**University of São Paulo
“Luiz de Queiroz” College of Agriculture**

**Agricultural resource efficiency and reduction of impacts under land-
use and climate change scenarios in Brazil**

Ana Paula Schwantes

Thesis presented to obtain the degree of Doctor of
Science. Area: Crop Science

**Piracicaba
2017**

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I dedicate this thesis to
my parents, Noeli and Jair,
my sister, Fernanda,
and my fiancé, Felipe.

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RESUMO

Eficiência do uso de recursos e redução de impactos da atividade agrícola sob cenários de mudança de uso da terra e climática no Brasil

O Cerrado é o segundo maior bioma brasileiro que originalmente, correspondia a 24% do território nacional, e desde os anos 1970 tem sido utilizado para atividades ligadas à agricultura e pecuária. Soja e milho são duas das mais importantes culturas graníferas encontradas nesta região, com uma estimativa de produtividade de aproximadamente 223 milhoes de toneladas na safra brasileira de 2016/17. Mudanças nas propriedades físicas do solo devido ao manejo do solo afetam a produtividade agrícola. Possíveis mudanças de variáveis climáticas também poderão afetar a produtividade agrícola, tanto por unidade de área (produtividade de terra) ou por unidade de volume de água (produtividade de água). Uma opção para estudar as relações entre a produtividade de água e de terra e como elas são afetadas pelas propriedades hidráulicas do solo e pelos fatores climáticos é pela utilização de um modelo agro-hidrológico. Neste trabalho, o objetivo foi quantificar os aspectos do balanço hídrico do solo e realizar estimativas da produtividade de água e de terra para soja em um solo argiloso e para milho em um solo de textura média, na região do Cerrado, utilizando simulações com o modelo SWAP para diferentes manejos de irrigação. Os efeitos na produtividade agrícola de uma previsão climática com aumento da temperatura do ar e redução da precipitação para os anos 2016-2040 foram também simulados. Os resultados mostram que um aumento na porosidade do solo, resultante de um manejo conservacionista do solo, leva a uma maior infiltração e resulta num aumento na produtividade da terra e da água, quando associado a cenários de irrigação. As maiores produtividades da água foram observadas com irrigação suplementar. As mudanças climáticas previstas levarão a uma diminuição de aproximadamente 20% na produtividade da terra ao final dos anos 2016-2040, em áreas não irrigadas.

Palavras-chave: Modelo SWAP; Cerrado; Balanço hídrico; Produtividade da terra e da água

ABSTRACT

Agricultural resource efficiency and reduction of impacts under land-use and climate change scenarios in Brazil

Cerrado is the second largest Brazilian biome and originally corresponded to 24% of the national territory, and since the 1970's has been under agriculture and cattle activities. Soybean and maize are two of the most important grain-crops found in this region, with an estimated production of approximately 223 millions of tons in the Brazilian 2016/17 harvest. Changes in soil physical properties due to soil management affect productivity. Possible changes in climatic variables may also affect agricultural productivity, either per unit area (land productivity) or per unit of water volume (water productivity). One option for studying the relation between land and water productivity and how they are affected by soil hydraulic properties and climatic factors is by using an agro-hydrological model. In this study, the aim was to quantify aspects of the soil water balance and to make estimates of land and water productivity for soybean in a clay soil and maize in a medium texture in the Cerrado region using SWAP simulations for different irrigation strategies. Effects on agricultural productivity of a climatic prevision with increasing the air temperature and rainfall reduction for the years 2016-2040 were also simulated. Results show that an increase of soil porosity, resulting from a conservation tillage management, leads to a higher infiltration capacity and is shown to increase land and water productivity, when associated to irrigation scenarios. Higher water productivities were observed with only supplementary irrigation. Predicted climate changes will lead to a decrease of approximately 20% by the end of the years 2016-2040 in land productivity, under rainfed conditions.

Keywords: SWAP model; Cerrado; Water balance; Land and water productivity

1. INTRODUCTION

World population growth coupled with lifestyle changes lead to an increased demand for agricultural food, feed and energy production. Brazil is one of the world's largest producers and distributors of agricultural products, with an estimated 60 million hectares of grain-sown area in the 2016/2017 harvest year (CONAB, 2017).

This large production results in intensified competition for natural resources. To enable sustainable growth of production, the available resources must be used efficiently, especially at a time when a global shortage crisis is imminent. The solution would be to expand production even more quickly, but this becomes difficult due to the price of arable land and the unavailability of new areas (Ficarelli, Ribeiro, 2009). Periods of rapid economic expansion in Brazil coincide with higher land prices due to increased demand for agricultural commodities (Rangel, 2000).

The economic importance of maize and soybean is characterized by their diverse forms of use, ranging from food and feed, to the high technology industry. They are staple foods for the population in many countries, used in animal feed because of the high nutritional and energy value, which is increasingly important in many countries for industrial and pharmaceutical applications, with maize being used for the production of starch, ethanol, plastic and the base for the production of antibiotics (Edwards, 2009).

Cerrado is the second largest Brazilian biome and originally corresponded to 24% of the national territory, or approximately two million square kilometers, presenting plant formations that range from dense forests to open fields (Aguiar et al., 2004; Ratter, 2002). It is one of the biomes with the most floristic diversity of the planet, and among the most threatened ones. Such diversity lies in the large number of potentially economic species ranging from food to those used in regional crafts (Felfili et al., 2004). Due to the good conditions of topography, type of terrain and ease of deforestation, the Cerrado represents the main grazing and beef producing region of Brazil (Aguiar et al., 2004).

The occupation of the Cerrado region in the last decades was the greatest Green Revolution in the history of mankind, according to Norman Borlaug. During the last five decades the Cerrado has played a major role in the growth of Brazilian agriculture, and it is expected to continue doing so. Agriculture in this region was a development tool and an important tool for ensuring the Brazil's food security (Mueller; Martha, 2008).

Land use in the Cerrado is relevant due to diverse social, economic and environmental issues, as well as the reallocation of agricultural activities in consolidated

regions of the Cerrado. Different segments of society have been monitoring the expansion of production and its possible impacts on the resources and quality of soil, water, air, vegetation and biodiversity, and as a result the adoption of practices with a lower environmental impact is necessary (Mueller; Martha, 2008).

One of the most important examples of land use change in the Cerrado biome has been the conversion of native vegetation into pasture and cropping areas (Carvalho et al., 2014). The advancement of the agricultural frontier has increased the pressure on natural resources, and led to a change of the natural vegetation. Myers et al. (2000) estimate that around 80% of the Cerrado's original area has already undergone some anthropic interference. One of the challenges is to combine the sustainability of this biome with the productive system (Lopes; Daher, 2008). The technological research, the improvement of productivity and the substitution of activities in areas of Cerrado already exploited by agriculture, such as maize intercropping with forage species (Oliveira et al., 2011), are fundamental to reduce the pressure on the remaining area.

Within this context, system modeling emerges as an important tool to evaluate possible scenarios of climate change and land use. Researchers in the field of agronomy develop their studies in many areas of knowledge, where the amount of information on diverse subjects is still possible to be expanded (Martin, 2007). For research results to become reliable there is a need for agricultural experiments that increasingly have a high cost of installation, maintenance and data collection. In addition, the time used for conducting such experiments is not always available. In other cases, there is no possibility of installing experiments because of the complexity of the problem, requiring that decision-making be rapid. To overcome this situation, a simplified representation of the problem can be proposed, but it is necessary to know in depth the basic concepts of system operation (Martin, 2007). In this way, it is possible to elaborate mathematical models that represent the problem more efficiently, making the monitoring of the dynamics of this system possible through the simulation of alternative scenarios. From climate data, relief and vegetation, i.e., air temperature, rainfall, solar radiation, land slope and soil type, it is possible to estimate crop yield at a given location (Martin, 2007).

In agriculture, simulation is important to understand the interactions in the soil-plant-atmosphere system, as well as to predict results of an environmental system or condition. In addition, analyses of plant growth responses as a function of certain factors improve the efficiency of crop production and provide directions for research (Wu et al., 1996). The simulation allows to create scenarios that are not yet known, alternative scenarios not

explored in real experiments, ideal scenarios, very difficult to reproduce in the field reality (Dourado Neto et al., 1998). Using data collected from agricultural producers, a detailed analysis of productivity per unit of water and land consumption is possible, as well as the behavior of the water balance components. The database developed for the scenarios for land use change in the Cerrado can increase the vision on these processes and serve as a guide to make an efficient use of resources in a scenario of adaptation of agricultural practices to climate change. One way to accomplish this task is to use the concept of water productivity and water footprint (Hoekstra et al., 2011).

Regarding climate change, studies for the Brazilian scenario show a possible increase in temperatures and a decrease in the annual accumulated rainfall (Marengo et al., 2012; Pinheiro et al., 2017). Soil water content is expected to decrease, and, consequently, plants on those soils will be affected, according to the soil hydraulic properties.

Within this context, the objectives of the present work are to perform a detailed analysis of the land and water productivity of the maize and soybean crops under the current production system, and under different soil porosity and irrigation scenarios (Chapter 2); and evaluate land and water productivity of maize under scenarios with modified climate parameters in the Cerrado biome (Chapter 3).

