Peer-reviewed version available at *Water* **2018**, *10*, 1820; doi:10.3390/w10121820

Article

A smart irrigation tool to determine the effects of ENSO on water requirements for tomato production in Mozambique

Eduardo Gelcer[1,2], Clyde W. Fraisse[1*], Lincoln Zotarelli[3], Daniel Perondi[1], Hipólito A. Malia[4], Carvalho C. Ecole[4], and Kati W. Migliaccio[1]

[1] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, 32611, USA.
[2] CAPES Foundation, Ministry of Education of Brazil, Brasilia, DF, 70040-020, Brazil.
[3] Horticultural Sciences Department, University of Florida, Gainesville, FL, 32611, USA.
[4] Mozambique Institute of Agricultural Research, Maputo, 3658, Mozambique.
*Correspondence: cfraisse@ufl.edu; Tel.: +1-352-392-1864 ext 271

Abstract: Irrigation scheduling is used by growers to determine the right amount and timing of water application. In most parts of Mozambique, 90% of the total yearly precipitation occurs from November to March. The El Niño Southern Oscillation (ENSO) phenomenon influences the climate in Mozambique and affects the water demand for crop production. The objectives of this work were to quantify the effects of ENSO phenomenon on tomato crop water requirements, and to create the AgroClimate irrigation tool (http://mz.agroclimate.org/) to assist farmers in improving irrigation management. This study was based on daily grid-based climate information from 1983 to 2016 from the Climate Forecast System Reanalysis. Daily crop evapotranspiration was calculated by Hargreaves equation and crop coefficients. This tool is available online and considers different planting dates, ENSO phases, and crop growing season lengths. Irrigation needs varied from less than 250 mm per growing cycle during winter to 550 mm during spring. Both El Niño and La Niña influenced the irrigation scheduling, especially from November to March. El Niño periods were related with increased water demand due to drier and warmer conditions while the opposite was observed for La Niña. The ENSO information might be used to understand climate variability and improve tomato irrigation scheduling in Mozambique.

Keywords: irrigation scheduling; *Solanum lycopersicum*; El Niño; water stress; decision support system; climate variability

---

1. Introduction

Tomato (*Solanum lycopersicum*) is the horticultural crop with the third largest area in Mozambique, only behind pumpkin and cucumber. Tomatoes are produced by more than 270,000 growers using an area larger than 36,000 ha [1]. Family agriculture accounts for approximately 84% of the tomato production area in the country [2]. For most areas in Mozambique, 90% of the rain occurs from November to March. However, the main tomato production season extends from March to October, which is the period with proper air temperatures for the crop development [3]. Therefore, irrigation is an essential practice for tomato production in the country. The irrigated area in Mozambique is around 118,000 ha [2] however, only 34% of the area is operational [4].

An adequate irrigation schedule defines the correct amount of water and the correct time for its application [5] and is beneficial during both dry and rainy seasons by providing more efficient use of water resources and less irrigation related leaching of agrochemicals. Patane et al. (2012) [6] observed that water stress during initial growth negatively affected tomato marketable yield. However, water

Peer-reviewed version available at *Water* **2018**, *10*, 1820; doi:10.3390/w10121820

restriction after flowering did not result in significant yield losses. Allen et al. (1998) [7] reported that tomato crops can tolerate up to 60% water deficit, while Marouelli et al. [8] reported that the tolerable deficit varies from 20% for sandy soils to 40% for clay soils.

Since growers cannot modify the weather conditions by modifying the microenvironment (e.g. cultivation under high tunnels) to avoid its variability, they have to understand how the variability occurs to benefit from it and to minimize its negative effects [9]. The El Niño-Southern Oscillation is the main phenomenon influencing climate variability around the world [9–13] and in Mozambique [3,14,15]. In Mozambique, the warm phase of ENSO (El Niño) is related to drier and warmer conditions in most parts of the country from December to May, while the cold phase of ENSO (La Niña) has the opposite effects during the same period [16]. Few authors have reported the effects of ENSO on horticultural production in Africa in general and in Mozambique in particular. ENSO phenomenon has greater impact on tomato crop planting date during the southern hemisphere fall and spring seasons than during the winter and summer [3]. Although ENSO influences the weather patterns during the summer, the air temperature and rainfall amounts are excessively high for tomato production, independently of the ENSO phase. Stige et al. (2006) [12] asserts that food production in Africa might be severely affected by ENSO conditions and observed 20-50% yield reduction for row crops in southern Africa during strong El Niño years. El Niño has been related to early start and termination of the rainy season and inconsistent rain events, causing increased dry spells [17].

The AgroClimate Mozambique (http://mz.agroclimate.org/) [16] is a decision support system created to organize climate and weather information in a user-friendly way, to inform the impacts of weather on specific crops as well as to provide management adaptation suggestions aimed at reducing crop production risk and increasing resource use efficiency. As climate information is only valuable if there is a clear management adaptation related to it [9], AgroClimate aims to assist growers, extension agents and researchers in the use of weather information to make management adaptations to reduce risks associated with climate variability. The AgroClimate Mozambique provides knowledge regarding the climate inter- and intra-years variability as well as information to help farmers make both strategic pre-season decisions and in-season operational decisions [18].

