central do Estado do Rio Grande do Sul, região Sul do Brasil, latitude de 29°41'24"S e longitude de 53°48'42"W e com altitude de 100 metros. A precipitação média anual da região é de 1712 mm. No entanto, nos meses de verão, devido à maior demanda evaporativa da atmosfera e a distribuição irregular das precipitações, frequentemente as chuvas são insuficientes para suprir as necessidades hídricas das culturas. O solo do local apresenta uma textura franca argilo siltosa, sendo classificado como Argissolo Vermelho distrófico arênico (Embrapa, 2006), sendo profundo e com presença de gradiente textural no perfil. Os experimentos foram instalados no interior de uma cobertura móvel “Rainfall Shelter”, com orientação Leste-Oeste, composta por duas estruturas metálicas de 16 x 10 m, ocupando área total de 74 x 10 m e com área experimental útil de 320m². A estrutura movimentava-se sobre trilhos metálicos, a partir de acionamento manual. A cobertura móvel foi acionada momentos antes da ocorrência de precipitações pluviais, permanecendo a área experimental coberta somente durante o período de ocorrência da precipitação. Dessa forma, foi possível aplicar tratamentos com irrigação deficitária com precisão, sem influência de chuvas.

Nos dois anos agrícolas o delineamento experimental utilizado foi o inteiramente casualizado, fatorial, com quatro repetições. No ano de 2010/11, os tratamentos foram constituídos de quatro manejos de irrigação: Irrigação plena, (R100) com reposição de 100% da evapotranspiração da cultura (ETc) estimada para condição sem déficit hídrico, e irrigações deficitárias (R80, R55 e R30) correspondendo, respectivamente, a 80%, 55% e 30%, de reposição da ETc estimada para uma condição sem déficit hídrico. A semeadura foi realizada no dia 13 de janeiro de 2011 em sistema de cultivo plantio direto, sob resíduos culturais de feijão (*Phaseolus vulgaris* L.) com aproximadamente 3 toneladas de massa seca por hectare. O híbrido semeado foi o P1630H com espaçamento entre linhas de 0,50 m e densidade de 6,5 plantas por m². As unidades experimentais foram compostas de parcelas de 3 x 6 m.

O segundo experimento foi conduzido no ano agrícola de 2011/12. Os tratamentos foram constituídos de seis manejos de irrigação: irrigação plena (R100) com reposição de 100% da evapotranspiração da cultura (ETc) estimada para condição sem déficit hídrico, e irrigações deficitárias (R80, R65, R55, R45 e R40), com reposição de 80%, 65%, 55%, 45% e 40%, respectivamente, da ETc estimada para uma condição sem déficit hídrico. A semeadura do milho foi realizada em 15 de outubro de 2011, em sistema de cultivo plantio direto, sobre restos culturais de aveia (*Avena sativa*) com 2,8 toneladas de massa seca por ha. O híbrido utilizado foi DKB240 com espaçamento entre linhas de 0,5 m e população média de 7,0 plantas por m². As unidades experimentais foram compostas de parcelas de 3x3 m. Em ambos os experimentos a adubação foi realizada de acordo a Comissão de Química e Fertilidade do Solo RS/SC (2004).

O sistema de irrigação era constituído de uma linha principal de condução de água, de onde foi derivada uma tubulação secundária para cada unidade experimental e nestas foram conectadas linhas laterais (tubos gotejadores). No início de cada linha secundária foram instalados registros que permitiram controlar a passagem de água e possibilitar irrigar simultaneamente todas as unidades experimentais de um mesmo tratamento. Foram utilizados tubos gotejadores autocompensantes de 16 mm de diâmetro com espaçamento entre gotejadores de 0,2 m, com pressão de serviço de 10 mca, e vazão de 1,3 l h⁻¹, resultando em uma taxa de aplicação de irrigação de 13 mm h⁻¹. As linhas laterais de gotejadores foram instaladas entre as fileiras de cultivo e espaçadas em 0,5 m.

A necessidade de irrigação foi determinada com base na evapotranspiração da cultura (ETc). A estimativa da evapotranspiração de referência (ET₀) foi realizada pelo método de Penman-Monteith, segundo Allen et al. (1998), utilizando os dados meteorológicos coletados na estação meteorológica automática do Instituto Nacional de Meteorologia (INMET), situada a cerca de 300 m da área experimental. A estimativa da ETc foi realizada multiplicando-se a

ETo pelo coeficiente de cultura simples (Kc). Os valores de Kc utilizados foram os propostos por Allen et al. (1998).

Para a determinação do conteúdo de água no solo foi utilizado um conjunto FDR (Frequency Domain Reflectometer), constituído por um datalogger CR1000 e multiplexadores AM16/32, e sensores CS626, (Campbell® Science Inc). As leituras foram realizadas diariamente, de forma automática, em intervalos de 15 minutos, desde a semeadura até a colheita. Os sensores foram instalados na porção central de cada parcela, representando as camadas de 0-0,1; 0,1-0,25; 0,25-0,55; 0,55-0,85 m de profundidade. Os sensores foram instalados na área experimental em junho de 2009 permanecendo até o momento na mesma posição. As linhas de cultivo foram posicionadas de tal forma que os sensores permanecessem entre as linhas de cultivo do milho.

Na verificação do balanço hídrico do solo, após a realização do experimento, foi utilizado o modelo SIMDualKc (Rosa et al., 2012). O modelo SIMDualKc adota a abordagem do coeficiente de cultivo dual (Allen et al., 2005) para estimar a evapotranspiração da cultura (ETc). O modelo simula o balanço hídrico do solo na zona radicular em nível de campo, utilizando um intervalo de tempo diário. O modelo SIMDualKc foi previamente calibrado e validado para o ano agrícola de 2010/11 (Martins et al., 2013). A partir dos parâmetros validados, foram realizadas as simulações para o ano agrícola de 2011/12. Os resultados dos componentes do balanço estão descritos na Tabela 1.

Para avaliar os impactos da adoção de sistemas de irrigação por gotejo, foram desenvolvidos diferentes alternativas para analisar os resultados econômicos do respectivo investimento. Na simulação desses projetos de irrigação por gotejo alternativos, utilizou-se o software DSS MIRRIG (Pedras et al., 2009). A estrutura conceitual do MIRRIG apresenta dois componentes principais: a base de dados e os modelos (projeto e avaliação dos sistemas de irrigação localizada). A base de dados é constituída por um conjunto de informações

referente às características dos emissores (gotejadores e micro-asperadores) e das tubulações disponíveis no mercado, das culturas, dos solos e dos setores de irrigação, em projeto ou em avaliação. A estrutura do modelo possui quatro componentes: (1) módulo de projeto interativo, para propor projetos alternativos de acordo com as tubulações e emissores disponíveis; (2) módulo de análise de desempenho que simula o funcionamento do sistema e calcula os indicadores utilizados como atributo relacionados à critérios de projeto adotados para a análise multicritério; (3) módulo de análise multicritério para classificar opções alternativas de projeto e; (4) um módulo de avaliação que suporta a análise dos dados coletados por meio de avaliações de campo que pode ser usado por projetistas e consultores de irrigação quando trabalhando de forma interativa com os agricultores para avaliar possíveis melhorias. O MIRRIG foi utilizado por ser um sistema de apoio à decisão que integra bancos de dados, ferramentas de modelagem e metodologias de análise multicritério, que são úteis para analisar e classificar um conjunto de alternativas. Sistemas de apoio à decisão são importantes nas atividades agrícolas e seu uso em projetos de irrigação é recente (Thysen & Detlefsen, 2006; Gonçalves et al., 2007; Smith et al., 2007).

Para a estimativa dos custos de produção, utilizou-se a avaliação do resultado econômico considerando a depreciação e do custo alternativo (Reis, 2007). Para o procedimento de estimativa do custo de produção, determinado pela soma de valores de todos os recursos e operações utilizados no processo produtivo de certa atividade, incluindo os respectivos custos alternativos ou de oportunidade.