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2. LAND AND WATER PRODUCTIVITY FOR RAINFED AND IRRIGATED FARMING SYSTEMS IN THE BRAZILIAN CERRADO

Abstract

Changes in soil physical properties due to soil management affect the water productivity, and irrigation strategies can optimize this component. An option for studying the relation between land and water productivity and how they are affected by soil hydraulic properties is by using an agro-hydrological model. In this study, we aimed to quantify aspects of the soil water balance and to make estimates of land and water productivity for soybean and maize cultivation in the Brazilian Cerrado region using SWAP simulations for different irrigation strategies. Our results show that an increase of soil porosity, resulting from a conservation tillage management, leads to a higher infiltration capacity and is shown to increase land and water productivity in medium texture soils, when associated to irrigation scenarios. Higher water productivities were observed with only supplementary irrigation. Modification of soil porosity, as to be expected from agricultural management, will bring about relevant alterations in the water balance components such as infiltrated water and bottom flux.

Keywords: SWAP model; Brazilian savanna; Soil porosity

2.1. Introduction

Limited crop water availability is one of the main stress factors reducing agricultural crop production and is an important issue related to food security in many developing countries. Drought stress affects crop development and light use efficiency. Crop yield may be significantly reduced or even completely lost due to insufficient water availability at different plant stages, depending on duration and severity (Boyer et al., 2004; Boyer et al., 2013; Golbashy et al., 2010; Moradi et al., 2012; Steduto, et al., 2012). Despite the yield loss under water-limited conditions, moderate drought stress is often associated to an increase in water use efficiency (Blum, 2009; Esmaeili, 2011; Kulathunga, 2013).

Demand for food, feed and energy together with water scarcity requires an increase in water use efficiency of agricultural production, especially in drought-prone agricultural areas. An example of such an area is the Brazilian savanna, also known by the local denomination

Cerrado. The Cerrado region comprises a large area of 2 million km² ranging through Brazil's northeastern, central and southeastern regions partly in transition to intensive and irrigated agriculture. Until a few decades ago, the Cerrado biome was predominantly under natural pastures developed under low technology cattle production. At present, the region undergoes a rapid process of land use change from natural pasture and original vegetation to soybeans, maize, sugarcane, medium and high technology pastures and integrated systems (crop-livestock or crop-livestock-forest), transforming Brazil into a main grain and cattle provider due to its favourable topographical and climatic conditions (Aguilar et al., 2004).

The introduced agricultural production systems are supposed to improve production from an economic point of view, while environmentally sustainable. It has been estimated that half of the Cerrado region is arable and has potential to be used for agriculture or livestock production (Goedert, 1989; Lopes, 1996; Oliveira and Ratter, 2002).

Climate in the Cerrado region is characterized by a dry winter, typically between May and September, and a rainy summer between October and April. The Köppen climate type is tropical, Aw in the major part, though some parts to the south are subtropical (Köppen Cw). Average precipitation is around 1500 mm y⁻¹, slightly lower than the potential evapotranspiration. Although the dry winter period limits water availability, irrigation makes agriculture feasible during this season and is used on large scale in the region, mainly using centre pivot irrigation systems. A comprehensive study on water limitations for soybean production in the Cerrado region has been reported by Sentelhas et al. (2015).

Being part of Brazil's Precambrian surface, soils in the Cerrado region are highly weathered and deep, mostly well drained with kaolinite clay and high contents of sesquioxides. Classified as Ferralsols in the World Reference Base classification system (FAO, 2006) or as Oxisols according to USDA Soil Taxonomy (Soil Survey Staff, 1999) these soils are characterized by a low fertility and pH, leading to a high free aluminum content which chemically impedes root growth (Batlle-Bayer et al., 2010; Walter, 2006). These chemical drawbacks are, however, very well manageable. Physically, Ferralsols are among the best soils in the world with a very stable microstructure, soil water availability being the main limitation.

Many studies have been performed to investigate the effect of agricultural management practices on soil physical properties, especially regarding the change from a conventional tillage system to no-till management. Macroporosity, hydraulic conductivity, and temporal variation of soil water content are usually shown to be affected. Generally, it is known that organic matter content increases under no-till (Batlle-Bayer et al., 2010; Corbeels

et al., 2006; Ferreira et al., 2016). In many cases, a decrease in macroporosity and hydraulic conductivity is observed (Azooz and Arshad, 1996; Osunbitana et al., 2005; Moret and Arrúe, 2007), but on the long term this tendency has been reported to invert (Green et al., 2003), possibly due to the increasing organic matter content and biological activity associated to no-till.

Irrigation management together with tillage practices put a challenge to the planning of water use. One of the questions to be addressed is how changes in soil physical properties due to soil management affect the water use efficiency, and how irrigation strategies can optimize this water use efficiency.

An option for studying the relation between land and water productivity and how they are affected by soil hydraulic properties is by using an agro-hydrological model. One such model is SWAP (Kroes et al., 2008), which combines a robust, Richards equation based hydrological module to the process based crop-growth model WOFOST (Van Diepen et al., 1989), including the transpiration reduction function proposed by Feddes et al. (1978). This combination of modules allows SWAP to reliably predict soil water balance components, land and water productivity as affected by soil hydraulic properties and meteorological boundary conditions.

In this study, we aimed to quantify aspects of the soil water balance and to make estimates of land and water productivity for soybean and maize cultivation in the Brazilian Cerrado region using SWAP simulations for different irrigation strategies. We test the sensitivity of water balance components and productivities to changes in soil hydraulic properties to be expected from occurring agricultural management changes.

2.2. Material and methods

2.2.1. Hydrological and crop growth modeling

The SWAP hydrological model (Kroes et al., 2008), which includes the WOFOST crop growth model (Van Diepen et al., 1989) was used to perform simulations of soil hydraulic conditions, water balance, water-limited crop growth and accumulated dry matter and dry grain mass. WOFOST simulates crop growth by quantifying photosynthesis, respiration and biomass maintenance and by partitioning net biomass accumulation according to the development stage (DVS) of the crop. Emergence corresponds to DVS=0, anthesis to

DVS=1 and maturity to DVS=2. Development stages are determined by the accumulated number of degree-days.

Potential evapotranspiration was calculated from daily weather data using the Penman-Monteith equation (Allen et al., 1998). At the bottom of the soil profile, unit-gradient free drainage was used as boundary condition. SWAP simulates 1-D vertical soil water flow using the Richards equation and an implicit finite difference scheme (Van Dam and Feddes, 2000). Relations between soil water content, pressure head and hydraulic conductivity are described by the Van Genuchten (1980) equations:

$$\Theta = \left[1 + |\alpha h|^n \right]^{\frac{1}{n}-1} \quad [2.1]$$

$$K = K_{sat} \Theta^\lambda \left[1 - \left(1 - \Theta^{\frac{n}{n-1}} \right)^{1-\frac{1}{n}} \right]^2 \quad [2.2]$$

in which $\Theta = (\theta - \theta_r) / (\theta_s - \theta_r)$, θ , θ_r and θ_s are water content, residual water content and saturated water content ($\text{m}^3 \text{m}^{-3}$), respectively, h is the pressure head (m), K and K_{sat} (m d^{-1}) are hydraulic conductivity and saturated hydraulic conductivity, respectively, and α (m^{-1}), n , and λ are empirical parameters. Relative transpiration T_r , the ratio between actual (T_a , m d^{-1}) and potential (T_p , m d^{-1}) transpiration is calculated using an adapted version of the reduction function proposed by Feddes et al. (1978):

$$T_r = \frac{T_a}{T_p} = \frac{\sum_p^n \alpha_p w_p R_p}{\sum_p^n w_p R_p} \quad [2.3]$$

where p is the soil layer number, n is the total number of soil layers, w_p (m) is the thickness of layer p , R_p is the relative root length density in layer p and α_p is the empirical reduction factor for layer p , defined by four typical soil water pressure heads h_1 , h_2 , h_3 , and h_4 , as follows: no uptake ($\alpha = 0$) occurs in the very wet ($h_p > h_1$) and very dry ($h_p < h_4$) range. Uptake is maximum ($\alpha = 1$) in the constant rate phase, for h_p between h_3 and h_2 . When h_p is between h_3 and h_4 , or between h_2 and h_1 , the reduction factor T_r is interpolated linearly. The relative

reduction in biomass accumulation is considered equal to the relative transpiration T_r as calculated by equation [2.3].

2.2.2. Experimental sites

To calibrate the SWAP model for maize and soybean grown under local Cerrado conditions, data from three experimental sites were collected from the agricultural years 2006/07 to 2014/15. Maize growing was evaluated in Correntina (13°20'S, 44°38'W, 560 m asl), and soybean production was studied for the Ipiranga do Norte (12°14'S, 56°09'W, 470 m asl) and Primavera do Leste (15°33'S, 54°17'W, 630 m asl) sites.