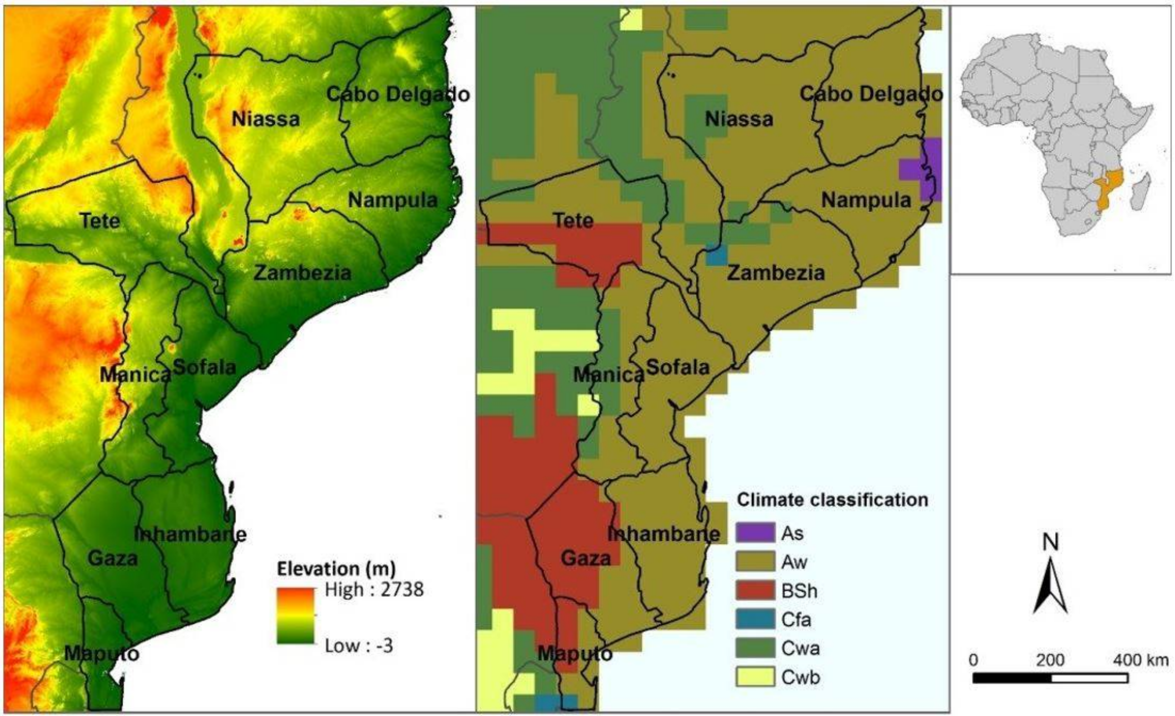
Due to lack of weather-related information and lack of soil sensors, growers typically make crop water management decisions based on field observations rather than on field measurements or on model estimations. An alternative solution for farmers is to use simple models based on crop evapotranspiration. These models have been developed to define the water requirement by a specific crop and to improve irrigation efficiency [5,19]. Muñoz-Carpena et al. (2005) [20] observed similar tomato crop yield when comparing traditional irrigation management with irrigation schedules based on historical evapotranspiration, tensiometers, and granular matrix sensor. The schedule based on historical evapotranspiration applied 45% less water than the traditional management, 39 to 51% more water than the treatments using tensiometers, and similar amount when compared with the matrix granular sensor. The last one is a more modern sensor, made of a porous material, similar to a tensiometer and that has been used in automatic irrigation systems. Water savings have been reported when using evapotranspiration based irrigation schedule compared to traditional (time-based) irrigation schedule for turfgrass [21,22]. Vellidis et al. (2016) [23] observed that ET-based irrigation schedule for cotton production over performed traditional schedule in yield, water use efficiency, and water application. The ET-based method had performance comparable with soil moisture sensors. However, model application is limited due to the large amount of inputs required, especially weather information which is not freely and widely available in Mozambique.

As ENSO is related to climate variability, and environmental conditions directly influence the water requirement of crops, the first objective of this study was to identify how the ENSO phenomenon affects crop water requirements for tomato production in Mozambique. The second objective was to develop the AgroClimate Mozambique irrigation tool (http://mz.agroclimate.org/) [16] to assist farmers in improving irrigation management, and reducing plant water stress and water losses.

2. Materials and Methods

2.1 Study area

Located in southeastern Africa, between the latitudes -10°28′ and -26°52′, with elevations varying from 0 to 2400 m above sea level (Figure 1 a), Mozambique has strong maritime influence, since the coast extends for more than 2400 km [24]. Several climates are observed within the country due to the latitude and elevation variability. Based on the Köppen-Geiger classification (Figure 1 b), the climate in Mozambique is equatorial savannah with dry winters (Aw) with some areas having hot semi-arid climate (BSh), while higher-elevation regions have warm temperate climate with dry winters and hot summers (Cwa) [25]. In the western part of Gaza, one of the driest regions of the country, the yearly rainfall is around 200 mm while in the Zambezia province, the annual rainfall is around 1200 mm [26]. In most parts of Mozambique, more than 90% of the annual rainfall occurs from November to March while less than 10% occurs from April to October. In November, the average maximum air temperature may reach 40 °C in lower elevation regions in the central part of the country. In June and July, the air temperature might be as low as 6 °C in high elevations at the Manica, Tete and Niassa provinces. The yearly average air temperature varies between 20 and 26 °C throughout the country [16].



(a) (b)

Figure 1. (a) Elevation (MapMart, 2014[1]) and (b) climate of Mozambique using Köppen classification [25]. As = Equatorial savannah with dry summer, Aw = Equatorial savannah with dry winter, BSh = Hot Steppe climate, Cfa = Warm temperate climate, fully humid with hot summer, Cwa = Warm temperate climate with dry winter and hot summer, and Cwb = Warm temperate climate with dry winter and warm summer. Source: Gelcer et al. (2018) [3].

2.2 Crop evapotranspiration

The water requirement of a crop is the same as the crop evapotranspiration (ET_C, mm day^{-1}), which is calculated by multiplying the reference evapotranspiration (ET_O, mm day^{-1}) by a crop coefficient (K_C) [7]:

$$ET_C = ET_O * K_C \tag{1}$$

---

[1] http://www.mapmart.com/

the Kc values vary depending on the crop development phase. For the present studies, the Kc values were adapted from [7,8,27] (Table 1). The length of each growing phase was estimated based on [7] using the same relative length of each phase for all growing cycles.

Table 1. Days after planting and crop coefficient (Kc) for each development phase for three generic varieties of tomato with 75-d, 90-d and 105-d growing cycle. Adapted from [7,8,27].