Para o cálculo de cada recurso fixo, adicionou-se à depreciação o custo alternativo do fator produtivo. Os itens considerados nos custos fixos e o procedimento de operacionalização foram os descritos por Conab (2010), seguindo os custos de produção regional para produção de milho para os dois anos agrícolas (Conab, 2013). A seguir são descritos os custos da terra, máquinas, implementos e benfeitorias e sistema de irrigação:

(a) Terra: Foi considerado seu custo alternativo, baseado no arrendamento da terra explorada. O arrendamento foi considerado como sendo aproximadamente 2 % sobre o preço real médio de venda;

(b) Máquinas, implementos e benfeitorias: Considerou-se o valor da depreciação que se refere à perda de valor ou eficiência produtiva, causada pelo desgaste pelo uso ou obsolescência tecnológica. Os valores referentes à vida útil, valor residual e depreciação foram os indicados pela Conab (2010);

(c) Manutenção de benfeitorias, máquinas e implementos: Na composição do custo os gastos com a manutenção e com os filtros e lubrificantes foram contabilizados de acordo com as horas trabalhadas por hectare. Para tanto, utilizou-se como gasto de manutenção, o valor de 1% do bem novo para máquinas e 0,08 % para benfeitorias e implementos;

(d) Sistema de irrigação: o valor de um sistema de irrigação é altamente influenciado pelas condições do local e pelos equipamentos utilizados. Neste trabalho, considerou-se um projeto dimensionado pelo MIRRIG a partir de quatro alternativas de gotejadores: i) Naan slim 16 mm 8mil com espaçamento entre gotejadores de 0.20 m, fita gotejadora com vida útil de 2 anos (NaanSlim 0,2); ii) Naan slim 16 mm 8mil com espaçamento entre gotejadores de 0.30 m, fita gotejadora com vida útil de 2 anos (NaanSlim 0,3); iii) Naan Tif 16 mm com espaçamento entre gotejadores de 0.20 m, tubo gotejador com vida útil de 4 anos (NaanTif 0,2); e iv) Naan Tif 16 mm com espaçamento entre gotejadores de 0.30 m, tubo gotejador com vida útil de 4 anos (NaanTif 0,3). Foram utilizadas estas combinações de gotejadores com espaçamento entre linhas laterais espaçadas a 0.90 m e 1.35 m. Foi considerado para o dimensionamento dos projetos uma área irrigada de 1 hectare.

O custo variável foi calculado pelo desembolso realizado para aquisição de produtos e serviços. Os recursos variáveis e a forma de operacionalização utilizados foram os descritos a seguir:

(a) Mão de obra: Para efeito dos custos de produção, o salário do trabalhador foi utilizado como a remuneração total recebida integral e diretamente como contraprestação pelo serviço prestado pelo empregador; a jornada do trabalho foi limitada em oito horas diárias, 44 horas semanais;

(b) Insumos: corresponderam aos gastos com aquisição dos insumos utilizados nos tratos culturais dos tratamentos nos dois anos agrícolas, que incluem fertilizantes de adubação de base e de cobertura, sementes, herbicidas e inseticidas;

(c) Máquinas e implementos: considerou-se os valores de hora trabalhada no custo variável. Para calcular o valor da hora trabalhada pelas máquinas foi definido o preço e a quantidade consumida dos itens de cada equipamento, em cada hora de trabalho, levando em consideração a potência, os gastos com o óleo diesel, filtro/lubrificantes, energia elétrica e os salários e encargos sociais e trabalhistas dos seus operadores, segundo os coeficientes técnicos definidos pela Conab (2010);

(d) Gastos com transporte: Foi considerado o custo e gastos com o transporte da mercadoria ao local de armazenamento, no limite de até 80 quilômetros da unidade de produção;

(e) Despesas de armazenamento: Os gastos com recepção, limpeza, secagem e armazenagem foram computados na estimativa de custos apenas para o período de uma quinzena de armazenamento.

(f) Despesas administrativas: As despesas administrativas representam os gastos, pagos ou incorridos, para a gestão do empreendimento rural, que não estão ligados à produção. Referem-se aos gastos de energia elétrica do imóvel, telefone, serviços de contador, rádio comunicador, material de consumo, computador, internet, veículo de passeio e combustível.

(g) Energia: o custo com energia elétrica utilizada na irrigação foi determinada a partir do consumo em kW por irrigação para cada tratamento multiplicado pela tarifa do kW. O valor do kWh utilizado no cálculo foi de R\$ 0,147363, tarifa convencional da concessionária AES Sul.

(h) Água: a cobrança pelo uso da água no meio rural ainda não se encontra devidamente regulamentada, sendo que neste estudo adotou-se uma tarifa de R\$ 0,02 por m³.

Para o cálculo do custo alternativo, a cada item dos recursos variáveis, foi considerada a taxa de juros real de 6% a.a. Os dados foram obtidos conforme determinações da Conab (2013) para produção de milho na região.

Para este estudo foi determinado a produtividade econômica da água, considerando o valor do rendimento econômico da cultura para uma dada produção obtida (Y_a) e o custo do total de água utilizada (TWU) (incluindo todos os custos agrícolas), em termos monetários obtém-se o índice de produtividade econômica da água (EWPR_{full-cost}):

$$\text{EWPR}_{\text{full-cost}} = \frac{\text{Valor } (Y_a)}{\text{Custo} (\text{TWU})} \quad (1)$$

EWPR_{full-cost} permite avaliar se uma opção de gestão leva a um rendimento positivo (EWPR ≥ 1) ou negativo (EWPR < 1), uma vez que compara o valor da produção com os custos agrícolas. Também considerou-se a produtividade da água (WP) (Pereira et al, 2012). No presente estudo a WP (kg m⁻³) é definida como a razão entre o rendimento real da cultura (Y_a , kg) e o consumo total de água (TWU, m³), considerando os valores de precipitação e irrigação.

$$\text{WP} = \frac{Y_a}{\text{TWU}} \quad (2)$$

A análise estatística foi realizada considerando-se um delineamento inteiramente casualizado para cada ano agrícola e constou da comparação entre médias da produção de

grãos e produtividade da água (WP), por meio do teste t de student ao nível de 5% de significância.

Resultados e Discussão

A lâmina total de água aplicada nos tratamentos, bem como a precipitação efetiva, escoamento superficial, drenagem profunda, depleção do conteúdo de água no solo na zona radicular, evapotranspiração atual da cultura (ETa) e a evapotranspiração máxima (ETm), simulados pelo SIMDualKc estão apresentados na Tabela 1. Os valores de evaporação de água no solo foram maiores para os tratamentos que receberam maiores lâminas de irrigação. Isto se deve ao maior número de irrigações, mantendo elevado o conteúdo de água na camada de evaporação do solo por um período com maior de exposição à radiação solar. A evapotranspiração atual da cultura foi inferior a evapotranspiração máxima da cultura, para os tratamentos com irrigação deficitária, pois o conteúdo de água no solo durante o ciclo de desenvolvimento da cultura foi inferior a fração de esgotamento de água no solo permitida, para que não ocorra déficit hídrico e a transpiração da cultura, não é potencializada.

As produtividades médias de grãos de milho, em função das diferentes estratégias de irrigação deficitária, estão apresentadas na Tabela 1. É importante mencionar que no inicio do ciclo de desenvolvimento, até o estádio V3, as precipitações pluviais que ocorreram não foram evitadas sobre a área experimental, para uniformizar a umidade do solo em todos os tratamentos. Após o estádio V3 todas as precipitações pluviais foram evitadas à fim de possibilitar a implantação dos tratamentos com irrigação deficitária. A produtividade de grãos foi significativamente afetada pelo manejo de irrigação deficitária, em ambos os anos agrícolas. Todas as produtividades obtidas nos tratamentos com irrigação deficitária foram inferiores a observada no tratamento R100, tratamento com reposição do total da ETc. A produtividade de tratamento R80 apresentou uma redução de 10% para o ano agrícola 2010/11 e de 5% no ano agrícola de 2011/12 em comparação com o R100. As plantas do

tratamento R55 que receberam 55% do total de irrigação do tratamento R100, apresentaram redução na produtividade de 17% para o ano agrícola 2010/11 e de 25% no ano agrícola de 2011/12 em relação ao tratamento R100. As plantas do tratamento com irrigação deficitária mais intensa (R30) apresentaram uma redução na produtividade de 42% em relação ao tratamento com 100% de reposição da ETc.

A produtividade da água foi maior para os tratamentos com aplicação de déficits hídricos mais elevados. O tratamento R100 apresentou uma WP de 1,99 e 1,74 Kg m⁻³, nos anos agrícolas 2010/11 e 2011/12, respectivamente. Os tratamentos com déficits mais elevados como o R30 apresentou WP de 2,87 Kg m⁻³ e R40 com 2,47 Kg m⁻³. Estes resultados indicam que as plantas dos tratamentos com irrigação deficitária foram mais eficientes na utilização do uso da água com maior produção de grãos por m³ aplicado de água, corroborando com os resultados apresentados por Fereres & Soriano (2007); Karam et al. (2003); Zwart & Bastiaanssen (2004).