Table 2.1 – Average accumulated rainfall and standard deviation (SD) for the period between 1985 to 2014 at the three studied locations, and cumulative rainfall in the studied agricultural years between 2006 and 2015. Shaded numbers represent years outside the average $\pm$ SD range

	Rainfall (mm y ⁻¹)					
	Correntina		Ipiranga		Primavera	
Average	1429		1669		1708	
Standard deviation	213		384		296	
Average $\pm$ 1 SD	1216-1642		1285-2053		1412-2004	
	Yearly basis July-June	Cropping season October-April	Yearly basis July-June	Cropping season September-March	Yearly basis July-June	Cropping season September-March
2006/07	1322	1201	-	-	-	-
2007/08	-	-	2091	1718	-	-
2008/09	1480	1246	1753	1364	-	-
2009/10	1418	1010	1603	1168	-	-
2010/11	1514	995	1838	1249	-	-
2011/12	1283	1149	1892	1252	-	-
2012/13	1466	1290	1985	1473	1861	1545
2013/14	1319	1051	1759	1408	2103	1613
2014/15	-	-	-	-	2049	1501

Soils of the experimental sites are sandy to medium textured in Correntina (0.23 kg kg⁻¹ clay content) and clayey in Ipiranga (0.45 kg kg⁻¹) and Primavera (almost 0.60 kg kg⁻¹) (Table 2.2). It is important to mention that the clay of these soils is of the 1:1 kaolinite type resulting in hydraulic properties very distinct from those of 2:1 clays commonly found in soils developed in temperate regions. Soils have been under no-tillage management for many years, incorporating phosphate fertilizer during sowing (Ipiranga and Primavera) or broadcast at the entire area (Correntina). No irrigation is regularly performed at any of the three study sites.

Meteorological data were collected from nearby weather stations that are part of the National Meteorology Institute network (INMET, 2015). Some missing data were completed according to Lathuillière (2011). Thirty years of observations (1985-2014) were considered, but seven years were missing for Ipiranga (1991-1997), 11 years for Primavera (1987-1994, 1996-1997 and 1999) and two for Correntina (1993 and 2007). Table 2.1 shows the average observed annual rainfall to be lower (1429 mm y^{-1}) in Correntina than in Ipiranga (1669 mm y^{-1}) and in Primavera (1708 mm y^{-1}), and a dry period occurs from May to September at all three locations (Fig. 2.1). Maximum air temperatures are somewhat lower (32°C) in Correntina than in Ipiranga and Primavera (36°C), and minimum temperatures are lowest (13°C) in Primavera and highest (18°C) in Correntina. The annual average air temperature is slightly higher (25.4°C) in Ipiranga than in Correntina (24.2°C) and Primavera (24.5°C).

Figure 2.1 – Total monthly precipitation (mm) and mean monthly temperature ($^\circ\text{C}$) observed between 1985 to 2014 in Correntina, Ipiranga and Primavera. Bars in precipitation columns represent one standard deviation

Table 2.2 – Texture and hydraulic property data (equations 2.1 and 2.2 parameters) for the soil at three experimental sites

Municipality	depth	clay content	silt content	sand content	organic matter content	α	n	θ_s	θ_r	K_{sat}	λ
	m	kg kg ⁻¹	kg kg ⁻¹	kg kg ⁻¹	kg kg ⁻¹	m ⁻¹		m ³ m ⁻³	m ³ m ⁻³	cm d ⁻¹	
Correntina	0-0.2	0.232	0.035	0.732	0.016	6.951	1.557	0.446	0.130	2.66	0.5
Ipiranga do Norte	0-0.01 0.01-0.02	0.445 0.465	0.104 0.106	0.451 0.429	0.026 0.016	4.843 4.663	1.414 1.411	0.475 0.467	0.207 0.213	0.216 0.216	0.5 0.5
Primavera do Leste	0-0.02 0.02-0.04	0.584 0.599	0.099 0.103	0.317 0.299	0.028 0.022	3.775 3.614	1.426 1.434	0.484 0.481	0.241 0.245	0.216 0.216	0.5 0.5

2.2.3. Soil hydraulic properties

Values for parameters α , n , θ_r and θ_s from equations [2.1] and [2.2] were estimated for each soil layer using the Tomasella et al. (2000) pedotransfer function developed based on data of more than 500 horizons in Brazilian soils:

$$\begin{aligned}
 X_i = & a_{i,1} + a_{i,2}S + a_{i,3}C + a_{i,4}D_b + a_{i,5}C_O + a_{i,6}S_C S_F + a_{i,7}S_C S + a_{i,8}S_C C \\
 & + a_{i,9}S_F S + a_{i,10}S_F C + a_{i,11}SC + a_{i,12}CS^2 + a_{i,13}FS^2 + a_{i,14}S^2
 \end{aligned} \quad [2.4]$$

where X_i is a parameter value, being $X_1 = \log(\alpha)$, $X_2 = n$, $X_3 = \theta_s$ and $X_4 = \theta_r$. S_C , S_F , S and C are the mass fractions (in %) of coarse sand (2-0.2 mm), fine sand (0.2-0.05 mm), silt (0.05-0.002 mm) and clay (<0.002 mm), respectively; D_b is the soil bulk density (g cm⁻¹); C_O is the mass fraction (in %) of soil organic carbon. Coefficients $a_{i,j}$ ($1 \leq i \leq 4$; $1 \leq j \leq 14$) are pedotransfer fitting coefficients described in Tomasella et al. (2000) – their table 8.

The available soil database did not contain specific data for coarse and fine sand as needed in equation [2.4], therefore, in agreement with reports for similar soils (Rosa et al., 2003; Resende and Rosolem, 2013) we assumed equal values for both fractions. Saturated hydraulic conductivity K_{sat} for the Correntina sandy soil was 2.66 m d⁻¹ (Pinto et al., 2015), and for the clayey soils we used 0.216 m d⁻¹ as determined by Hunke et al. (2015) for a similar soil. For the λ parameter in equation 2.2, the value of 0.5 was used according to Mualem (1976).

2.2.4. Model calibration and evaluation

For calibration and validation of soybean crop parameters, data from the Ipiranga and Primavera sites were used, comprising 19 water-limited yields obtained between 2007 and 2015. Data refer to soybean production during the main cropping season, sowing dates going from around the second half of September to harvest around the beginning of March. Calibration and validation of the maize crop parameters were performed using 42 yield observations from the Correntina site between 2006 and 2014. Maize sowing dates started in October and harvest dates finished in April.

To reserve independent data for model validation, only a randomly selected half of the available data was used in the parameter calibration procedure, whereas the other half was used for validation. A semi-automated assisted procedure was developed for both steps of the procedure.

Parameter calibration of WOFOST model parameters was performed following the protocol described by de Wit (2010). The calibration comprised the following parameters: temperature sum from emergence to anthesis (TSUMEA, °C) and between anthesis and maturity (TSUMAM, °C), crop base temperature (TBASE, °C), leaf lifespan (SPAN, d), development stage at the onset of maximum leaf assimilation rate reduction (DVS_{amax}), maximum leaf assimilation rate (AMAX, $kg\ ha^{-1}\ h^{-1}$) and permanent wilting pressure head (h_4 , m). Further crop parameters were assumed as listed in Boons-Prins et al. (1993) for maize (their appendix B1) and for soybean (their appendix H1). Critical pressure heads for the onset of the falling transpiration rate phase (h_3 from Feddes et al., 1978) were modified from the Taylor and Ashcroft (1972) critical pressure heads for grain crops root water extraction ($h_3 = -3\ m$ at high potential transpiration, $5\ mm\ d^{-1}$, and $h_3 = -6\ m$ at low potential transpiration rate, $1\ mm\ d^{-1}$).

First, TSUMEA, TSUMAM and TBASE were adjusted using literature information on soybean (Correa, 2008) and maize (Muchow and Carberry, 1989). Simulated yields for specific scenarios were then confronted to observed yields, finding the optimum combination of crop parameters SPAN, DVS and AMAX and hydrological parameters by minimizing the Root Mean Square Error (RMSE) between observed and simulated yields.

2.2.5. Irrigation and land use change scenarios

Yield and crop water use data were simulated for several scenarios of irrigation management. For this purpose, field capacity was defined as corresponding to the hydraulic conditions at a bottom flux of 1 mm d^{-1} at the 0.6 m depth. This field capacity conditions were determined in a separate simulation of internal redistribution, starting at saturation, without evapotranspiration, as described in de Jong van Lier and Wendroth (2016).

Irrigation was supposed to be of the sprinkler type, and vegetation water retention of 2.5 mm was used. Four irrigation strategies were simulated: full irrigation (I_{100}), two supplementary irrigation scenarios (I_{66} and I_{33}) and a baseline rainfed scenario (I_0). Full irrigation implied in replenishing the soil water content to field capacity, whereas supplementary scenarios I_{66} and I_{33} replenish to 2/3 or 1/3, respectively, of field capacity. Corresponding pressure heads and water contents are listed in Table 2.3, as well as the critical pressure head to trigger irrigation in each scenario. At the occurrence of drought stress, the amount of irrigation (L_F , mm) was calculated as:

$$L_F = \left(\frac{F}{100\%} [\theta_{FC} - \theta_{PWP}] + \theta_{PWP} - \theta_a \right) z_i \quad [2.5]$$

where z_i (mm) is the rooted soil depth, θ_{FC} ($\text{m}^3 \text{ m}^{-3}$) is the water content at field capacity, θ_{PWP} ($\text{m}^3 \text{ m}^{-3}$) is the water content at permanent wilting point, θ_a ($\text{m}^3 \text{ m}^{-3}$) is the actual water content, and F (%) is the fraction of available water to be replenished ($F = 100, 66$ or 33%). In the case of multiple layers, equation [2.5] was applied per layer.