Development phase	Days after planting			Kc
	75-d cycle	90-d cycle	105-d cycle	
Initial growth	0-17	0-20	0-24	0.60
Crop development	18-39	21-47	25-55	0.90
Late season	40-61	48-74	56-86	1.15
Harvest	60-75	75-90	87-105	0.90

The ETo was calculate using the Hargreaves method [28], since this method only requires air temperature data and showed low error for Mozambique when compared to ETo estimated using the FAO-56 Penman-Monteith equation [29,30], which is the standard equation to estimate ETo. The Hargreaves equation is:

$$ET_O = 0.0023(T_{avg} + 17.8)(T_{max} - T_{min})^{0.5} R_a \tag{2}$$

where, T_{max} and T_{min} are maximum and minimum air temperatures (°C); T_{avg} is daily mean air temperature (°C), based on the average of T_{max} and T_{min}; and R_a is extraterrestrial radiation (MJ m^{-2} d^{-1}) [7]. Daily historical gridded-based air temperature information was obtained from Climate Forecast System Reanalysis (CFSR) [31] with spatial resolution of 0.25°x0.25° for the period between 1983 and 2016.

2.3 Irrigation schedule

The growing season length varies depending on the variety and period of the year. Therefore, three possible growing cycles represented by three generic (hypothetical) varieties with 75-day, 90-day, and 105-day growing cycle (from planting to harvest) were selected. The irrigation schedule used 24 possible planting dates per year, the first and the sixteenth day of each month. For each planting date and crop variety, the average daily ETc based on all years with available data was determined. As most farmers in Mozambique have limited or no access to internet, the irrigation schedule does not need access to in-season weather information and was based on average of historical values of ETc. For each variety, daily ETc was calculated using the daily ETo and the corresponding Kc for the crop development stage (Table 1).

For ease of management and to reduce the number of adjustments in the irrigation equipment during the growing season [5,32], the irrigation amount was kept constant for a 10-day period, similar to the irrigation scheduling tool developed by Migliaccio et al. (2015) [22]. The water depth per irrigation event was determined by dividing the 10-day total ETc by the number of irrigation events in that period. The number of events varied depending on the crop development stage and on the root zone depth. Early growth stages received irrigation more frequently at lower rates due to shallower root zone, while the crop development and late season phases had higher application rates [5]. As recommended by Marouelli et al. (2008) [8], irrigation events ceased five days before the end of the season to increase the uniformity of the tomato fruits and soluble solid content, and to reduce the chances of disease occurrence. The irrigation tool provides the frequency of irrigation events as well as the water depth. Table 2 shows the frequency of application for each 10-day period.

Table 2. Recommended interval between irrigation events for three crop varieties (75-d, 90-d and 105-d growing cycles) from day 1 after planting (DAP) until the end of the cycle.

75-d cycle		90-d cycle		105-d cycle	
DAP	Irrig. Freq.	DAP	Irrig. Freq.	DAP	Irrig. Freq.
1-10	Daily	1-10	Daily	1-10	Daily
11-20	2 day	11-20	2 day	11-20	2 day
21-30	3 day	21-30	3 day	21-30	2 day
31-40	3 day	31-40	3 day	31-40	3 day
41-50	3 day	41-50	3 day	41-50	3 day
51-60	3 day	51-60	3 day	51-60	3 day
61-70	4 day	61-70	3 day	61-70	3 day
71-75	No irrig.	71-80	4 day	71-80	3 day
		81-85	4 day	81-90	4 day
	-	85-90	No irrig.	91-100	4 day
	-		-	101-105	No. irrig

2.4 Irrigation Schedule pre-evaluation

A soil water balance for each year was performed to quantify the daily soil water deficit and verify if the proposed irrigation schedule meets the crop water demand. The water balance used the methodology proposed by Woli et al. (2012) [33] to estimate soil water content:

$$W_i = W_{i-1} + I_i - T_i - D_i - R_i \tag{3}$$

where, W_i and W_{i-1} are the available water (mm) in the root zone on *i*th and (*i*-1)th days, I_i is the irrigation amount (mm), T_i is the crop transpiration (mm), D_i is drainage (mm), and R_i is runoff (mm) on the *i*th day. Drainage and runoff were calculated as described by Woli et al. (2012) [33]. The only input of water was through irrigation based on the calendar. Rainfall was not included in the soil water balance because it has low importance during the main tomato growing season. In addition, the large year to year weather variability are not well represented by average historical rainfall values do not represent the current situation.

To adjust the water balance for a tomato crop, daily ET_C replaced daily ET_O to calculate T_i and the root depth had a linear growth from 6 cm on the planting day to 40 cm on the 40th day of the cycle. Soil field capacity (FC) and permanent wilting point (PWP) were calculate using the soil information provided by ISRIC – World Soil Information (2013) [34] and the methodology proposed by Rawls et al. (1982) [35].

For irrigation management, the readily available water (RAW) is the operating range of soil water content [36]. The RAW is the fraction (p) of the total available water (TAW) that can be extracted from the root zone without suffering water stress. If the soil water content is between RAW and TAW, the crop does not suffer with water stress [7]:

$$\mathrm{RAW} = \mathrm{p} * \mathrm{TAW} \tag{4}$$

$$\mathrm{TAW} = 1000(\theta_{FC} - \theta_{PWP}) * Z_r \tag{5}$$

where, θ_{FC} and θ_{PWP} are the soil water content at soil field capacity and permanent wilting point (m m^{-3}), and Z_r is the rooting depth (m). According to Marouelli et al. (2008) [8], p for tomato varies from 0.6 for clay soils to 0.8 for sand soils.

2.5 Influence of ENSO on Irrigation Schedule

The online irrigation tool provides irrigation schedule for each ENSO phase to help growers utilize the expected ENSO cycle for improving their irrigation management during the season. Each one of the 792 growing cycles (33 years x 24 planting dates per year) was classified as El Niño, La

Peer-reviewed version available at Water 2018, 10, 1820; doi:10.3390/w10121820

Niña, or Neutral using the Oceanic Niño Index (ONI) from NOAA[2] (Appendix A). Then, the average daily ET_C per ENSO phase per planting date was calculated and grouped as described in the section *2.3 Irrigation* schedule.