Na Tabela 2 são apresentados os valores de participação dos itens que compõem os custos totais de produção de milho, para os dois anos agrícolas, detalhando o custo relacionado à irrigação para os tratamentos estudados, e os custos fixos do sistema de irrigação para os tubos gotejadores (Naan Slin 0,2; Naan Slim 0,3; Naan Tif 0,2; e Naan tif 0,3) nos espaçamentos de linhas laterais de 0,9 e 1,35 m. Verificou que, para todos os tratamentos avaliados, os custos relacionados a irrigação compõem cerca de 45% do custo total de produção (custo de produção mais os custos relacionados à irrigação). O custo fixo, de depreciação dos gotejadores foi o item que mais onerou os custos relacionados à irrigação. Os custos com energia elétrica e água pouco contribuiram para o custo de produção total (entre 1 e 3%) para todos os tratamentos, como pode ser observado na tabela 2. A reduzida diferença observada nos custos de energia elétrica e de água entre os tratamentos deveu-se

exencialmente ao baixo consumo de energia elétrica pelo sistema de irrigação por gotejamento.

É conhecimento que, os custos de produção de milho dependem basicamente do nível tecnológico adotado pelo produtor, e da variação anual do custo dos insumos de produção. Mas também, pode variar em função do sistema de cultivo e práticas de manejo e do tipo de cultivares utilizadas (Sangoi et al., 2003, 2006) e épocas de semeadura (Forsthofer et al., 2006).

Uma análise de sensibilidade foi realizada considerando as quatro alternativas de tubos gotejadores. Foram criados três cenários de preços do milho para o manejo da irrigação atual: considerando valores atuais de mercado ($R\$ 0,40 \text{ Kg}^{-1}$); e cenários que representam um aumento/diminuição dos preços do milho em -25% e +25% ou seja, $R\$ 0,30$ e $0,50 \text{ Kg}^{-1}$, respectivamente, para os conjuntos de tubos gotejadores alternativos. A variação da cotação do milho foi realizada para avaliar os impactos sobre $\text{EWPR}_{\text{full-custo}}$.

Na Tabela 3 estão apresentadas as quatro combinações de tubos gotejadores para o espaçamento entre laterais de 0,90 m nos diferentes cenários de variação da cotação do milho. Considerando-se a cotação do preço do milho de $R\$ 0,40 \text{ kg}^{-1}$, os valores $\text{EWPR}_{\text{full-custo}}$ variaram de 0,40 a 0,95. Nestas condições, o cultivo de milho irrigado por gotejamento não apresenta viabilidade econômica para nenhuma das estratégias de irrigação avaliadas, isso é, tanto para a irrigação plena como para a irrigação deficitária, pois os valores de $\text{EWPR}_{\text{full-custo}}$ foram inferiores a 1. O mesmo ocorreu para o cenário com redução da cotação do preço de comercialização do milho em 25%. Somente se observa um retorno econômico, quando o preço de comercialização do milho aumentou em 25% e, mesmo assim, somente nos tratamentos R100, (irrigação plena) e R80, (irrigação deficitária) e utilizando os tubos gotejadores NaanSlim 0,2 e NaanSlim 0,3. Nesse caso os valores máximos de $\text{EWPR}_{\text{full-custo}}$ variaram entre 1,12 e 1,19 para o tratamento R100 utilizando o gotejador NaanSlim 0,3. Os

valores menores referem-se aos tratamentos com maior déficit hídrico (menor aplicação de irrigação) devido a menor produtividade observada em consequência do maior déficit de irrigação aplicado.

Para a condição de maior espaçamento entre linhas laterais, espaçamento de 1,35 cm (Tabela 4), os valores de EWPR_{full custo} de todos os tratamentos foram mais elevados, devido a redução no custo fixo anual com linhas laterais. Nas condições de preços de comercialização e custos de produção avaliados, somente o tratamento sem déficit hídrico (R100) apresentou valores mais elevados ou próximo a 1 para os tubos gotejadores NaanSlim. Quando o preço do milho aumentou para R\$ 0,50 Kg⁻¹, alguns tratamentos apresentaram rendimentos positivos, mesmo para os tratamentos com irrigação deficitária. Nesta condição, observou-se valores de EWPR_{full-custo} superiores a 1 para os tratamentos R100, R80 e R55, para o ano agrícola de 2010/11 e R100, R80 e R65, para o ano agrícola de 2011/12, utilizando-se o gotejadores NaanSlim. A utilização do tubo gotejador NaanTif somente foi viável para a condição do tratamento R100 e com o preço de comercialização do milho incrementado em 25%. Entretanto, para o cenário em que o preço de comercialização do milho foi reduzido para R\$ 0,30 kg⁻¹, todas as alternativas apresentam um retorno econômico negativo, mesmo após a redução do custo fixo anual das linhas laterais. Esses resultados indicam que, os resultados econômicos são particularmente sensíveis aos preços de comercialização das commodities, como observado por Rodrigues et al. (2010).

Os resultados demonstram que a viabilidade econômica da irrigação deficitária na irrigação por gotejamento é extremamente dependente dos preços das commodities e do custo de aquisição das linhas laterais, pois esse custo representa o maior componente do custo da irrigação por gotejamento. O aumento do espaçamento entre linhas laterais de 0,90 m para 1,35 m ocasiona uma redução de aproximadamente 33% no custo total das linhas laterais. e consequentemente em aumento do EWPR_{full-custo} atingindo situações de rendimento positivo.

O baixo retorno econômico observado provavelmente está associado ao elevado custo de instalação do sistema de irrigação por gotejamento, principalmente pelo alto custo das linhas laterais e por sua reduzida vida útil. Devido a este custo elevado, em muitos casos, a irrigação por gotejamento para culturas semeadas em linha e com espaçamento reduzido, a exemplo do milho, não tem sido considerada uma alternativa viável. No entanto, o aumento no espaçamento entre linhas laterais de tubos gotejadores é o fator mais importante para reduzir os elevados custos da irrigação por gotejamento (Lamm et al., 1997; Bozkurt et al., 2006). Os custos da tubulação lateral representam aproximadamente de 45% do custo total de um sistema de irrigação para a cultura do milho, e a substituição de uma linha lateral de gotejamento por linha de cultivo para duas linhas de cultivo por linha de gotejamento, resulta em uma considerável redução nos custos (Bozkurt et al., 2006).

Os custos da irrigação por gotejamento são diretamente proporcionais ao número de emissores, ou o espaçamento entre emissores ao longo das linhas laterais e, principalmente ao espaçamento entre laterais (Colombo & Or, 2006). Henggeler (1995) relata que linhas de gotejamento com um espaçamento de 1 m aumentam o custo do sistema em aproximadamente 40% quando comparado ao espaçamento de 2 m. Couto et al. (2013), testando espaçamentos de 1,10 m e 1,65 m para a cultura do milho, cultivada em espaçamento entre linha de 0,55 m não encontraram diferenças significativas na produtividade e recomendam a utilização de um espaçamento de 1,65 m por ser mais econômico.

Neste estudo foi realizada uma análise de sensibilidade utilizando o preço de comercialização do milho de ($R\$ 0,40 \text{ Kg}^{-1}$) e considerando três cenários de alteração do custo de irrigação: um cenário que representou a condição atual de custos de irrigação e outros dois com um aumento/diminuição dos custos da irrigação em -25% e +25% para os gotejadores utilizados neste estudo. Na Tabela 5 são apresentados os resultados da variação do $\text{EWPR}_{\text{Full}}^{\text{cust}}$ considerando as alterações no custo da irrigação, para as quatro combinações de tubos

gotejadores, no espaçamento entre laterais de 0,90 m. Com a redução dos custos da irrigação em 25%, somente o tratamento R100 apresentou um $EWPR_{Full\ cust}$ maior que 1, utilizando o gotejador Naanslim com espaçamento entre emissores de 0,30 m. Com o aumento dos custos de irrigação em 25% os resultados de $EWPR_{Full\ cust}$ foram menores, e nenhum tratamento apresentou viabilidade econômica.

Quando foi aumentado o espaçamento entre linhas de gotejadores para 1,35 m (Tabela 6) e consequentemente, reduzido os custos de irrigação em 25%, os tratamentos R100 e R80 com os tubos gotejadores NaanSlin 0,2 e NaanSlim 0,3 apresentam $EWPR_{Full\ cust}$ superior a 1. Os demais tratamentos apresentam $EWPR_{Full\ cust}$ inferior a 1, mesmo para a condição de redução em 25% do custo da irrigação. Na situação de preços de comercialização do milho a irrigação deficitária utilizando o sistema de irrigação por gotejamento não é uma alternativa economicamente viável. Uma maneira para viabilizar esta tecnologia é a diluição dos custos anuais fixos do sistema de irrigação, com a utilização de uma outra cultura irrigada cultivada em segunda safra. Resultados de simulação econômica da rotação de culturas irrigadas apresentados por Rosa (2004) demonstram que a utilização de rotação de culturas com dois cultivos no verão apresentam maior receita líquida do que sistemas com um único cultivo no verão.