Table 2.3 – Water content and pressure head corresponding to field capacity for soils in Correntina, Ipiranga and Primavera, determined using a bottom flow criterion of 1 mm d^{-1}

Scenario	Symbol	Irrigation start	Correntina (Maize)		Ipiranga (Soybeans)		Primavera (Soybeans)	
		Pressure head (cm)	Pressure head (cm)	Water content ($\text{m}^3 \text{ m}^{-3}$)	Pressure head (cm)	Water content ($\text{m}^3 \text{ m}^{-3}$)	Pressure head (cm)	Water content ($\text{m}^3 \text{ m}^{-3}$)
Full irrigation	I_{100}	-500	-57.6	0.280	-32.0	0.412	-39.4	0.430
Supplementary irrigation	I_{66}	-1000	-102.6	0.234	-81.2	0.354	-98.2	0.375
Supplementary irrigation	I_{33}	-2000	-281.5	0.190	-311.6	0.297	-359.5	0.321
No irrigation	I_0	-	-	-	-	-	-	-

Land use change scenarios were simulated considering that soil management implies in a change in total porosity. This may be a reduction due to compaction, normally caused by agricultural machinery, but porosity may also increase due to conservation management resulting in increased organic matter contents in favor of a better soil structure. Changes in porosity affect soil water retention parameters and soil hydraulic conductivity. Five porosity scenarios were tested in this study: the current scenario (S_0), an increase in total porosity by $0.02 \text{ m}^3 \text{ m}^{-3}$ (S_2) or by $0.04 \text{ m}^3 \text{ m}^{-3}$ (S_4) and a decrease in total porosity by $0.02 \text{ m}^3 \text{ m}^{-3}$ (S_{-2}) or by $0.04 \text{ m}^3 \text{ m}^{-3}$ (S_{-4}). For each scenario, the corresponding increase or decrease in saturated hydraulic conductivity was estimated using a Childs and Collins-George (1950)-like approach. Other soil hydraulic parameters (α , n , λ) were supposed to be unaffected. Irrigation strategies and porosity scenarios were then combined to generate the respective soil water balance and land and water productivities.

2.2.6. Land and water productivity

Land and water productivity for soybean and maize were determined from the output of SWAP simulations, with and without irrigation. Land productivity Y (kg ha^{-1}) was considered as the final dry grain mass per hectare and is a SWAP output variable. Water productivity Ω (kg m^{-3}) was calculated from land productivity and accumulated actual evapotranspiration ET_a (m) during the crop development as:

$$\Omega = \frac{Y}{10^4 ET_a} \quad [2.6]$$

where the factor $10^4 [\text{m}^2 \text{ ha}^{-1}]$ stands for the conversion between square meters and hectares. The water productivity increase obtained by irrigation unit ($\Delta\Omega_I$, kg m^{-3}) was estimated by the difference between the respective land productivity in an irrigation scenario Y_I (kg ha^{-1}) and in the rainfed scenario Y_0 (kg ha^{-1}), divided by the amount of applied irrigation water (I , m):

$$\Delta\Omega_I = \frac{Y_I - Y_0}{10^4 I} \quad [2.7]$$

2.3. Results and discussion

2.3.1. Calibration, sensitivity analysis and model evaluation

Rainfall was within the range defined by the thirty-year observations standard deviation for all observed years in Correntina. In Ipiranga, the first year (2007/08) showed an above average rainfall amount, whereas for the Primavera location two out of the three observed years were above average with respect to rainfall (Table 2.1).

The complete hydraulic parameter set (parameters of equations 2.1 and 2.2) per soil layer estimated from the pedotransfer functions using the soil analysis of the farmers at the different locations is reported in Table 2.2. The Ipiranga and Primavera soils have higher clay contents and a higher organic matter content than the Correntina soils, resulting in lower values of α and higher values of θ_r and θ_s . These properties are associated to a higher water holding capacity and, in general, a higher crop water availability.

Table 2.4 shows crop parameters used in the simulations, some of them based on local information, some reported by Boons-Prins et al. (1993) and Taylor and Ashcroft (1972), and others obtained by own calibration. Yield predictions by the SWAP model showed high sensitivity to the parameter defining the lifespan of leaves, and the best fitted value was 19 days for soybean and 33 days for maize (Fig. 2.2). Regarding the maximum carbohydrate assimilation rate, for maize the four-point piecewise linear reduction given in Boons-Prins et al. (1993) was used (footnote under Table 2.4), whereas for soybean a two-point piecewise linear shape was calibrated, defined by a maximum value and a development stage of onset of reduction of this maximum value. DVS 1.7 resulted in the lowest RMSE range, together with a maximum assimilation rate of $37 \text{ kg ha}^{-1} \text{ h}^{-1}$.

Table 2.4 – Crop, climate and soil parameters used in the SWAP model for maize and soybean

	Maize	Soybean
<i>Source: own calibration</i>		
Leaf lifespan (SPAN, d)	33	19
Development stage of onset of maximum carbohydrates assimilation (DVS _{amax})	-	1.7
Maximum carbohydrate assimilation rate (AMAX, kg ha ⁻¹ h ⁻¹)	-	37
Depth of pressure head or moisture content sensor for irrigation purposes (m)	0.05	0.05
<i>Modified from Taylor and Ashcroft (1972)</i>		
Critical pressure head at high T_p (h_{3h} , m)	-3	-3
Critical pressure head at low T_p (h_{3l} , m)	-6	-6
Permanent wilting point - Pressure head (h_4 , m)	-30	-50
- Water content (h_4 , m ³ m ⁻³)	0.146	0.240 ^a 0.267 ^b
<i>Source: Boons-Prins et al. (1993)</i>		
Temperature sum from emergence to anthesis (TSUMEA, °C d)	700	860
Temperature sum from anthesis to maturity (TSUMAM, °C d)	1300	720
Development stage of onset of maximum carbohydrates assimilation (DVS _{amax})	1.25	-
Maximum carbohydrate assimilation rate (AMAX, kg ha ⁻¹ h ⁻¹)	70 ^c	-
Initial rooting depth (m)	0.1	0.05
Maximum daily increase in rooting depth (m d ⁻¹)	0.015	0.012
Relative root length density at soil surface	1	1
<i>Source: local information</i>		
Temperature base (TBASE, °C)	10	10
Temperature sum from emergence to anthesis (TSUMEA, °C d)	700	860
Temperature sum from anthesis to maturity (TSUMAM, °C d)	1300	720
Maximum rooting depth (m)	1	0.6
Rainfall intensity (mm d ⁻¹)	300	300

^a Ipiranga soil. ^b Primavera soil. ^c Reducing to 63 at DVS 1.5, 49 at DVS 1.75 and 21 at DVS 2.

Fig. 2.3 shows observed and simulated land productivity data for all plots from calibration and validation runs. Whereas one would expect a higher RMSE for the validation data set, soybean calibration and validation show similar values of RMSE, about 10% of the respective yields. For maize, RMSE of calibration is also around 10% of yield values, but in this case the RMSE for validation is higher, close to 15% of yield. Considering the large amount of involved variables and the fact that only a few of them were calibrated for the specific boundary conditions of this study, these results seem within the limits of the acceptable.

SOYBEAN

MAIZE

Figure 2.2 – Average predicted land productivity Y (t ha⁻¹) and its RMSE (t ha⁻¹) as a function of parameter value for leaf lifespan (SPAN), maximum carbohydrate assimilation rate (AMAX), and development stage at onset of maximum carbohydrates assimilation (DVSamax). Bars in first column represent the standard deviation (SD) of 10 values of Y for soybean and 21 for maize

Figure 2.3 – Observed versus predicted land productivity values obtained from calibration and validation runs with the SWAP model for soybean in Ipiranga and Primavera, and maize in Correntina

2.3.2. Sensitivity of land and water productivity under present scenario

To illustrate simulation results and how drought stress affects yield as simulated with the SWAP model, Fig. 2.4 shows simulated pressure head in the surface (0-0.2 m) and subsurface (0.2-0.4 m) layer and relative dry maize mass together with infiltrated water and accumulated rainfall for S_0I_0 scenarios in Correntina from two different cropping seasons.

The 2011-2012 season shows pressure head within the optimum range during the entire cycle. A small reduction of productivity due to drought stress can be observed at the end of the cycle, in the full grain stage at onset of senescence. Some small reductions were simulated earlier during the cycle, due to water shortage in a layer that is not shown in the graph.