To identify how ENSO warm and cold phases influence tomato water requirements, crop water requirement maps were created showing the deviation from historical average (average for all years) when El Niño or La Niña was present. For this evaluation, a generic variety with 90-day growing cycle was selected. The average of cumulative ET_C for all years with available data was subtracted from the cumulative average ET_C for each ENSO phase. Therefore, a negative or positive deviation indicates that a situation having respectively lower or higher crop water requirement.

2.6 AgroClimate tool development

The irrigation tool available on AgroClimate Mozambique (http://mz.agroclimate.org/rega) is used as a plug-in in CMS Wordpress and was developed using the HTML5, CSS3, and JavaScript languages. The HTML (Hyper Text Markup Language) allows text interpretation by browsers, providing new features [37] and its last generation is the HTML5. The CSS (Cascading Style Sheets) improves the presentation of HTML documents [38] while the CSS affects the format of buttons, address inputs, dialog boxes and windows. JavaScript is an interpreted language with object-orientation capabilities used in web browsers. The scripts built with JavaScript can interact with the users, control the web browsers and alter the document content showed in a browser window [39].

The tool structure (coding) and layout are in Portuguese, the official language of Mozambique. It allows local web-designers to administrate and maintain the tool, and increase the interaction and understanding of the tool by growers. The users have the option to translate the tool to other languages using a Google plug-in. The current study uses screenshots in English to increase the understanding of the tool. All images can be easily downloaded and stored for posterior use to increase outreach opportunities and use of the tool in locations with restricted or no access to internet.

The tool was created based on tools available on AgroClimate Mozambique [3,16], on the AgroClimate version for the Southeast USA [9], and on FAWN [40]. Moreover, the creation of this tool considered suggestions from growers and extension agents from Mozambique, from researchers from the Mozambique Agricultural Research Institute (IIAM), and from the University of Florida. The tool can be easily adapted to other crops, since it relies on the combination of ET_O and K_C to determine an irrigation schedule. This approach has been widely used to determine water demand for several crops [5,7,27,41,42]. For that, the only required parameters are the other crops K_C, length of each growing phase, and total growing season length.

When the user accesses the irrigation tool, the modules and the content are displayed. The first module is composed of the planting date, the second one of the ENSO phase, the third one of the crop type, and the fourth one of the growing season length. When the tool is loaded, a default selection is used but the user can select the best combination that represents their field conditions.

3. Results and discussion

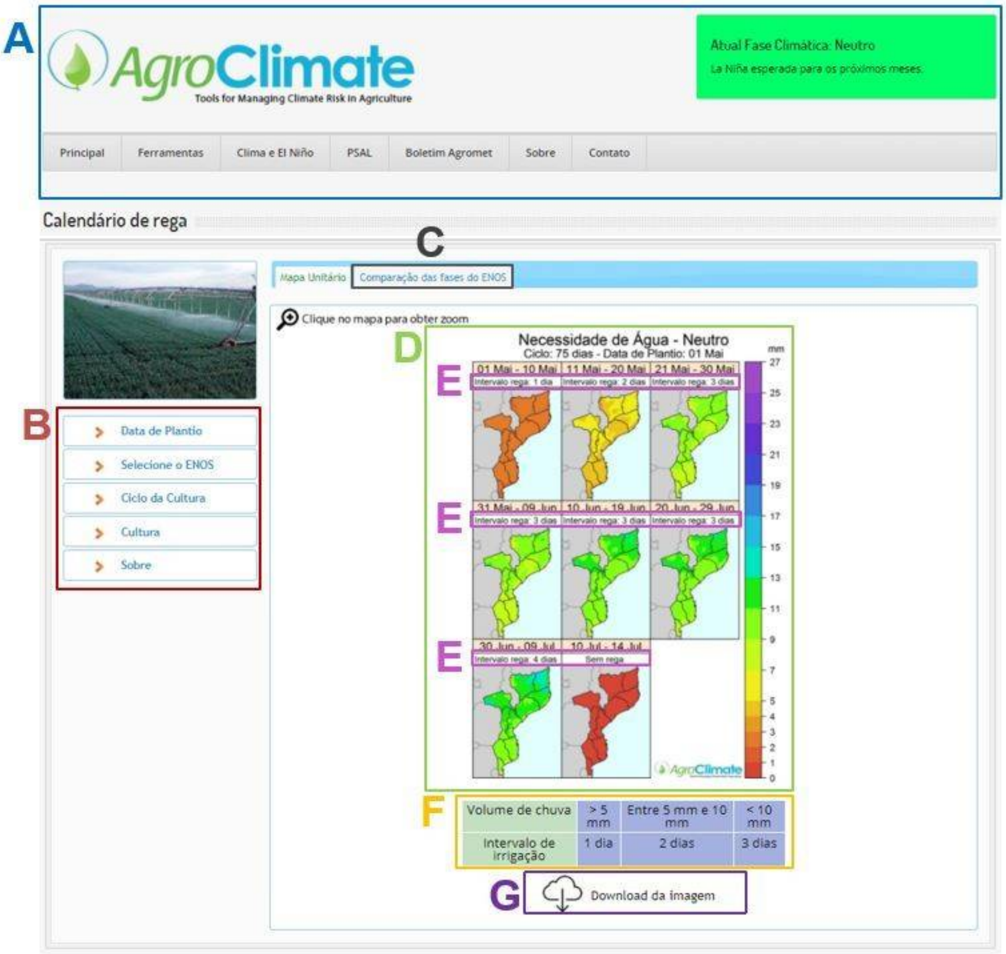
On the pre-evaluation of the tool, the proposed schedule was applied for the 34 years with weather information. The lowest simulated soil water contents (p) were observed for the growing cycles starting from March to May. For the cycles starting from June to February, the use of the tool resulted in values of p close to 1, which means nearly zero water stress. However, between March and May, the values of p were higher than 0.8 in all situations. Marouelli et al. (2008) [8] asserts that the minimum values of p, for tomato vary from 0.6 for clay soils to 0.8 to sand soils. According to Allen et al. (1998) [7] the values of p should be higher than 0.4. These results indicate that the proposed irrigation schedule is appropriate since the slight simulated water stress would not negatively affect the crop.