Os resultados econômicas avaliados de utilização dos tubos gotejadores NaanTif, neste experimento, não apresentam viabilidade econômica, independentemente do espaçamento entre as linhas laterais de gotejadores (0,9 e 1,35m) e/ou com a redução dos custos relacionados a irrigação em 25%. Isto ocorre devido ao seu elevado custo inicial de instalação e pela reduzida vida útil especificada pelo fabricante.

Conclusões

1. Nas condições consideradas neste estudo os tratamentos com irrigação deficitária apresentam produtividade inferior à irrigação plena, entretanto, apresenta uma maior produtividade da água, para a cultura do milho irrigado por gotejamento.

2. A adoção da irrigação deficitária na cultura do milho irrigado por gotejamento não apresenta viabilidade econômica nas condições atuais de preço de comercialização milho de utilizado neste estudo, porém um aumento do preço de comercialização do milho em 25% torna-se viável para déficits com reposição de 80% da evapotranspiração .

3. A viabilidade econômica da irrigação deficitária por gotejamento está dependente do custo fixo de aquisição das linhas laterais, do espaçamento entre as linhas de gotejamento e do preço de comercialização do milho.

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Tabela 1 - Componentes do balanço hídrico para a cultura do milho nos diferentes tratamentos para os anos agrícolas de 2010/2011 e 2011/2012, produção de grãos e produtividade da água. Santa Maria, RS.

Tratamento	I	Pe	Dr	Ru	De	ET _a	E	T	ET _m	Produção	WP
					(mm)					Kg/ha	Kg m ⁻³
2010/11											
R100	389	72	86	2	3	365	34	331	365	9190 a	1,99 b
R80	316	72	33	2	19	361	31	330	361	8340 a	2,15 b
R55	218	72	24	2	89	342	29	313	342	7650 b	2,64 a
R30	113	72	22	2	118	272	25	247	328	5312 c	2,87 a
2011/12											
R100	433	75	78	0	92	525	47	478	538	8888 a	1,75 c
R80	350	75	57	0	100	504	42	462	533	8456 ab	1,99 b
R65	280	75	12	0	111	452	39	413	530	7628 b	2,15 b
R55	240	75	12	0	110	406	32	374	488	6742 b	2,14 b
R45	195	75	12	0	118	385	36	348	505	6262 bc	2,32 a
R40	175	75	12	0	121	352	33	319	501	6174 bc	2,47 a

Letras que diferem na coluna indicam diferença significativa pelo teste Tukey em nível de 5% de probabilidade de 5% de probabilidade de erro; I= irrigação; Pe=precipitação efetiva; Dr= drenagem; Ru= escoamento superficial; De= Depleção de água na zona radicular; ET_a= Evapotranspiração atual; E= evaporação; T=transpiração; ET_m= Evapotranspiração máxima; WP= Produtividade da água; R100 reposição de 100 % da ET_c; R80 reposição de 80 % da ET_c; R65 reposição de 65 % da ET_c; R55 reposição de 55 % da ET_c; R45 reposição de 45 % da ET_c; R40 reposição de 40 % da ET_c e R30 reposição de 30 % da ET_c.

Tabela 2 - Custo de produção para a cultura do milho (R\$/ha) para os anos agrícolas de 2010/11 e 2011/12. Custos relacionados à irrigação para cada tratamento e custos das diferentes alternativas de tubos gotejadores em (R\$/ha). Santa Maria, RS.

CUSTOS	Custos de Produção		Custo Relacionados à irrigação			
	2010/11	2011/12	Tratamento	Água e energia	Tubo gotejador	Espaçamento Linha laterais (m)
Terra	361,5	363,0	Ano agrícola 2010/11			0,9 1,35
Benfeitorias	58,0	59,6	R100	112,3	NaanSlim 0.2	1750,0 1150,0
Máquinas e implementos	141,7	144,4	R80	91,3	NaanSlim 0.3	1470,0 970,0
Manutenção	61,2	62,7	R55	63,0	NaanTif 0.2	3050,0 2000,0
Total Custo Fixo	622,5	629,6	R30	32,6	Naantif 0.3	2650,0 1750,0
Mão de obra	49,5	57,6	Ano agrícola 2011/12			
Insumos	1005,0	1120,6	R100	125,0		
Máquinas e implementos	206,1	212,1	R80	101,1		
Transporte	81,0	59,4	R65	80,9		
Armazenagem	143,1	142,6	R55	69,3		
Administrativas	54,7	38,7	R45	56,3		
Custo alternativo	88,6	91,3	R40	50,5		
Assistência técnica	21,9	25,8				
Total Custo Variável	1649,8	1748,0				
Custo de produção	2272,3	2377,7				

R100 reposição de 100 % da ET_c; R80 reposição de 80 % da ET_c; R65 reposição de 65 % da ET_c; R55 reposição de 55 % da ET_c; R45 reposição de 45 % da ET_c; R40 reposição de 40 % da ET_c e R30 reposição de 30 % da ET_c

Tabela 3 - Análise de sensibilidade do índice de produtividade econômico da água, quando se considerando o custo total de cultivo (EWPR_{full custo}) para a cotação do milho e as opções de tubos gotejadores com linhas espaçadas em 0,9 m, nos anos agrícolas de 2010/11 e 2011/12. Santa Maria, RS.

Ano	Tratamento	Naanslim 0,2	Naanslim 0,3	Naantif 0,2	Naantif 0,3
R\$ 0,30 Kg Milho					
2010/11	R100	0,67	0,72	0,51	0,55
	R80	0,61	0,65	0,46	0,50
	R55	0,56	0,60	0,43	0,46
	R30	0,39	0,42	0,30	0,32
2011/12	R100	0,63	0,67	0,48	0,52
	R80	0,60	0,64	0,46	0,49
	R65	0,54	0,58	0,42	0,45
	R55	0,48	0,52	0,37	0,40
	R45	0,45	0,48	0,34	0,37
	R40	0,44	0,48	0,34	0,36
R\$ 0,40 Kg Milho (valor atual)					
2010/11	R100	0,89	0,95	0,68	0,73
	R80	0,81	0,87	0,62	0,67
	R55	0,75	0,80	0,57	0,61
	R30	0,52	0,56	0,40	0,43
2011/12	R100	0,84	0,89	0,64	0,69
	R80	0,80	0,86	0,61	0,66
	R65	0,72	0,78	0,55	0,60
	R55	0,64	0,69	0,49	0,53
	R45	0,60	0,64	0,46	0,49
	R40	0,59	0,63	0,45	0,49
R\$ 0,50 Kg Milho					
2010/11	R100	1,11	1,19	0,85	0,91
	R80	1,01	1,09	0,77	0,83
	R55	0,94	1,01	0,71	0,77
	R30	0,66	0,70	0,50	0,54
2011/12	R100	1,04	1,12	0,80	0,86
	R80	1,00	1,07	0,76	0,82
	R65	0,91	0,97	0,69	0,75
	R55	0,80	0,86	0,61	0,66
	R45	0,75	0,80	0,57	0,62
	R40	0,74	0,79	0,56	0,61

R100 reposição de 100 % da ET_c; R80 reposição de 80 % da ET_c; R65 reposição de 65 % da ET_c; R55 reposição de 55 % da ET_c; R45 reposição de 45 % da ET_c; R40 reposição de 40 % da ET_c e R30 reposição de 30 % da ET_c

Tabela 4 - Análise de sensibilidade do índice de produtividade econômica da água, quando se considerando o custo total de cultivo (EWPR_{full custo}) para a cotação do preço de comercialização do milho e as opções de tubos gotejadores com linhas espaçadas em 1,35m, nos anos agrícolas de 2010/11 e 2011/12. Santa Maria, RS.