In the 2012-2013 cropping season, some drought stress was simulated at the onset of the season, making the relative dry mass to reduce to around 80%. Although the pressure head was outside the optimum range only in the surface layer, at this stage of crop development (around one week after emergence) the root system is still very shallow and surface water depletion can lead to severe biomass reduction, as simulated. Later in the season, by the end of December and the beginning of January, a more severe drought stress was simulated. This period coincides with a development stage with high leaf CO_2 assimilation, therefore, consequent relative dry mass reduction was large. Under a potential evapotranspiration condition during this DVS, the crop was simulated to accumulate 4882 kg ha^{-1} of dry grain, whereas the amount including drought stress was 1252 kg ha^{-1} (26%).

Figure 2.4 – Pressure head, relative land productivity, accumulated rainfall, and infiltrated water simulated for two scenarios S₀I₀ with maize in Correntina

Fig. 2.5 shows results from two soybean scenarios S₀I₀ from Ipiranga. In both cases some stress is simulated due to excess water. During several weeks in November/2012, rainfall occurred almost every day resulting in an almost saturated soil. Out of 30 days in this month, on 21 rainfall was measured and on 14 days a reduction in dry matter accumulation due to excess water was simulated. The next month (December) was similarly wet and plants were simulated under excess water stress during 18 days out of the month. Extreme events

occurred on November 11 (83 mm) and December 18 (61 mm), dates on which highest excess water stress was simulated.

Figure 2.5 – Pressure head, relative land productivity, accumulated rainfall, and infiltrated water simulated for two scenarios S_0I_0 with soybean in Ipiranga

Using scenario S_0I_0 in 2013 (Fig. 2.5), a high Y of 3326 kg ha^{-1} was achieved with the optimum condition of the soil water pressure head and no drought stress. Again, some excess water stress was observed during the first days of November, in the top soil layer. As the crop was in an early vegetative stage ($DVS = 0.62$), there was no significant effect on the final Y .

Water balance components for the clayey soils under soybean crop cultivation are shown in Table 2.6. An average rain amount of 153 cm during the crop cycle occurred, and $123.4 (\pm 15.7)$ cm actually infiltrated in the soil, but $74.5 (\pm 17.2)$ cm were lost in the bottom flux, because of the free drainage of the soil profile. These results show that even with all the water losses during time by runoff, plant interception, bottom flux, and evaporation, the crop still is supplied with the demanded water. According to Farias et al. (2007), under Brazilian conditions a soybean crop needs from 45 to 80 cm of water per cycle, depending on the climate conditions, crop management and crop cycle. In this study, evapotranspiration was $43.2 (\pm 3.7)$ cm on average for 19 emergence dates in the different cropping seasons, and no irrigation was necessary.

For soybean, an Ω of 0.685 kg m^{-3} and an average Y of 2920 kg ha^{-1} were simulated (Table 2.6). According to Sadras et al. (2010), Ω ranges from 0.6 to 1.0 kg m^{-3} for soybean in rainfed conditions. Y was 7756 kg ha^{-1} (Table 2.5) for maize, with an Ω of 1.476 kg m^{-3} . In the review on measured crop water productivity for some crops by Zwart and Bastiaanssen (2004), Ω was ranging from 1.1 to 2.7 kg m^{-3} . The large simulated difference between Ω for the two soil textures can be ascribed to climate and soil management, and irrigation when it is the case.

In the medium texture soil with maize cultivation, $59.7 (\pm 8.3) \text{ cm}$ were lost by bottom flux, and $115.6 (\pm 6.8) \text{ cm}$ were infiltrated water. Maize ET_a ranges from 48 to 80 cm (Allen et al., 1998); $52.6 (\pm 4.5) \text{ cm}$ was simulated in scenario S_0I_0 (Table 2.5). In this case, when irrigation became available, differences in the water balance components were observed, as well in the land productivity, and these results will be discussed in the next item.

2.3.3. Sensitivity of land and water productivity to land use change and irrigation scenarios

According to Hoekstra et al. (2011), the pressure on water resources of a certain location is reduced when it is possible to increase Ω . If a supplementary irrigation management is chosen, the goal should be to reach the maximum Ω instead of the maximum Y .

Fig. 2.6 compares maize Y in Correntina under irrigation scenarios in one plot (season 2012/2013). It is possible to observe that Y increases along increased irrigation scenarios, described in Table 2.3, and reaches the maximum Y for scenario I_{100} . In the I_{100} scenario, the pressure head remains always within the range of maximum soil water uptake by the plant, the no-stress range between -57.6 and -500 cm (Table 2.3).

The same increasing tendency is observed in the average results for all plots (Table 2.5). In this Table, all combinations of porosity and irrigation scenarios are compared with respect to Y and Ω . The predictions of Y and Ω for maize on the medium-textured soil show a low sensitivity to soil porosity. Y increases by about 11% from rainfed I_0 to fully irrigated I_{100} . Ω also increases from I_0 to I_{100} by about 7% I_0 to I_{100} . For maize, when I_{100} was applied in all the soil scenarios, maximum Y was achieved, but the maximum $\Delta\Omega$ was observed at in the intermediate irrigation scenario I_{66} for all the porosity scenarios, except for scenario S_2I_{33} . Regarding water use, in places where restrictions about irrigation exist, this result indicates

that the aim of agriculture should consider not only high Y , but also the efficiency of the use of each unit of evapotranspired water.

For the soybean scenarios, no irrigation was simulated, independent of the porosity scenario (Table 2.6). All of these simulation scenarios refer to the rainy cropping season. These locations show high rainfall amounts (Table 2.6) which, linked to the clayey soils, resulted in no need for irrigation. No drought stress was observed in the different locations, years and scenarios. Y tends to increase according to the porosity increase, as well as the infiltrated water (around 5%), and, consequently, the bottom flux (7%). Results show that the adoption of good agricultural practices, here represented by an increase in soil porosity, is important to increase soil water infiltration and land productivity.

Figure 2.6 – Relative land productivity predicted for maize (2012/2013 season) under different irrigation managements

Table 2.5 – Predicted water balance components and standard deviations (irrigation, bottom flux, plant interception, transpiration, evaporation and infiltrated water), and land and water productivity for the soil and irrigation scenarios with maize in Correntina

		I ^a	B _{flux} ^b	Interc ^c	Runoff	Transp ^d	Evap ^e	I _{water} ^f	Y	Ω	□Ω
					cm				kg ha ⁻¹	kg m ⁻³	
S ₋₄	I ₀	0.0	-60.3	3.7	2.2	31.6	20.6	115.4	7655	1.47	0.0
	SD	0.0	8.3	0.6	0.5	3.1	1.3	6.8	1266		
	I ₃₃	1.8	-61.2	3.8	2.2	32.2	20.7	117.1	7871	1.49	1.20
	SD	1.5	8.1	0.6	0.4	3.1	1.3	7.2	1162		
	I ₆₆	3.7	-62.2	3.9	2.2	33.0	20.7	118.9	8160	1.52	1.35
	SD	3.0	8.0	0.6	0.4	3.3	1.3	7.9	1123		
	I ₁₀₀	6.9	-64.5	3.8	2.2	34.0	20.7	122.2	8607	1.57	1.33
	SD	5.8	9.0	0.6	0.4	3.8	1.3	9.8	1126		
S ₋₂	I ₀	0.0	-60.5	3.7	1.9	31.7	20.6	115.7	7690	1.47	0.0
	SD	0.0	8.3	0.6	0.4	3.2	1.3	6.7	1264		
	I ₃₃	1.7	-61.4	3.8	1.9	32.3	20.7	117.3	7885	1.49	1.12
	SD	1.6	8.2	0.6	0.4	3.2	1.3	7.3	1178		
	I ₆₆	3.8	-62.4	3.9	1.9	33.2	20.7	119.3	8228	1.53	1.40
	SD	3.1	8.0	0.6	0.4	3.4	1.3	7.9	1112		
	I ₁₀₀	7.1	-64.9	3.9	1.9	34.0	20.7	122.6	8620	1.58	1.26
	SD	5.9	9.0	0.6	0.4	3.8	1.3	9.8	1131		
S ₀	I ₀	0.0	-59.7	3.7	2.0	32.0	20.6	115.6	7756	1.48	0.0
	SD	0.0	8.3	0.6	0.4	3.2	1.3	6.8	1272		
	I ₃₃	1.5	-61.4	3.8	1.6	32.4	20.7	117.4	7889	1.49	0.89
	SD	1.7	8.6	0.6	0.3	3.1	1.3	7.6	1163		
	I ₆₆	3.8	-62.8	3.9	1.6	33.3	20.7	119.7	8273	1.53	1.31
	SD	3.2	7.9	0.6	0.3	3.4	1.3	7.9	1103		
	I ₁₀₀	7.2	-65.4	3.9	1.6	34.0	20.7	123.0	8625	1.58	1.17
	SD	5.8	8.6	0.6	0.3	3.8	1.3	9.6	1129		
S ₂	I ₀	0.0	-61.1	3.7	1.4	31.8	20.6	116.2	7706	1.47	0.0
	SD	0.0	8.2	0.6	0.3	3.2	1.3	6.7	1267		
	I ₃₃	1.5	-62.9	3.8	0.0	32.5	20.7	119.0	7938	1.49	1.52
	SD	1.7	8.8	0.6	0.0	3.2	1.3	7.9	1153		
	I ₆₆	3.9	-63.2	3.9	1.4	33.3	20.7	119.9	8261	1.53	1.40
	SD	3.2	7.9	0.6	0.3	3.4	1.3	7.9	1108		
	I ₁₀₀	7.3	-65.8	3.9	1.4	34.1	20.7	123.3	8643	1.58	1.25
	SD	6.0	8.9	0.6	0.3	3.8	1.3	9.8	1131		
S ₄	I ₀	0.0	-61.2	3.7	1.2	31.9	20.6	116.4	7739	1.47	0.0
	SD	0.0	8.3	0.6	0.3	3.2	1.4	6.8	1265		
	I ₃₃	1.5	-62.0	3.8	1.2	32.5	20.7	117.8	7914	1.49	1.14
	SD	1.8	8.6	0.6	0.3	3.2	1.3	7.7	1157		
	I ₆₆	3.9	-63.4	3.9	1.2	33.4	20.7	120.1	8306	1.54	1.40
	SD	3.3	7.9	0.6	0.3	3.4	1.3	8.0	1101		
	I ₁₀₀	7.4	-66.1	3.9	1.2	34.1	20.7	123.6	8640	1.58	1.18
	SD	6.0	8.7	0.6	0.3	3.8	1.3	9.7	1129		