---

[2] http://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php

The irrigation tool in AgroClimate Mozambique (http://mz.agroclimate.org/rega) presents the daily crop water demand for a 10-day period for Mozambique. For that, the user must select the planting date, ENSO phase, crop type, and growing season length. The maps are then generated showing the irrigation depth per event, in millimeters, the information of irrigation frequency, and a table with days to delay application in the case of rain events (Figure 2). Different maps show the irrigation water depth required for a 10-day period within the growing cycle. The schedule was organized in 10-day periods for easiness of management and due to low variability of ET_O within a period. The average ET_O of a 5-day period can be used to determine daily water requirement for the subsequent 15-day period [43]. Migliaccio et al. (2015) [22] observed different application schedules for irrigation controllers that use on-site evapotranspiration estimative and irrigation schedule based on the nearest weather station. However, they did not observe difference in total water applied and turf grass quality. Vellidis et al. (2016) [23] tested a similar system in Florida and Georgia, USA, and found precise irrigation requirements using an evapotranspiration model. However, their system is based on automated weather stations with real-time data. Such a system using real-time weather data could not be implemented in Mozambique due to its economic feasibility. Moreover, farmers do not access the internet frequently, therefore daily updates using real-time weather data would not result in an effective management adaptation.

The resulting irrigation scheduling tool displays several maps with the irrigation depth per irrigation event, the irrigation frequency, and how many days the irrigation event should be delayed in case of a rainfall event (Figure 2). The Section A (Figure 2 A) shows information about the AgroClimate Mozambique website, the current ENSO phase, and the menu bar. On Section B (Figure 2 B), the user selects the crop management characteristics. Once the user makes any selection, the maps on Section C (Figure 2 C) are updated to match the selection. The Section D (Figure 2 D) has a suggestion of irrigation frequency, which varies depending on the crop development stage, irrigation system, and irrigation depth for the period. The Section E (Figure 2 E) indicates how rainfall events can affect the schedule. Depending on the amount of rain, the irrigation might be delayed for one, two or three days. All images available on the website are available for download (Section F, Figure 2 F) to facilitate their use when internet access is not available or restricted.



Atual Fase Climática: Neutro
La Niña esperada para os próximos meses.

Volume de chuva	> 5 mm	Entre 5 mm e 10 mm	< 10 mm
Intervalo de irrigação	1 dia	2 dias	3 dias

Figure 2. Screenshot of the irrigation scheduling tool in AgroClimate Mozambique (http://mz.agroclimate.org/rega). It shows the daily average water requirement for 90-day cycle tomato crops planted on May 1st. A shows information about the AgroClimate Mozambique website, the current ENSO phase, and the menu bar; B allows the user to select the management options more similar to what is observed in the field; C shows the ENSO phases comparison; D is the irrigation depth for each 10-day period; E is the irrigation frequency; F indicates how rainfall events can affect the schedule and depending on the amount of rain, the irrigation might be delayed for one, two or three days; and G allows the download of the images.

This tool can be used by extension agents and farmers to create an irrigation schedule for the upcoming season and to make in-season decisions. Applying the correct amount of water at the right timing is fundamental for increased water use efficiency and for a successful crop [44,45], as well as for reducing labor, costs and nutrients leaching. During the first ten days of the crop development, the tool can be very helpful to define irrigation needs. During this period, the tomato crop is very sensitive to water stress due to adaptation to the field conditions and due to shallow roots system. However, excess of irrigation can increase the occurrence of diseases and may reduce crops final stand [46]. During vegetative growth, moderate water stress may not affect yield [45] and can contribute for root development [46,47]. However, more severe stress may reduce the total biomass, yield and fruit size [6,48]. Even if moderate stress may benefit the crop development, the tool was designed to result in nearly no water stress since the soils in Mozambique are well drained [49] and waterlogging is less likely to occur than water stress.

Flowering and fruit development are the most sensitive periods for tomato crop [7,46,48]. For these specific crop stages, the online tool can be extremely helpful. Moderate to severe water stress can decrease plant height, stem diameter [47], pollen viability and fruit size [46], and can significantly

Peer-reviewed version available at *Water* **2018**, *10*, 1820; doi:10.3390/w10121820

reduce yield [48]. Differently from the fruit development phase, the maturation phase has a reduced water consumption [27,50] and the irrigation events should occur in larger intervals [46]. Moderate stress during this period, results in slightly reduction in yield but increased brix and fruit quality [46,48,50]. Excess of irrigation increase the risk of diseases but severe stress may result in high yield and quality losses.

The ENSO information in the tool can assist farmers and extension agents to determine crop irrigation needs considering climate variability. ENSO plays a key role to define irrigation needs from February to April. Before February, the conditions are not proper for tomato crop development independently on the ENSO phase [3], and after April, the conditions are similar for all ENSO phases. Due to warmer conditions during El Niño, the irrigation needs are higher than during La Niña cycles and long-term averages. When combined with ENSO forecast, the online tool can be used by farmers to define the irrigation schedule for the upcoming season.

For researchers and irrigation engineers, the online tool helps to set up irrigation trials and design irrigation systems. When setting up a trial in a new location, researchers can use the tool as a baseline to define crop water requirements. The minimum requirements for pump size and irrigation equipment can also be define based on the information generated by the irrigation tool combined with the size of the irrigated area.

3.1 Spatial and temporal variability of water requirements

The total crop water requirement is the total crop evapotranspiration (ETc) throughout the growing season. The ETc is a function of the environmental conditions (air temperature, solar radiation, relative humidity and wind speed) and crop development stage. As the crop and management practices are the same for all maps in Figure 3, the variability in environmental conditions is the only factor causing variation of water needs among the maps. Overall, the locations with lower elevation have higher crop water requirement due to higher air temperature, while locations at higher elevations have lower crop water requirement. At lower elevations in Tete, the average total ETc for a single season can be as high as 550 mm, while at high elevations (>600 m) it does not exceed 400 mm. The highest cumulative ETc values occur for tomato crops planted from September to December in the central and southern regions, especially in Zambezi, Tete, and Sofala, where the average total ETc is always above 400 mm. The minimum values of average total ETc are observed in Niassa for crops planted from February to August when the values might be lower than 250 mm.