Ano	Tratamento	Naanslim 0,2	Naanslim 0,3	Naantif 0,2	Naantif 0,3
R\$ 0,30 Kg Milho					
2010/11	R100	0,78	0,82	0,63	0,67
	R80	0,71	0,75	0,57	0,61
	R55	0,66	0,69	0,53	0,56
	R30	0,46	0,49	0,37	0,39
2011/12	R100	0,73	0,77	0,59	0,63
	R80	0,70	0,74	0,57	0,60
	R65	0,63	0,67	0,51	0,54
	R55	0,56	0,59	0,45	0,48
	R45	0,52	0,55	0,42	0,45
	R40	0,52	0,55	0,42	0,44
R\$ 0,40 Kg Milho (valor atual)					
2010/11	R100	1,04	1,10	0,84	0,89
	R80	0,95	1,00	0,76	0,81
	R55	0,88	0,93	0,71	0,75
	R30	0,61	0,65	0,49	0,52
2011/12	R100	0,97	1,02	0,79	0,84
	R80	0,93	0,98	0,76	0,80
	R65	0,85	0,89	0,68	0,72
	R55	0,75	0,79	0,61	0,64
	R45	0,70	0,74	0,56	0,60
	R40	0,69	0,73	0,56	0,59
R\$ 0,50 Kg Milho					
2010/11	R100	1,30	1,37	1,05	1,11
	R80	1,19	1,25	0,96	1,01
	R55	1,10	1,16	0,88	0,94
	R30	0,77	0,81	0,62	0,66
2011/12	R100	1,22	1,28	0,99	1,04
	R80	1,17	1,23	0,94	1,00
	R65	1,06	1,11	0,86	0,91
	R55	0,94	0,99	0,76	0,80
	R45	0,87	0,92	0,71	0,75
	R40	0,86	0,91	0,70	0,74

R100 reposição de 100 % da ET_c; R80 reposição de 80 % da ET_c; R65 reposição de 65 % da ET_c; R55 reposição de 55 % da ET_c; R45 reposição de 45 % da ET_c; R40 reposição de 40 % da ET_c e R30 reposição de 30 % da ET_c

Tabela 5 - Análise de sensibilidade do índice de produtividade econômico da água, quando se considerando o custo total de cultivo (EWPR_{full custo}) para o preço de comercialização atual do milho e as opções de tubos gotejadores com linhas espaçadas em 0,9 metros, nos anos agrícolas de 2010/11 e 2011/12, considerando alteração no custo relacionado a irrigação. Santa Maria, RS.

Ano	Tratamento	Naanslim 0,2	Naanslim 0,3	Naantif 0,2	Naantif 0,3
Redução em 25% do custo relacionado a irrigação					
2010/11	R100	1,00	1,06	0,79	0,85
	R80	0,91	0,97	0,72	0,77
	R55	0,84	0,89	0,66	0,71
	R30	0,59	0,63	0,46	0,50
2011/12	R100	0,94	1,00	0,75	0,80
	R80	0,90	0,95	0,71	0,76
	R65	0,81	0,86	0,65	0,69
	R55	0,72	0,76	0,57	0,61
	R45	0,67	0,71	0,53	0,57
	R40	0,66	0,70	0,53	0,56
Custo relacionado a irrigação (valor atual)					
2010/11	R100	0,89	0,95	0,68	0,73
	R80	0,81	0,87	0,62	0,67
	R55	0,75	0,80	0,57	0,61
	R30	0,52	0,56	0,40	0,43
2011/12	R100	0,84	0,89	0,64	0,69
	R80	0,80	0,86	0,61	0,66
	R65	0,72	0,78	0,55	0,60
	R55	0,64	0,69	0,49	0,53
	R45	0,60	0,64	0,46	0,49
	R40	0,59	0,63	0,45	0,49
Aumento em 25% do custo relacionado a irrigação					
2010/11	R100	0,80	0,86	0,59	0,64
	R80	0,73	0,79	0,54	0,59
	R55	0,67	0,73	0,50	0,54
	R30	0,47	0,51	0,35	0,38
2011/12	R100	0,75	0,81	0,56	0,61
	R80	0,72	0,78	0,54	0,58
	R65	0,65	0,71	0,49	0,53
	R55	0,58	0,63	0,43	0,47
	R45	0,54	0,58	0,40	0,44
	R40	0,53	0,58	0,40	0,43

R100 reposição de 100 % da ET_c; R80 reposição de 80 % da ET_c; R65 reposição de 65 % da ET_c; R55 reposição de 55 % da ET_c; R45 reposição de 45 % da ET_c; R40 reposição de 40 % da ET_c e R30 reposição de 30 % da ET_c

Tabela 6 - Análise de sensibilidade do índice de produtividade econômico da água, quando se considerando o custo total de cultivo (EWPR_{full custo}) para o preço de comercialização do milho e as opções de tubos gotejadores com linhas espaçadas a 1,35metros, nos anos agrícolas de 2010/11 e 2011/12, considerando alterações nos custos relacionados a irrigação. Santa Maria, RS.

Ano	Tratamento	Naanslim 0,2	Naanslim 0,3	Naantif 0,2	Naantif 0,3
Redução em 25% do custo relacionado a irrigação					
2010/11	R100	1,14	1,19	0,95	1,00
	R80	1,04	1,09	0,87	0,91
	R55	0,96	1,00	0,80	0,84
	R30	0,67	0,70	0,56	0,59
2011/12	R100	1,07	1,11	0,90	0,94
	R80	1,02	1,06	0,86	0,90
	R65	0,92	0,96	0,77	0,81
	R55	0,82	0,85	0,69	0,72
	R45	1,14	1,19	0,95	1,00
	R40	1,04	1,09	0,87	0,91
Custo relacionado a irrigação (valor atual)					
2010/11	R100	1,04	1,10	0,84	0,89
	R80	0,95	1,00	0,76	0,81
	R55	0,88	0,93	0,71	0,75
	R30	0,61	0,65	0,49	0,52
2011/12	R100	0,97	1,02	0,79	0,84
	R80	0,93	0,98	0,76	0,80
	R65	0,85	0,89	0,68	0,72
	R55	0,75	0,79	0,61	0,64
	R45	0,70	0,74	0,56	0,60
	R40	0,69	0,73	0,56	0,59
Aumento em 25% do custo relacionado a irrigação					
2010/11	R100	0,95	1,01	0,75	0,80
	R80	0,87	0,93	0,68	0,73
	R55	0,81	0,86	0,63	0,67
	R30	0,57	0,60	0,44	0,47
2011/12	R100	0,90	0,95	0,71	0,75
	R80	0,86	0,91	0,68	0,72
	R65	0,78	0,83	0,61	0,65
	R55	0,69	0,73	0,54	0,58
	R45	0,64	0,68	0,51	0,54
	R40	0,64	0,68	0,50	0,53

R100 reposição de 100 % da ET_c; R80 reposição de 80 % da ET_c; R65 reposição de 65 % da ET_c; R55 reposição de 55 % da ET_c; R45 reposição de 45 % da ET_c; R40 reposição de 40 % da ET_c e R30 reposição de 30 % da ET_c

DISCUSSÃO

Neste trabalho foi realizado um estudo da viabilidade econômica da irrigação deficitária na cultura do milho no Rio Grande do Sul, utilizando diferentes sistemas de irrigação. Inicialmente realizou-se uma calibração e validação do modelo SimDualKc (Artigo I). O modelo SimDualKc (Rosa et al., 2012 a;b) utiliza a abordagem dos coeficientes de cultivos duais proposta por Allen et al. (1998, 2005). Esta metodologia considera separadamente a transpiração da cultura e a evaporação de água no solo para a determinação da evapotranspiração da cultura (ETc), através do coeficiente de cultivo basal (K_{cb}) e do coeficiente de evaporação do solo (K_e). Isto permitiu analisar com precisão a maneira como a precipitação e a água da irrigação foi utilizada pela cultura do milho.

O modelo SIMDualKc foi testado utilizando dados de experimentos com milho irrigado por aspersão e gotejamento, utilizando diferentes tratamentos de irrigação plena e deficitária. A avaliação consistiu em comparar os resultados do modelo com observações de campo da quantidade de água disponível no solo (ASW). Os resultados indicam que o modelo foi capaz de simular o conteúdo de água no solo de um cultivo de milho, usando a abordagem dos coeficientes de cultivo duais nas diferentes condições hídricas avaliadas a nível de campo. As simulações efetuadas com o modelo SIMDualKc demonstram uma boa concordância com os dados observados no campo. Os indicadores estatísticos utilizados para avaliar a capacidade do modelo para simular a água disponível no solo demonstraram que o modelo não apresentou qualquer tendência de sobre ou subestimar o conteúdo de água no solo durante as fases de desenvolvimento da cultura.