Average annual rainfall in all the scenarios= 121 cm crop cycle⁻¹. ^aIrrigation; ^bBottom flux; ^cCrop interception; ^dTranspiration; ^eEvaporation; ^fInfiltrated water.

Table 2.6 – Predicted water balance components and standard deviations (irrigation, bottom flux, plant interception)

		B _{Flux} ^a	Interc ^b	Runoff	Transp ^c	Evap ^d	I _{water} ^e	Y	Ω
				cm				kg ha ⁻¹	kg m ⁻³
S ₋₄	I ₀ ; I ₃₃ ; I ₆₆ ; I ₁₀₀	-72.8	3.2	28.4	16.9	26.2	121.3	2876	0.677
	SD	16.9	0.5	4.0	2.1	1.6	15.4	289	
S ₋₂	I ₀ ; I ₃₃ ; I ₆₆ ; I ₁₀₀	-73.6	3.2	27.4	17.0	26.1	122.3	2899	0.681
	SD	16.9	0.5	4.0	2.1	1.6	15.3	285	
S ₀	I ₀ ; I ₃₃ ; I ₆₆ ; I ₁₀₀	-74.5	3.3	26.3	17.2	26.0	123.4	2920	0.685
	SD	17.2	0.5	3.8	2.2	1.5	15.7	272	
S ₂	I ₀ ; I ₃₃ ; I ₆₆ ; I ₁₀₀	-75.9	3.3	24.7	17.4	25.9	124.9	2940	0.689
	SD	18.1	0.6	3.4	2.2	1.5	16.4	265	
S ₄	I ₀ ; I ₃₃ ; I ₆₆ ; I ₁₀₀	-77.6	3.4	22.8	17.5	25.8	126.8	2963	0.693
	SD	18.0	0.6	3.1	2.2	1.5	16.2	268	

Average annual rainfall in all the scenarios = 153 cm crop cycle⁻¹. ^aBottom flux; ^bCrop interception; ^cTranspiration; ^dEvaporation; ^eInfiltrated water.

2.4. Conclusions

1. Irrigation was predicted to increase maize productivity on medium textured soils by about 11%, while increasing water productivity by 7%. Maximum land productivity was achieved with a full irrigation scenario, but higher water productivities were observed with only supplementary irrigation.
2. Modification of soil porosity, as to be expected from agricultural management, will bring about relevant alterations in some water balance components, as infiltrated water and bottom flux, and is shown to increase land and water productivity in medium texture soils, when associated to irrigation scenarios.
3. There is no demand for irrigation in soybean cropping on clayey soils during the rainy season in the studied Cerrado region. Soybean land productivity increased 1.5% when soil porosity increased by 0.04 m³ m⁻³, while water productivity increased around 1%.

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3. LAND AND WATER PRODUCTIVITY OF MAIZE AND SOYBEAN CROPPING SYSTEM UNDER SCENARIOS WITH MODIFIED CLIMATE VARIABLES IN THE CERRADO BIOME

Abstract

Modified climate parameters have been carried out in Brazil and a warming trend in the oncoming years is believed to occur by the vast majority of researchers. Concerns about the vulnerability of agricultural production to modified climate parameters are increasing and their impacts were widely predicted by using crop models together with climate change scenarios. In this study, we generated crop and climate data from two representative soils cultivated with maize and soybean in Brazil, for the period 2016–2040, to investigate whether a predicted climate change would have a significant impact on water balance components, soil water content and land and water productivity. Our results show that: the rainfall amount reduction over time provides a soil drier condition, and soil water flow to the roots is expected to be reduced due to frequently lower unsaturated hydraulic conductivity of coarse textured soils when compared to those of fine texture. As a consequence, transpiration decreased 21% in the medium texture soil; temperature increase has shown to increase transpiration in 10% during the rainy season in a clay soil; maize and soybean land productivity decreased approximately 20% in a medium texture soil and in a clay soil. Water productivity decreased 42%.

Keywords: SWAP model; Brazilian savannah; Temperature increase; Drought

3.1. Introduction

The cerrado is the second largest biome in Brazil, its original size corresponds to 24% of the Brazilian territory, presenting plant formations that range from dense forests to open fields (Aguiar et al., 2004). This vegetation has been replaced by agricultural fields and cattle ranching since the 1970's, and nowadays is considered as the most important agricultural frontier in Brazil.

Climate in the Cerrado region is characterized by a dry winter, typically between May and September, and a rainy summer between October and April. The Köppen climate type is tropical, Aw in the major part, though some parts to the south are subtropical (Cw). Average precipitation is around 1500 mm y⁻¹. Regarding climate change, regional scenarios applied in

the Brazilian territory have shown a very likely increase in air temperatures and a decrease in the annual accumulated rainfall, reducing water availability both at watershed and soil profile scales (Marengo et al., 2012; Pinheiro et al., 2017). Under such scenarios and depending on the soil hydraulic properties, soil water fluxes are expected to decrease, and, consequently, crops grown on those soils may be affected. Concerns about the vulnerability of agricultural production to climate change are increasing and the impact of these scenarios on crop yield has been widely predicted by crop models.

From climate data, terrain and vegetation, such as air temperature, rainfall, solar radiation, land slope and soil type, it is possible to estimate crop yield at a given location (Martin, 2007). In agriculture, yield simulation is important to understand the interactions in the soil-plant-atmosphere system, as well as to predict impacts of changes in environmental driving forces or soil properties on crop yield. In addition, analyses of plant growth responses as a function of certain factors improve the efficiency of crop production and provide directions for research (Wu et al., 1996). Such simulations allow to investigate likely scenarios and alternative scenarios not explored in real experiments due to unfeasible aspects to be reproduced in the field reality (Dourado Neto et al., 1998).

Maize is a staple food and energy provider for the population in many countries (Edwards, 2009), and in Brazil, together with soybean, it is one of the most representative crops both in cultivated area and production. Recent reports estimate 60 million hectares of grain-sown area in the 2016/2017 harvest year, with a production of approximately 223 million tons (CONAB, 2017). These crops played an important role in the expansion of the Brazilian agriculture over the years, especially in the Cerrado region.

Within this context, our objective was to study the effects of modified climate variables based on regional scenarios of climate change on the soil-water balance components and land and water productivity of two representative Cerrado sites. Agro-hydrological simulations were performed focusing on the agricultural years 2016-2040.

3.2. Material and methods

3.2.1. Study areas

The study was carried out for two experimental sites under Cerrado conditions, for the agricultural years 2016-2040. Table 3.1 shows the location of the selected soils. Soybean production was simulated for the municipality of Ipiranga do Norte (12°14'S, 56°09'W, 470

m asl, located in Mato Grosso State), with a clayey soil type. Maize production was simulated for the climate conditions of the Correntina municipality (13°20'S, 44°38'W, 560 m asl, located in Bahia state), in a sandy clay loam soil which corresponds to a medium texture. In the following we will refer to locations according to their soil texture, i.e., clay and medium texture (FAO-Unesco, 1974). For the studied sites, two emergence dates (ED) were considered, one at the beginning and the other approximately in the middle of the common sowing season, according to local information collected from farmers. For maize, ED1 was October 08 and ED2 was November 24, while for soybeans, September 29 and November 03. It is important to mention that both soils are economically important in soybean and maize production, but simulations were organized according to the available data for the calibration of the SWAP model, described in chapter 2 of this thesis: maize on the medium texture soil and soybean on the clay soil.