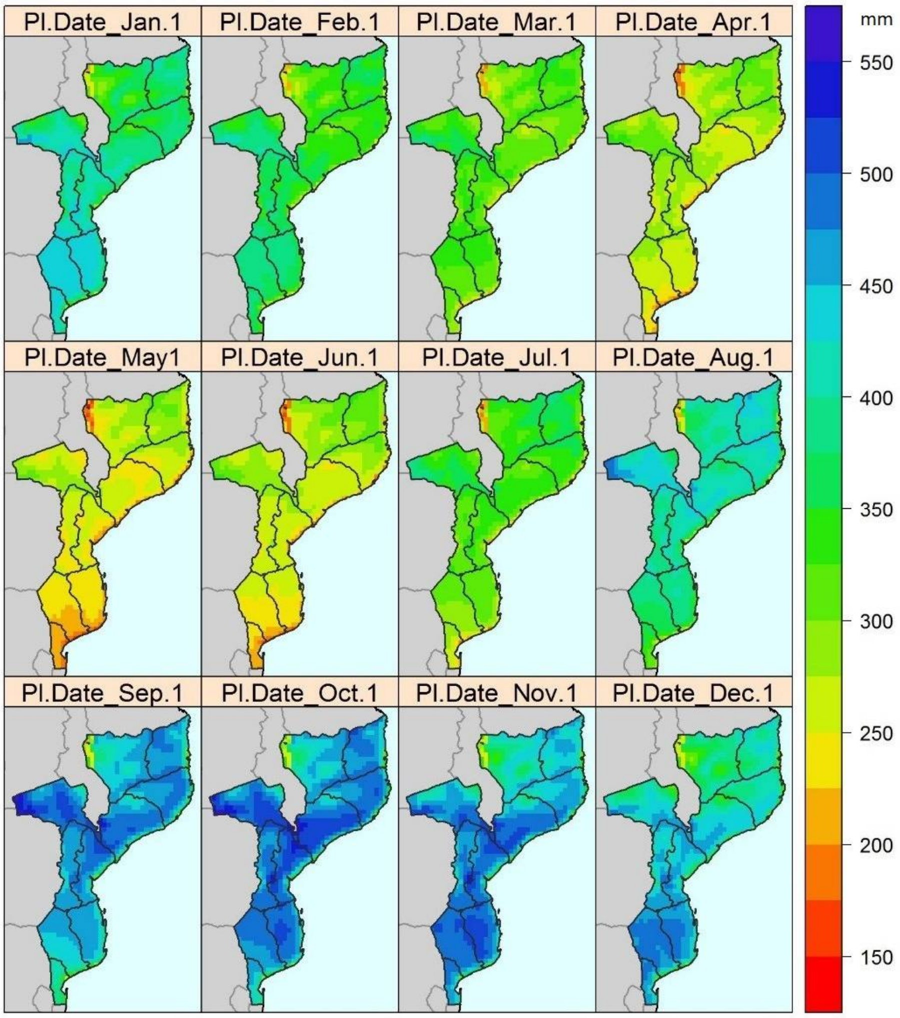


Figure 3. Spatial and temporal variability of tomato crop total water requirement (mm) for Mozambique for a generic variety with 90-day growing cycle planted in the first day of each month.

Although September is the end of winter, the water demand is similar to the one observed during summer (December to February). In September, the rainfall amount is below 15 mm for most parts of the country resulting in high air temperatures, low relative humidity and water demands similar to summer. During summer, the air temperatures are slightly higher than in September, but the relative humidity is also higher and rainfall is abundant, causing an overall reduction in ET_C. Moreover, the crops planted in September have part of the growing cycle in October and November, which are months with the highest air temperatures in several parts of the country [16]. From November to March the irrigation schedule tool might be used to plan the irrigation events to reduce soil water percolation and to avoid the effects of dry spells, especially during critical periods, such crop establishment, flowering and fructification [46]

Tomato crops planted from April to June have the lowest water requirements because they grow in the period with the lowest air temperatures of the year, resulting in lower ET_C. From May to July, the average air temperature varies from 16 to 24^{o}C for most parts of the country. During this period, the irrigation scheduling tool assists farmers to define how much and when water should be applied. As 90% of the rain occurs from October to March, from April to September the water resources are scarce and water for irrigation is limited, and the irrigation tool might be used to optimize water use and reduce crop water stress. Migliaccio et al. (2015) [22] used an irrigation scheduling tool and observed water savings when compared with time-based irrigation, indicating that evapotranspiration-based methods can be employed to improve irrigation management. For Vellidis

Peer-reviewed version available at *Water* **2018**, *10*, 1820; doi:10.3390/w10121820

et al. (2016) [23], evapotranspiration-based schedule provided similar results to soil sensor-based schedule.

3.2 ENSO Influence on water requirement

As ENSO is directly related to variability of rainfall and air temperature in Mozambique, especially during summer months, it also affects the water demand by crops. Both El Niño and La Niña showed influence in water demand, mainly from November to March (Figures 4 and 5). During El Niño, the rain amount is lower during this period causing higher incoming solar radiation and air temperature, and lower relative humidity, resulting in higher ETc. The opposite happens during La Niña, causing reduced water demand. For most parts of Mozambique, especially central and southern parts, the deviation of crop water requirement varies from 10 to 50 mm during El Niño and from -10 to -40 mm during La Niña. In some regions, the difference between El Niño and La Niña varies from 30 to 50 mm, what represents about 10 % of the total crop water demand for the whole cycle. El Niño also presented positive deviations during April in most provinces, during May in the central region, and during October in the south. La Niña had negative deviation in April, June and October in the central part of the country. ENSO had low influence on crop water requirements from May to September since ENSO has lower influence in Mozambique's climate during this period. These results are in agreement with previous ENSO studies in Mozambique. Mavie (1999) [14] and Lobo (1999) [15] observed significant positive deviation for air temperature during El Niño events during summer and no significant difference during winter, which was related to increased crop water requirement during El Niño years.