O modelo permitiu a determinação K_{cb} e observou-se que este parâmetro foi idêntico para os sistemas de irrigação por aspersão e gotejamento. Portanto, os parâmetros de culturas determinados neste trabalho podem ser usados em outros lugares no Sul do Brasil. Outros parâmetros do solo como o total de água evaporável, a água facilmente evaporável e a fração de depleção para não causar deficit hídrico, podem ser extrapolados para outros locais usando abordagens compatíveis com as do presente estudo. O modelo pode ser aplicado efetivamente na utilização dos coeficientes de cultivos duais para avaliar o uso da água de irrigação. Os resultados demonstraram que o modelo pode simular e avaliar diferentes situações e mudanças nos componentes do balanço hídrico, como a adoção de diferentes lâminas de irrigação. A evaporação do solo é um componente importante de ETc durante a fase inicial de desenvolvimento da cultura. No entanto, o valor da evaporação relativo a ETc é altamente

influenciado pelo resíduo vegetal depositado na superfície do solo. Após a etapa inicial, a evaporação do solo diminui progressivamente até se tornar quase insignificante devido aos efeitos adicionais de cobertura do resíduo, do desenvolvimento da cultura e da baixa energia disponível na superfície do solo. A relação da E_s/ET_c variou de 6 a 9% entre os tratamentos, demonstrando a importância dos resíduos vegetais na redução da evaporação do solo. Apesar dos resultados serem adequados, há a necessidade de aprofundar os trabalhos de pesquisa nessa área, com mais experimentos instalados em nível de campo, para avaliar os impactos dos resíduos vegetais na evaporação do solo, considerando os diferentes tipos e graus de decomposição da cobertura vegetal. Além disso, o modelo SIMDualKc deve ser melhorado para incluir uma rotina que caracterize esse armazenamento adicional que representa a cobertura do resíduo, para ser possível modelar as perdas de água por evaporação de uma cobertura morta.

A viabilidade econômica da irrigação deficitária foi testada (Artigo II e III), utilizando diferentes sistemas de irrigação e cenários de variação de preços e custos de produção, adotando indicadores de produção e econômicos para avaliação dos resultados. Este estudo demonstrou que os indicadores de uso de água, tanto econômicos, quanto os de produtividade podem ser ferramentas adequadas para avaliar os impactos da irrigação deficitária. Comparar a produtividade da água em diferentes cenários de restrição de água podem também auxiliar na análise da viabilidade da irrigação deficitária. O índice de produtividade econômica da água $EWPR_{full-cost}$, relacionando os valores de rendimento por unidade de custos agrícolas, revelou-se adequado para avaliar a viabilidade da irrigação deficitária.

Os resultados demonstram que a adoção de uma estratégia de irrigação deficitária para a cultura do milho resulta em maior produtividade do total de água (WP) utilizada na produção, e aumenta (WP_{Irrig}) quando utiliza somente a água da irrigação em comparação os tratamentos com irrigação deficitária e com a irrigação plena. Isto é, particularmente, evidente para WP_{Irrig} , pois está dependente apenas da utilização da água de irrigação.

A viabilidade da irrigação deficitária é extremamente dependente do preço de comercialização do milho e do custo fixo anual do sistema de irrigação, enquanto diferenças nos custos de água, eletricidade e mão de obra relacionada à irrigação ocasionou reduzido impacto nos resultados econômicos. Este comportamento deve-se basicamente à estrutura de preços vigente na cadeia produtiva do milho e da irrigação. Como o custo da água é mínimo ou mesmo zero pela grande oferta de água e pelo incipiente sistema de cobrança pelo uso da água, os resultados econômicos da implementação da irrigação deficitária não são

expressivos. Por outro lado, os impactos de uma possível taxa ou tarifa pelo uso dos recursos hídricos, ou uma tributação por unidade de água aplicada, teria um impacto relativamente pequeno na produtividade econômico da água. No entanto, levando-se em consideração a volatilidade dos preços no mercado, a aplicação desta tarifa pode ocasionar impactos negativos quando aplicados em regiões com escassez de água. Neste caso, o impacto na EWPR_{full-cost} não pode ser desconsiderada.

A utilização da irrigação deficitária em sistemas de irrigação por pivô central a partir de projetos que procuram melhorar a eficiência de irrigação, torna-se uma alternativa recomendável. No entanto, apesar da melhoria da produtividade da água (WP) e da produtividade econômica da água (EWP) em aproximadamente 11%, os resultados não permitiram conclusões definitivas sobre a adequação do uso do pivô central para irrigação deficitária. Especialmente, levando em consideração os impactos dos preços de comercialização do milho e do custo de produção, a não ser apenas se um déficit hídrico leve for adotado e com ocorrência de precipitações pluviais frequentes. A viabilidade da utilização da irrigação deficitária em pivô central para períodos com baixa precipitação pluvial ainda é incerto, necessitando a realização de mais estudos.

No caso da irrigação por gotejamento (Artigo III), os resultados indicaram não existir viabilidade econômica para a irrigação deficitária. Considerando a irrigação plena, verificou-se que a irrigação só é viável para cenários de aumento do preço do milho e uma redução dos custos relacionados a irrigação, devido ao elevado custo fixo anual do sistema de gotejamento.

Os resultados indicaram que, de maneira geral a viabilidade econômica da irrigação deficitária em milho depende basicamente das oscilações dos preços no mercado, da uniformidade de aplicação dos sistemas de irrigação, da variabilidade dos custos de produção e dos custos relacionados à irrigação, além da distribuição das precipitações pluviais durante o desenvolvimento da cultura. Esta avaliação demonstra que a análise da irrigação deficitária e, consequente definição de métodos adequados para a sua viabilidade, requer não apenas o conhecimento da estrutura dos custos de produção, mas, principalmente deve incluir os impactos da flutuação dos custos e desempenho do sistemas de irrigação e a rentabilidade das culturas.

CONCLUSÃO

A viabilidade econômica da irrigação deficitária em milho dependerá das oscilações dos preços do milho no mercado e da variabilidade dos custos de produção. A adoção da irrigação deficitária aumenta a produtividade da água e da produtividade de água utilizada na irrigação.

A utilização da irrigação deficitária na cultura do milho em sistemas de irrigação por pivô central é recomendável somente como irrigação suplementar as precipitações pluviais. A melhoria da eficiência de irrigação aumenta a produtividade da água e a viabilidade econômica do sistema pivô central.

Em sistemas de irrigação por gotejamento a irrigação deficitária para a cultura do milho não pode ser recomendada devido ao alto custo fixo de aquisição das linhas laterais, e está dependente do espaçamento entre as linhas de gotejamento e do preço de comercialização do milho.

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ANEXOS

Anexo A

Estilos e normas de citações e referências bibliográficas conforme as normas da revista Biosystems Engineering

Types of paper

There are three types of paper. The inclusion of figures and tables will reduce the allowable number of words and 250 words should be allowed for each such figure or table.

1. Research papers(Full length Articles)

These are the normal type of paper published and make up the main bulk of the Journal. They should not normally exceed seven Journal pages, that is, about 5500 words.

2. Research notes(Short Communications)

These enable important findings to be speedily communicated and facilitate the reporting of work not meriting a full length paper. They should not exceed two Journal pages, that is, about 1500 words.

3. Review papers

These are intended to be in-depth studies of the state-of-the-art in the chosen subject. They should not normally exceed 10 Journal pages, that is, about 8000 words.

Guide for authors

Subdivision - numbered sections

Divide your article into clearly defined and numbered sections. Subsections should be numbered

1.1 (then 1.1.1, 1.1.2, ...), 1.2, etc. (the abstract is not included in section numbering).

Use this numbering also for internal cross-referencing: do not just refer to 'the text'. Any subsection may be given a brief heading. Each heading should appear on its own separate line.

Introduction: State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

Material and methods: Provide sufficient detail to allow the work to be reproduced. Methods already published should be indicated by a reference: only relevant modifications should be described.

Theory/calculation: A Theory section should extend, not repeat, the background to the article already dealt with in the Introduction and lay the foundation for further work. In contrast, a Calculation section represents a practical development from a theoretical basis.

Results: Results should be clear and concise.

Discussion: This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

Conclusions: The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

Appendices: If there is more than one appendix, they should be identified as A, B, etc. Formulae and equations in appendices should be given separate numbering: Eq. (A.1), Eq. (A.2), etc.; in a subsequent appendix, Eq. (B.1) and so on. Similarly for tables and figures: Table A.1; Fig. A.1, etc.

Essential title page information

Title: Concise and informative. Titles are often used in information-retrieval systems. Avoid

abbreviations and formulae where possible.

Author names and affiliations: Where the family name may be ambiguous (e.g., a double name), please indicate this clearly. Present the authors' affiliation addresses (where the actual work was done) below the names. Indicate all affiliations with a lower-case superscript letter immediately after the author's name and in front of the appropriate address. Provide the full postal address of each affiliation, including the country name and, if available, the e-mail address of each author.

Abstract: A concise and factual abstract is required. The abstract should state briefly the purpose of the research, the principal results and major conclusions. It should not exceed 250 words. An abstract is often presented separately from the article, so it must be able to stand alone. For this reason, References should be avoided, but if essential, then cite the author(s) and year(s). Also, non-standard or uncommon abbreviations should be avoided, but if essential they must be defined at their first mention in the abstract itself.