Table 3.1 – Texture and hydraulic property data (equations 3.1 and 3.2 parameters) for the soil at two experimental sites

Municipality/ Soil texture	depth	clay content	silt content	sand content	organic matter content	α	n	θ_s	θ_r	K_{sat}	λ
	m	kg kg ⁻¹	kg kg ⁻¹	kg kg ⁻¹	kg kg ⁻¹	m ⁻¹		m ³ m ⁻³	m ³ m ⁻³	cm d ⁻¹	
Correntina/ Medium	0-0.2	0.232	0.035	0.732	0.016	6.951	1.557	0.446	0.13	2.66	0.5
Ipiranga do Norte/Clay	0-0.01	0.445	0.104	0.451	0.026	4.843	1.414	0.475	0.207	0.216	0.5
	0.01-0.02	0.465	0.106	0.429	0.016	4.663	1.411	0.467	0.213	0.216	0.5

The clay soil contains 0.45 kg kg⁻¹ of clay, while the medium texture soil contains about 0.23 kg kg⁻¹ (Table 3.1). It is important to mention that the clay mineralogy of these soils is 1:1 kaolinitic, resulting in hydraulic properties very distinct from those of 2:1 clays commonly found in soils developed in temperate regions. Soils have been under no-tillage management for many years, with phosphate fertilizer incorporation during sowing (clay) or at the total area (medium). No irrigation is regularly performed at these two sites.

Meteorological data were collected from nearby weather stations that are part of the National Meteorology Institute network (INMET, 2015). Annual rainfall is lower (1429 mm y⁻¹ ± 213) at the medium texture site than at the clay site (1669 mm y⁻¹ ± 384), and a dry period occurs from May to September at both locations. The annual average air temperature is slightly lower (24.2 °C) at the first location in comparison to the second (25.4 °C).

3.2.2. Hydrological and crop growth modeling

The SWAP hydrological model (Kroes et al., 2008), which includes the WOFOST crop growth module (Van Diepen et al., 1989) was used to perform simulations of soil water balance, water-limited crop growth and accumulated dry matter and dry grain mass. WOFOST simulates crop growth by quantifying photosynthesis, respiration and biomass maintenance and by partitioning net biomass accumulation according to the development stage (DVS) of the crop. Emergence corresponds to DVS=0, anthesis to DVS=1 and maturity to DVS=2. Development stages are determined by the accumulated number of degree-days.

Potential evapotranspiration was calculated from daily weather data using the Penman-Monteith equation (Allen et al., 1998). At the bottom of the soil profile, unit-gradient free drainage was used as boundary condition. SWAP simulates 1-D vertical soil water flow using the Richards equation and an implicit finite difference scheme (Van Dam and Feddes, 2000). Relations between soil water content, pressure head and hydraulic conductivity are described by the Van Genuchten (1980) equations:

$$\Theta = \left[1 + |\alpha h|^n \right]^{\frac{1}{n}-1} \quad [3.1]$$

$$K = K_{sat} \Theta^\lambda \left[1 - \left(1 - \Theta^{\frac{n}{n-1}} \right)^{1-\frac{1}{n}} \right]^2 \quad [3.2]$$

in which $\Theta = (\theta - \theta_r) / (\theta_s - \theta_r)$, θ , θ_r and θ_s are water content, residual water content and saturated water content ($\text{m}^3 \text{m}^{-3}$), respectively, h is the pressure head (m), K and K_{sat} (m d^{-1}) are hydraulic conductivity and saturated hydraulic conductivity, respectively, and α (m^{-1}), n , and λ are empirical parameters. Relative transpiration T_r , the ratio between actual (T_a , m d^{-1}) and potential (T_p , m d^{-1}) transpiration is calculated using an adapted version of the reduction function proposed by Feddes et al. (1978):

$$T_r = \frac{T_a}{T_p} = \frac{\sum_p^n \alpha_p w_p R_p}{\sum_p^n w_p R_p} \quad [3.3]$$

where p is the soil layer number, n is the total number of soil layers, w_p (m) is the thickness of layer p , R_p is the relative root length density in layer p and α_p is the empirical reduction factor for layer p , defined by four typical soil water pressure heads h_1 , h_2 , h_3 , and h_4 , as follows: no uptake ($\alpha = 0$) occurs in the very wet ($h_p > h_1$) and very dry ($h_p < h_4$) range. Uptake is maximum ($\alpha = 1$) in the constant rate phase, for h_p between h_3 and h_2 . When h_p is between h_3 and h_4 , or between h_2 and h_1 , the reduction factor T_r is interpolated linearly. The relative reduction in biomass accumulation is considered equal to the relative transpiration T_r as calculated by equation [3.3].

Results from the calibration and evaluation procedures of the SWAP model described in chapter 2 were used in this chapter. Some of the parameters are available in Table 2.4. Further specific information for different crops can be found at Boons-Prins et al. (1993) report.

3.2.3. Soil hydraulic properties

Values for parameters α , n , θ_r and θ_s from equations [3.1] and [3.2] were estimated for each soil layer using the Tomasella et al. (2000) pedotransfer function developed based on data of more than 500 horizons in Brazilian soils:

$$X_i = a_{i,1} + a_{i,2}S + a_{i,3}C + a_{i,4}D_b + a_{i,5}C_o + a_{i,6}S_C S_F + a_{i,7}S_C S + a_{i,8}S_C C + a_{i,9}S_F S + a_{i,10}S_F C + a_{i,11}SC + a_{i,12}CS^2 + a_{i,13}FS^2 + a_{i,14}S^2 \quad [3.4]$$

where X_i is a parameter value, being $X_1 = \log(\alpha)$, $X_2 = n$, $X_3 = \theta_s$ and $X_4 = \theta_r$. S_C , S_F , S and C are the mass fractions (in %) of coarse sand (2-0.2 mm), fine sand (0.2-0.05 mm), silt (0.05-0.002 mm) and clay (<0.002 mm), respectively; D_b is the soil bulk density (g cm^{-3}); C_o is the mass fraction (in %) of soil organic carbon. Coefficients $a_{i,j}$ ($1 \leq i \leq 4$; $1 \leq j \leq 14$) are pedotransfer fitting coefficients described in Tomasella et al. (2000) – their table 8.

The available soil database did not contain specific data for coarse and fine sand as needed in equation [3.4], therefore, in agreement with reports for similar soils (Rosa et al., 2003; Resende and Rosolem, 2013) we assumed equal values for both fractions. Saturated hydraulic conductivity K_{sat} for the Correntina sandy soil was 2.66 m d^{-1} (Pinto et al., 2015), and for the clayey soils we used 0.216 m d^{-1} as determined by Hunke et al. (2015) for a similar

soil. For the λ parameter in equation [3.2], the value of 0.5 was used according to Mualem (1976).

3.2.4. Scenario with modified climate variables

Statistical weather generator software uses data series and its statistical properties to produce a series of synthetic daily climatic data (Pinheiro et al., 2017). The Climatic data generator (ClimGen) described by Stöckle, Campbell and Nelson (1999) was used to generate daily data from year 2016 to year 2040, for two locations in the Cerrado biome. Baseline data from the period 1975-2014 and 1980-2014 were used for the stochastic series realizations, for the medium and clay soil, respectively. The synthetically generated daily weather data consist of rainfall, daily maximum and minimum temperature, solar radiation, air humidity, and wind speed.

Scenarios with modified climate variables were implemented according to the regional downscaling performed by Marengo et al. (2012) for the Brazilian territory. In the generated period of time, 9% of rainfall reduction and 1.9 °C of air-temperature increase are projected for the Amazon basin, corresponding to our clay soil. While for the São Francisco basin (medium texture soil) is projected rainfall reduction up to 15% and air-temperature increase in the order of 1.5 °C.

Rainfall reduction and temperature increase were linearly incorporated into a stochastic weather generator model such that the maximum changes were reached by the year 2040. As the stochastic weather generator relies on random numbers, one hundred stochastic realizations were performed in order to obtain scenarios with more representativeness. The 100 generated weather datasets were integrated into the agro-hydrological model SWAP, resulting in 100 water balance simulations for each year of the period.

3.2.5. Land and water productivity

Land and water productivity for soybean and maize were determined from the output of SWAP simulations. Land productivity Y (kg ha⁻¹) was considered as the final dry grain mass per hectare and is a SWAP output variable. Water productivity Ω (kg m⁻³) was calculated from land productivity and accumulated evapotranspiration ET_a (m) during the crop development as:

$$\Omega = \frac{Y}{10^4 ET_a} \quad [3.5]$$

where the factor $10^4 \text{ [m}^2 \text{ ha}^{-1}\text{]}$ stands for the conversion between square meters and hectares. The water productivity increase obtained by irrigation unit ($\Delta\Omega_I$, kg m^{-3}) was estimated by the difference between the respective land productivity in an irrigation scenario Y_I (kg ha^{-1}) and in the rainfed scenario Y_0 (kg ha^{-1}), divided by the amount of applied irrigation water (I , m):

$$\Delta\Omega_I = \frac{Y_I - Y_0}{10^4 I} \quad [3.6]$$

3.3. Results and discussion

3.3.1. Generated climatic data

The 100 stochastic daily rainfall series simulated by ClimGen for each year in the period 2016-2040 resulted in total annual rainfall ranging from 1283 to 1392 for areas with medium texture soil, while for clay soil areas it ranged from 1794 to 1903 mm (Fig. 3.1). Annual average was 1333 and 1850 mm and the average standard deviation was 194 and 230 mm, respectively. As result of the incorporated alterations in rainfall and air-temperature, a decrease tendency can be observed in the rainfall for both locations and an increase in the air temperature. The average observed data from INMET rainfall baseline climate series is 1451 mm (± 225) for the medium soil and 1943 mm (± 327) for the clay soil, while temperature for the respective area is 24.7°C (± 2.2) and 27.2°C (± 2.5).