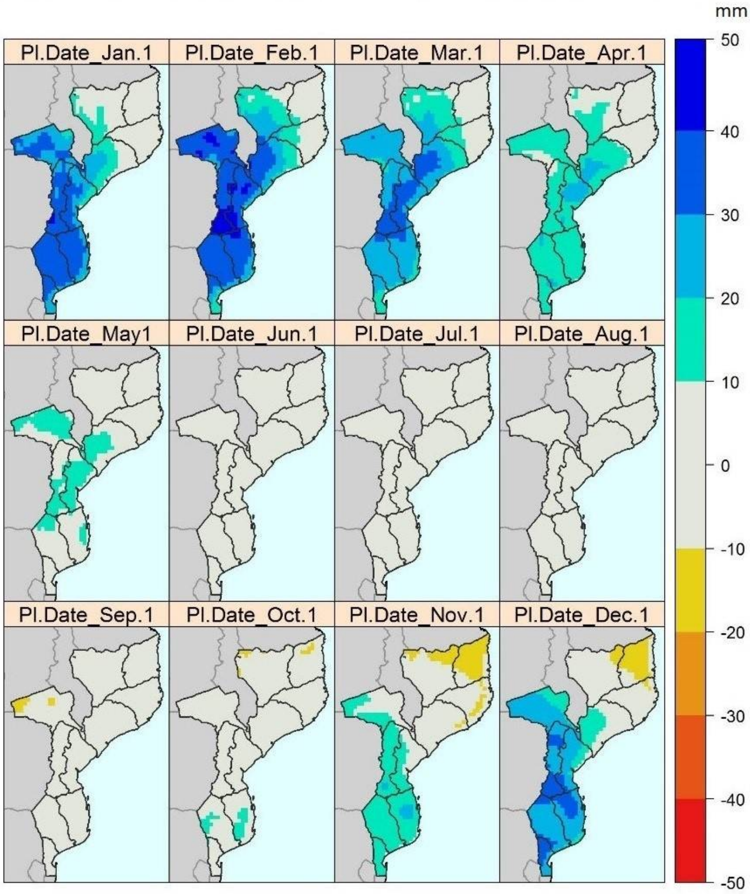


Figure 4. Spatial and temporal of deviation for El Niño of tomato crop total water requirement (mm) for Mozambique for a generic variety with 90-day growing cycle planted in the first day of each month.

Peer-reviewed version available at Water 2018, 10, 1820; doi:10.3390/w10121820

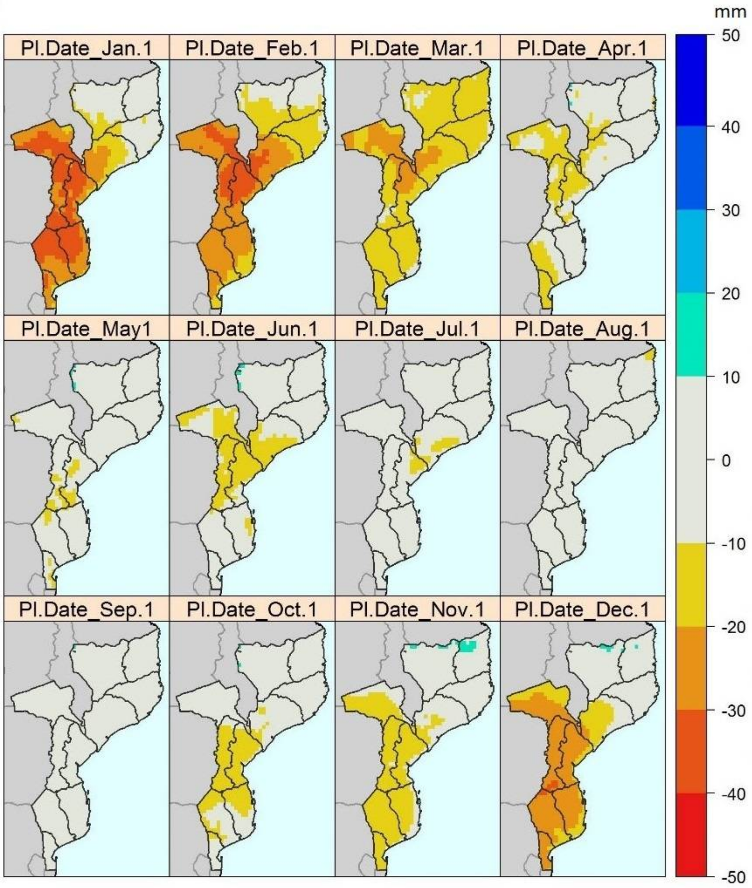


Figure 5. Spatial and temporal of deviation for La Niña of tomato crop total water requirement (mm) for Mozambique for a generic variety with 90-day growing cycle planted in the first day of each month.

Farmers try to plant tomato in February or March when the conditions are not appropriated for the crop development to benefit from higher market price caused by the lack of product available [51]. In these cases, the ENSO information has higher value since this is the period with increased influence of ENSO in the water demand by the crop. The irrigation tool can be used in educational programs to help farmers to understand how crop water requirements vary during the year, and from year to year. The ENSO forecast combined with the tool provides information for decision makers to determine if the water demand is above, below or equal the average of other years. More spatial and temporal information can be obtained from the irrigation tool (http://mz.agroclimate.org/rega) [16].

The irrigation scheduling tool available on AgroClimate Mozambique has some limitations based on the methods used for its development. The crop coefficients utilized in this study may differ from the ones observed in the field due to variations on crop management such as row spacing and variety. Moreover, the ETo was calculated using the Hargreaves equation, which is based on restrict amount of weather variables and the daily values may differ from the real ones. However, most small farmers in Mozambique have no access to information and to water loss quantification, therefore these results are useful to assist them and should be used as guideline to define crop water requirement for a growing season, especially when combined with ENSO forecast. This tool should be used together with local expertise from extension agents and growers. Although there are several climate phenomena affecting the region, such as Indian Ocean Dipole which may affect the rainfall occurrence [52], the ENSO conditions have a certain pattern of occurrence and can be forecasted in advance, making it useful for this type of study. Furthermore, this study is based on gridded data that are result of reanalysis and have coarse spatial resolution. Therefore, the tool may limit the information in regions with large elevation variability and should be interpreted for a whole region and for a single pixel.