Keywords: Immediately after the abstract provide a maximum of 6 keywords, using UK spelling and avoiding general and plural terms and multiple concepts (avoid, for example,

"and", "of"). Be sparing with abbreviations: only abbreviations firmly established in the field may be eligible. These keywords will be used for indexing purposes.

Symbols and abbreviations: Define all symbols that are used in the document in a Nomenclature table placed before the introduction and also give the units. In choosing symbols, please seek to ensure that the same symbol or subscript/superscript is not given more than one meaning in the text. Abbreviations that are not standard in this research field should also be included in the Nomenclature. Where possible please avoid the use of symbols and abbreviations in the abstract. Both symbols and abbreviations must be defined at their first use in the text, as well as in the Nomenclature. Ensure consistency of abbreviations throughout the article. Please use SI units only. It is not necessary to give the SI unit and (say) its Imperial equivalent. Engineering Notation, where units are in multiples of 1,000, should be used. Thus, we wish to see the use of mm and m and not cm.

Math formulae: Present simple formulae in the line of normal text where possible and use the exponent form (e.g. $m s^{-1}$ not m/s). In principle, variables are to be presented in italics. Powers of e are often more conveniently denoted by exp. Number consecutively any equations that have to be displayed separately from the text (if referred to explicitly in the text).

Footnotes: Footnotes should be used sparingly. Number them consecutively throughout the article, using superscript Arabic numbers. Many wordprocessors build footnotes into the text, and this feature may be used. Should this not be the case, indicate the position of footnotes in the text and present the footnotes themselves separately at the end of the article. Do not include footnotes in the Reference list.

Table footnotes: Indicate each footnote in a table with a superscript lowercase letter.

Tables

Number tables consecutively in accordance with their appearance in the text. Place footnotes to tables below the table body and indicate them with superscript lowercase letters. Avoid vertical rules. Be sparing in the use of tables and ensure that the data presented in tables do not duplicate results described elsewhere in the article.

References

Citation in text

Please ensure that every reference cited in the text is also present in the reference list (and vice versa). Any references cited in the abstract must be given in full. Unpublished results and personal communications are not recommended in the reference list, but may be mentioned in the text. If these references are included in the reference list they should follow the standard reference style of the journal and should include a substitution of the publication date with either 'Unpublished results' or 'Personal communication'. Citation of a reference as 'in press' implies that the item has been accepted for publication.

Web references

As a minimum, the full URL should be given and the date when the reference was last accessed. Any further information, if known (DOI, author names, dates, reference to a source publication, etc.), should also be given. Web references can be listed separately (e.g., after the reference list) under a different heading if desired, or can be included in the reference list.

Reference style

Text: Citations in the text should follow the referencing style used by the American Psychological Association. You are referred to the Publication Manual of the American Psychological Association, Sixth Edition, ISBN 1-4388-0559-6, copies of which may be ordered from <http://books.apa.org/books.cfm?id=4200067> or APA Order Dept., P.O.B. 2710, Hyattsville, MD 20784, USA or APA, 3 Henrietta Street, London, WC3E 8LU, UK. Details concerning this referencing style can also be found at <http://humanities.byu.edu/linguistics/Henrichsen/APA/APA01.html>.

List: references should be arranged first alphabetically and then further sorted chronologically if necessary. More than one reference from the same author(s) in the same year must be identified by the letters "a", "b", "c", etc., placed after the year of publication.

Examples:

Reference to a journal publication:

Van der Geer, J., Hanraads, J. A. J., & Lupton R. A. (2000). The art of writing a scientific article. *Journal of Scientific Communications*, 163, 51-59.

Reference to a book:

Strunk, W., Jr., & White, E. B. (1979). *The elements of style*. (3rd ed.). New York: Macmillan, (Chapter 4).

Reference to a chapter in an edited book:

Mettam, G. R., & Adams, L. B. (1994). How to prepare an electronic version of your article. In B. S. Jones, & R. Z. Smith (Eds.), *Introduction to the electronic age* (pp. 281-304). New York: E-Publishing Inc.

For APA style references in the text the following rules apply (note the use of .and. and .&):

- For publications by one author, when the name is mentioned in the text, use [...] Smith (1999)
 - [...]; when the name is not directly part of the text use [...] (Smith, 1999).
- For publications by two authors, when the names are mentioned in the text, use [...] Smith and Jones (1999) [...]; when the names are not part of the text use [...] (Smith & Jones, 1999).
- For publications by three to five authors, when the names are mentioned in the text, use [...] Smith, Jones, White, and Brown (1999) [...]; when the names are not mentioned use [...] (Smith, Jones, White, Brown, 1999) for the first instance the reference is mentioned. For subsequent references use Smith et al. 1999. For subsequent references within the same paragraph the year may be omitted.
- For publications by more than five authors, when the names are mentioned in the text, use [...] Smith et al. (1999) [...]; when the names are not mentioned use [...] (Smith et al., 1999).
 - For references with the same first author and year, cite as many names of co-authors as are necessary to distinguish the two references (rather than using a and b after the year, as in other reference systems). Use a and b after the year only if all authors' names as well as the year are identical.
 - If just one name precedes it, no comma should appear before .and., .&. or .et al... In the other case a comma should appear.
 - For works without author, list the title of the work instead of the author.

Anexo B

Estilos e normas de citações e referência bibliográficas conforme as normas da revista Pesquisa Agropecuária Brasileira

Forma e preparação de manuscritos

O texto deve ser digitado no editor de texto Microsoft Word, em espaço duplo, fonte Times New Roman, corpo 12, folha formato A4, com margens de 2,5 cm e com páginas e linhas numeradas.

Organização do Artigo Científico

A ordenação do artigo deve ser feita da seguinte forma:

Artigos em português - Título, autoria, endereços institucionais e eletrônicos, Resumo, Termos para indexação, título em inglês, Abstract, Index terms, Introdução, Material e Métodos, Resultados e Discussão, Conclusões, Agradecimentos, Referências, tabelas e figuras.

O título, o resumo e os termos para indexação devem ser vertidos fielmente para o inglês, no caso de artigos redigidos em português e espanhol, e para o português, no caso de artigos redigidos em inglês.

O artigo científico deve ter, no máximo, 20 páginas, incluindo-se as ilustrações (tabelas e figuras), que devem ser limitadas a seis, sempre que possível.

Título

Deve representar o conteúdo e o objetivo do trabalho e ter no máximo 15 palavras, incluindo-se os artigos, as preposições e as conjunções. Deve ser grafado em letras minúsculas, exceto a letra inicial, e em negrito. Deve ser iniciado com palavras chaves e não com palavras como “efeito” ou “influência”.

Não deve conter nome científico, exceto de espécies pouco conhecidas; neste caso, apresentar somente o nome binário. Não deve conter subtítulo, abreviações, fórmulas e símbolos.

As palavras do título devem facilitar a recuperação do artigo por índices desenvolvidos por bases de dados que catalogam a literatura.

Resumo

O termo Resumo deve ser grafado em letras minúsculas, exceto a letra inicial, na margem esquerda, e separado do texto por travessão. Deve conter, no máximo, 200 palavras, incluindo números, preposições, conjunções e artigos.

Deve ser elaborado em frases curtas e conter o objetivo, o material e os métodos, os resultados e a conclusão. Não deve conter citações bibliográficas nem abreviaturas. O final do texto deve conter a principal conclusão, com o verbo no presente do indicativo.

Termos para indexação

A expressão Termos para indexação, seguida de dois-pontos, deve ser grafada em letras minúsculas, exceto a letra inicial. Os termos devem ser separados por vírgula e iniciados com letra minúscula. Devem ser no mínimo três e no máximo seis, considerando-se que um termo pode possuir duas ou mais palavras.

Não devem conter palavras que componham o título. Devem conter o nome científico (só o nome binário) da espécie estudada.

Introdução

A palavra Introdução deve ser centralizada e grafada com letras minúsculas, exceto a letra inicial, e em negrito. Deve apresentar a justificativa para a realização do trabalho, situar a importância do problema científico a ser solucionado e estabelecer sua relação com outros trabalhos publicados sobre o assunto. O último parágrafo deve expressar o objetivo de forma coerente com o descrito no início do Resumo.

Material e Métodos

A expressão Material e Métodos deve ser centralizada e grafada em negrito; os termos Material e Métodos devem ser grafados com letras minúsculas, exceto as letras iniciais. Deve ser organizado, de preferência, em ordem cronológica.

Deve apresentar a descrição do local, a data e o delineamento do experimento, e indicar os tratamentos, o número de repetições e o tamanho da unidade experimental. Deve conter a descrição detalhada dos tratamentos e variáveis e evitar o uso de abreviações ou as siglas.