Figure 3.1 – Mean annual rainfall and air temperature with trend lines $\pm$ standard deviations of 100 stochastic daily data series associated with rainfall reduction and air temperature increase simulated for 2016-2040 relative to 1975-2014 at a medium texture soil and 1980-2014 at a clay soil

3.3.2. Hydrological, crop and productivity simulation

Changes in the climatic elements as rainfall and temperature affect hydrologic processes (McKenney and Rosenberg, 1993). Although the increasing air temperature and decreasing rainfall usually lead to an evapotranspiration increase (Abteu and Melesse, 2013), it varies with regions and climatic conditions (Wang et al., 2014). In this study, decrease tendencies of 4% and 1.5% were observed in the medium texture and clay soil areas, respectively.

Simulated actual transpiration, actual evaporation and plant interception for the medium texture and clay soil areas are shown in Figs 3.2 and 3.3 and Table 3.2. There is a tendency of decreasing plant transpiration and plant interception along the predicted years for both areas, for two emergence dates. Evaporation increased independently of the emergence date.

Slight differences could be observed when the two emergence dates are compared for each crop. For maize in areas of the medium texture soil, at ED1 in the year 2039-40, the predicted values of transpiration, evaporation and interception ranged between 133-298, 168-281, and 5-33 mm, respectively. At ED2, all the three water balance components were higher

than at ED1, 13% for transpiration, 27% for evaporation, and 21% for interception. Comparing the average of these two emergence dates to the results of 42 maize plots of the same site during agricultural years 2006-2014 (Table 3.3) with average transpiration ranged between 288-352 mm, a decrease of 21% of transpiration and 43% of interception for the agricultural year 2039-40. Meanwhile, an increment of 22% for evaporation occurred.

Figure 3.2 – Mean annual actual transpiration, actual soil evaporation and maize interception losses with their standard deviation and trend lines in one emergence date at a medium texture soil

Figure 3.3 – Mean annual actual transpiration, actual soil evaporation and soybean interception losses with their standard deviation and trend lines in one emergence date at a clay texture soil

According to the described trend in the annual accumulated rainfall values in the oncoming years, improvements on water use turn out to be necessary. In comparison to 2006-2014, Y should decrease linearly along the years (Fig. 3.4 and Table 3.4), independent of the ED. Consequently, the behaviour of Ω follows the same trend in both EDs. In the last

agricultural year, maize Y will reach 6161 and 6039 kg ha⁻¹ at ED1 and ED2 the medium texture soil areas. The annual decline rate will be in the order of 51 and 46 kg ha⁻¹, higher in first ED probably due to the rainfall regime that is not very regular in the early cropping season. Ω will decrease linearly until an average of 1.0 kg m⁻³ in the agricultural year 2039-40.

Regarding the clay soil area and the current yield scenario, soybean Y decreases in the period 2016-2040, reaching 2227 and 2420 at ED1 and ED2, respectively. This represents a magnitude of around 20% less productivity than in the current scenario, and an annual decline rate of 11 and 17 kg ha⁻¹, while Ω decreased 42%.

For the soybean crop in 2039-40 in the clay soil areas, transpiration decreased 6% in the ED2 (Table 3.2) when compared to ED1 (Figure 3.3), while evaporation and interception increased 35% and 25%. When the average of the two soybean emergence dates is compared to the results from 2006-20014 for 19 plots (Table 3.3), transpiration increased 10% and evaporation, 26%. In the mean time, interception was 32% lower.

Figure 3.4 – Mean simulated land productivity with their standard deviation and trend lines in one emergence date in a medium and clay texture soil

Table 3.2 – Transpiration, evaporation and plant interception rate for one emergence date in a medium texture and a clay soil, for 2016-2040

	Medium	Clay
Emergence date	24-November	03-November
Transpiration _{ini} (mm)	296.2	199.2
SD	20.2	13.8
Transpiration _{final} (mm)	265.7	183.8
SD	25.4	13.5
Rate	-1.3306	-0.8761
Evaporation _{ini} (mm)	279.6	371.7
SD	20.5	23.3
Evaporation _{final} (mm)	326.0	413.0
SD	25.7	25.7
Rate	0.9012	0.6759
Interception _{ini} (mm)	31.4	28.7
SD	6.2	4.5
Interception _{final} (mm)	23.3	20
SD	6.1	3.8
Rate	-0.3798	-0.3859

Table 3.3 – Predicted water balance components and standard deviations (bottom flux, plant interception, transpiration, evaporation and infiltrated water), and land and water productivity for a medium and a clay soil under present climate scenario

		B _{Flux} ^a	Interc ^b	Runoff	Transp ^c	Evap ^d	I _{water} ^e	Y	Ω
Soil texture		mm				kg ha ⁻¹			
Medium		-597	37	20	320	206	1156	7756	1.48
	SD	83	6	4	32	13	68	1272	
Clay		-745	33	263	172	260	1234	2920	0.685
	SD	172	5	3.8	22	15	157	272	

Average annual rainfall at the medium texture soil = 1210 mm crop cycle⁻¹ and at the clay soil = 1530 mm crop cycle⁻¹. ^aBottom flux; ^bCrop interception; ^cTranspiration; ^dEvaporation; ^eInfiltrated water.

Evapotranspiration is not water-limited in places with high accumulated rainfall. At the medium texture soil area, 30 years average annual rainfall ranged from 1216 mm to 1642 mm, while at the clay area, ranged from 1285 mm to 2053 mm, concentrated in around half of the year from September to April. In the medium texture soil area, transpiration decreased in relation to the current scenario. As the rainfall amount was reduced over time, soil drier condition became prevalent, thus reduced water flow towards roots is expected due to frequently lower unsaturated hydraulic conductivities of coarse textured soils areas when compared to those of fine texture (Reichardt and Tim, 2004).

Regarding root water uptake, soil water availability is important in the surface layers in the Cerrado region because the annual crops usually have higher root density at a small

soil depth. Daily average soil water pressure head over two depths at the beginning (2016-17) and at the end of the simulated period show large variations during cropping seasons, especially for 2039-40 (Fig. 3.5).

In the agricultural year 2039-40 year, drought stress was simulated close to the maize anthesis, from DVS 0.86 to 1.29 (November 16, 2039 to December 8, 2039), with pressure head values reaching -2226 cm. Although at this stage of crop development the root system is close to reach the maximum depth, the pressure head was below h_3 in both soil layers, and water depletion in the soil profile lead to an average relative biomass reduction of 0.6.

Figure 3.5 – Soil water pressure head at 0-0.2 and 0.2-0.4 m depth along the maize cropping for the first (2016-2017) and last (2039-2040) simulated year. Values of h_2 and h_3 according to Feddes et al., 1978.

Under potential evapotranspiration conditions during this time of the crop cycle, the simulated crop could accumulate 8626 kg ha^{-1} of total plant mass. Later in the season, during the month of December and the beginning of January, a sequence of rain events was simulated, and soil water pressure head was between the limits of the high and the low transpiration rates, where it is possible to the crop to maintain an adequate root water uptake.

It is also important to mention that, in comparison to the agricultural year 2016-17, the temperature increase lead to a shortening of the maize cycle, as well as for the soybean cycle in the clay soil area. Temperature increase is also defining transpiration rates during the rainy season in these two situations. In regions with high rainfall and consequently, elevated air humidity and a proper soil water content for the crop, transpiration rates increase.

Table 3.4 – Average predicted land and water productivity, angular and linear coefficients of the tendency line at a medium texture (maize crop) and clay soil (soybean)

Soil texture	Emergence date	Y_{ini}	a	R^2	Ω_{ini}	b	R^2
		kg ha ⁻¹	kg ha ⁻¹ y ⁻¹		kg m ⁻³	kg m ⁻³ y ⁻¹	
Medium	8-Oct	7274	-51	0.9292	1.205	-0.007	0.9412
	24-Nov	7168	-46	0.8975	1.242	-0.007	0.8502
Clay	29-Sep	2477	-11	0.8776	0.397	-0.001	0.7456
	3-Nov	2846	-17	0.9758	0.499	-0.002	0.7642

3.4. Conclusions

1. Rainfall amount reduction over time provides a soil drier condition, and soil water flow to the roots is expected to be reduced due to frequently lower unsaturated hydraulic conductivity values in coarse textured soil area when compared to those of fine texture. As a consequence, transpiration decreased 21% in the medium texture soil area.
2. Temperature increase has shown to increase transpiration in 10% during the rainy season in clay soil area.
3. Maize and soybean land productivity decreased approximately 20% in the medium texture soil area and in the clay soil area, by the end of the predicted years. Water productivity decreases ranged from 28 to 47%.

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