Os materiais e os métodos devem ser descritos de modo que outro pesquisador possa repetir o experimento. Devem ser evitados detalhes supérfluos e extensas descrições de técnicas de uso corrente. Deve conter informação sobre os métodos estatísticos e as transformações de dados. Deve-se evitar o uso de subtítulos; quando indispensáveis, grafá-los em negrito, com letras minúsculas, exceto a letra inicial, na margem esquerda da página.

Resultados e Discussão

A expressão Resultados e Discussão deve ser centralizada e grafada em negrito, com letras minúsculas, exceto a letra inicial. Todos os dados apresentados em tabelas ou figuras devem ser discutidos. As tabelas e figuras são citadas sequencialmente. Os dados das tabelas e figuras não devem ser repetidos no texto, mas discutidos em relação aos apresentados por outros autores. Evitar o uso de nomes de variáveis e tratamentos abreviados.

Dados não apresentados não podem ser discutidos. Não deve conter afirmações que não possam ser sustentadas pelos dados obtidos no próprio trabalho ou por outros trabalhos citados. Não apresentar os mesmos dados em tabelas e em figuras.

Conclusões

O termo Conclusões deve ser centralizado e grafado em negrito, com letras minúsculas, exceto a letra inicial. Devem ser apresentadas em frases curtas, sem comentários adicionais, com o verbo no presente do indicativo. Devem ser elaboradas com base no objetivo do trabalho. Não podem consistir no resumo dos resultados. Devem apresentar as novas descobertas da pesquisa. Devem ser numeradas e no máximo cinco.

Referências

A palavra Referências deve ser centralizada e grafada em negrito, com letras minúsculas, exceto a letra inicial.

Devem ser de fontes atuais e de periódicos: pelo menos 70% das referências devem ser dos últimos 10 anos e 70% de artigos de periódicos. Devem ser normalizadas de acordo com a NBR 6023 da ABNT, com as adaptações descritas a seguir.

Devem ser apresentadas em ordem alfabética dos nomes dos autores, separados por ponto-e-vírgula, sem numeração e com os nomes de todos os autores da obra.

Devem conter os títulos das obras ou dos periódicos grafados em negrito e conter somente a obra consultada, no caso de citação de citação.

Todas as referências devem registrar uma data de publicação, mesmo que aproximada. Devem ser trinta, no máximo.

Exemplos:

Artigos de Anais de Eventos (aceitos apenas trabalhos completos)

AHRENS, S. A fauna silvestre e o manejo sustentável de ecossistemas florestais. In: SIMPÓSIO LATINO-AMERICANO SOBRE MANEJO FLORESTAL, 3., 2004, Santa Maria. Anais. Santa Maria: UFSM, Programa de Pós-Graduação em Engenharia Florestal, 2004. p.153-162.

Artigos de periódicos

SANTOS, M.A. dos; NICOLÁS, M.F.; HUNGRIA, M. Identificação de QTL associados à simbiose entre *Bradyrhizobium japonicum*, *B. elkanii* e soja. Pesquisa Agropecuária Brasileira, v.41, p.67-75, 2006.

Capítulos de livros

AZEVEDO, D.M.P. de; NÓBREGA, L.B. da; LIMA, E.F.; BATISTA, F.A.S.; BELTRÃO, N.E. de M. Manejo cultural. In: AZEVEDO, D.M.P.; LIMA, E.F. (Ed.). O agronegócio da mamona no Brasil. Campina Grande: Embrapa Algodão; Brasília: Embrapa Informação Tecnológica, 2001. p.121-160.

Livros

OTSUBO, A.A.; LORENZI, J.O. Cultivo da mandioca na Região Centro-Sul do Brasil. Dourados: Embrapa Agropecuária Oeste; Cruz das Almas: Embrapa Mandioca e Fruticultura, 2004. 116p. (Embrapa Agropecuária Oeste. Sistemas de produção, 6).

Teses

HAMADA, E. Desenvolvimento fenológico do trigo (cultivar IAC 24 - Tucuruí), comportamento espectral e utilização de imagens NOAA-AVHRR. 2000. 152p. Tese (Doutorado) - Universidade Estadual de Campinas, Campinas.

Fontes eletrônicas

EMBRAPA AGROPECUÁRIA OESTE. Avaliação dos impactos econômicos, sociais e ambientais da pesquisa da Embrapa Agropecuária Oeste: relatório do ano de 2003. Dourados: Embrapa Agropecuária Oeste, 2004. 97p. (Embrapa Agropecuária Oeste. Documentos, 66). Disponível em: . Acesso em: 18 abr. 2006.

Citações

Não são aceitas citações de resumos, comunicação pessoal, documentos no prelo ou qualquer outra fonte, cujos dados não tenham sido publicados. A autocitação deve ser evitada. Devem ser normalizadas de acordo com a NBR 10520 da ABNT, com as adaptações descritas a seguir.

Redação das citações dentro de parênteses

Citação com um autor: sobrenome grafado com a primeira letra maiúscula, seguido de vírgula e ano de publicação. Citação com dois autores: sobrenomes grafados com a primeira letra maiúscula, separados pelo "e" comercial (&), seguidos de vírgula e ano de publicação. Citação com mais de dois autores: sobrenome do primeiro autor grafado com a primeira letra maiúscula, seguido da expressão et al., em fonte normal, vírgula e ano de publicação. Citação de mais de uma obra: deve obedecer à ordem cronológica e em seguida à ordem alfabética dos autores. Citação de mais de uma obra dos mesmos autores: os nomes destes não devem ser repetidos; colocar os anos de publicação separados por vírgula.

Citação de citação: sobrenome do autor e ano de publicação do documento original, seguido da expressão “citado por” e da citação da obra consultada. Deve ser evitada a citação de citação, pois há risco de erro de interpretação; no caso de uso de citação de citação, somente a obra consultada deve constar da lista de referências.

Redação das citações fora de parênteses

Citações com os nomes dos autores incluídos na sentença: seguem as orientações anteriores, com os anos de publicação entre parênteses; são separadas por vírgula.

Fórmulas, expressões e equações matemáticas

Devem ser iniciadas à margem esquerda da página e apresentar tamanho padronizado da fonte Times New Roman.

Não devem apresentar letras em itálico ou negrito, à exceção de símbolos escritos convencionalmente em itálico.

Tabelas

As tabelas devem ser numeradas seqüencialmente, com algarismo arábico, e apresentadas em folhas separadas, no final do texto, após as referências. Devem ser auto-explicativas. Seus elementos essenciais são: título, cabeçalho, corpo (colunas e linhas) e coluna indicadora dos tratamentos ou das variáveis. Os elementos complementares são: notas-de-rodapé e fontes bibliográficas.

O título, com ponto no final, deve ser precedido da palavra Tabela, em negrito; deve ser claro, conciso e completo; deve incluir o nome (vulgar ou científico) da espécie e das variáveis dependentes. No cabeçalho, os nomes das variáveis que representam o conteúdo de cada coluna devem ser grafados por extenso; se isso não for possível, explicar o significado das abreviaturas no título ou nas notas-de-rodapé.

Todas as unidades de medida devem ser apresentadas segundo o Sistema Internacional de Unidades. Nas colunas de dados, os valores numéricos devem ser alinhados pelo último algarismo. Na comparação de médias de tratamentos são utilizadas, no corpo da tabela, na coluna ou na linha, à direita do dado, letras minúsculas ou maiúsculas, com a indicação em nota-de-rodapé do teste utilizado e a probabilidade.

Devem ser usados fios horizontais para separar o cabeçalho do título, e do corpo; usá-los ainda na base da tabela, para separar o conteúdo dos elementos complementares. Fios horizontais adicionais podem ser usados dentro do cabeçalho e do corpo; não usar fios verticais.

As tabelas devem ser editadas em arquivo Word, usando os recursos do menu Tabela; não fazer espaçamento utilizando a barra de espaço do teclado, mas o recurso recuo do menu Formatar Parágrafo.

Notas de rodapé das tabelas

Notas de fonte: indicam a origem dos dados que constam da tabela; as fontes devem constar nas referências. Notas de chamada: são informações de caráter específico sobre partes da tabela, para conceituar dados. São indicadas em algarismo arábico, na forma de expoente, entre parênteses, à direita da palavra ou do número, no título, no cabeçalho, no corpo ou na coluna indicadora. São apresentadas de forma contínua, sem mudança de linha, separadas por ponto.

Para indicação de significância estatística, são utilizadas, no corpo da tabela, na forma de expoente, à direita do dado, as chamadas ns (não-significativo); * e ** (significativo a 5 e 1% de probabilidade, respectivamente).