4 Conclusions

ENSO-based irrigation schedule can assist farmers to better understand climate variability and plan the irrigation events considering inter-annual climate variability. ENSO-based decisions might be more useful from November to March but it may improve irrigation schedule from April to June and contribute to maximize water use efficiency. El Niño was related to increased water use due to higher air temperatures and solar radiation, and lower relative humidity associated with it. The opposite was observed for La Niña, which was related to reduction in water requirements.

Crops planted from September to December have higher water requirement than crops planted during the remaining of the year. During this period, the total water use by the crop might be as high as 550 mm. During the dry and cold season, the water need was lower, being as low as 250 mm in several parts of the country.

The irrigation tool in AgroClimate Mozambique was designed based on other tools that are widely used, and with the support of potential users. It has a user-friendly interface to display the water demand depending on the planting date, ENSO phase, and crop growing season length. Although the tool does not consider real time data, it might be used by growers and extension agents to reduce the effects of dry spells and percolation during rainy season, and to reduce water stress and maximize the water use during dry season.

Author Contributions: Conceptualization, Eduardo Gelcer, Clyde W. Fraisse, Lincoln Zotarelli , Hipólito A. Malia and Carvalho C. Ecole; Data curation, Eduardo Gelcer and Daniel Perondi; Formal analysis, Eduardo Gelcer; Investigation, Eduardo Gelcer; Methodology, Eduardo Gelcer, Clyde W. Fraisse, Lincoln Zotarelli and Kati W. Migliaccio; Project administration, Clyde W. Fraisse and Lincoln Zotarelli ; Software, Daniel Perondi; Supervision, Clyde W. Fraisse and Lincoln Zotarelli ; Writing – original draft, Eduardo Gelcer and Daniel Perondi; Writing – review & editing, Eduardo Gelcer, Clyde W. Fraisse, Lincoln Zotarelli , Daniel Perondi, Hipólito A. Malia, Carvalho C. Ecole and Kati W. Migliaccio.

Acknowledgments: This study and website (http://mz.agroclimate.org/) are made possible by the support of the American People through the United States Agency for International Development (USAID) under the Feed the Future Initiative. The contents of this study and website are the sole responsibility of authors and do not necessarily reflect the views of USAID or the United States Government.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Three-month ENSO classification using the Oceanic Niño Index (ONI) where NE (⬜) is Neutral, EN (🟥) is El Niño and LN (🟦 is La Niña [53].

Year	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ	DJF
1983	EN	EN	EN	EN	EN	NE	NE	NE	NE	NE	NE	NE
1984	NE	NE	NE	NE	NE	NE	NE	NE	LN	LN	LN	LN
1985	LN	LN	LN	LN	LN	NE	NE	NE	NE	NE	NE	NE
1986	NE	NE	NE	NE	NE	NE	NE	EN	EN	EN	EN	EN
1987	EN	EN	EN	EN	EN	EN	EN	EN	EN	EN	EN	EN
1988	EN	NE	NE	LN	LN	LN	LN	LN	LN	LN	LN	LN
1989	LN	LN	LN	LN	NE	NE	NE	NE	NE	NE	NE	NE
1990	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
1991	NE	NE	NE	NE	EN	EN	EN	EN	EN	EN	EN	EN
1992	EN	EN	EN	EN	EN	EN	NE	NE	NE	NE	NE	NE
1993	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
1994	NE	NE	NE	NE	NE	NE	NE	NE	EN	EN	EN	EN

Peer-reviewed version available at Water 2018, 10, 1820; doi:10.3390/w10121820

1995	EN	EN	NE	NE	NE	NE	LN	LN	LN	LN	LN	LN
1996	LN	LN	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
1997	NE	NE	NE	EN	EN	EN	EN	EN	EN	EN	EN	EN
1998	EN	EN	EN	EN	NE	LN	LN	LN	LN	LN	LN	LN
1999	LN	LN	LN	LN	LN	LN	LN	LN	LN	LN	LN	LN
2000	LN	LN	LN	LN	LN	LN	LN	LN	LN	LN	LN	LN
2001	LN	LN	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
2002	NE	NE	NE	NE	EN	EN	EN	EN	EN	EN	EN	EN
2003	EN	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
2004	NE	NE	NE	NE	NE	EN	EN	EN	EN	EN	EN	EN
2005	EN	EN	EN	NE	NE	NE	NE	NE	NE	NE	NE	NE
2006	NE	NE	NE	NE	NE	NE	NE	EN	EN	EN	EN	EN
2007	NE	NE	NE	NE	NE	NE	LN	LN	LN	LN	LN	LN
2008	LN	LN	LN	LN	LN	NE	NE	NE	NE	NE	NE	NE
2009	NE	NE	NE	NE	NE	EN	EN	EN	EN	EN	EN	EN
2010	EN	EN	EN	NE	NE	LN	LN	LN	LN	LN	LN	LN
2011	LN	LN	LN	NE	NE	NE	LN	LN	LN	LN	LN	LN
2012	LN	LN	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
2013	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
2014	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE
2015	NE	EN	EN	EN	EN	EN	EN	EN	EN	EN	EN	EN

References

1. Instituto Nacional de Estatística. *Censo Agro-Pecuário 2009-2010: Resultados preliminares*; Maputo, Mozambique, 2011.
2. FAO FAOSTAT. Available online: http://www.fao.org/faostat/en/ (accessed on 25 March 2017).
3. Gelcer, E.; Fraisse, C. W.; Zotarelli, L.; Stevens, F. R.; Perondi, D.; Barreto, D. D.; Malia, H. A.; Ecole, C. C.; Montone, V.; Southworth, J. Influence of El Niño-Southern Oscillation (ENSO) on agroclimatic zoning for tomato in Mozambique. *Agric. For. Meteorol*. **2018**, 248, 316–328, 10.1016/j.agrformet.2017.10.002.
4. Ecole, C. C.; Malia, H. A. Caracterização da horticultura em Moçambique. In *Horticultura em Moçambique: Características, tecnologias de produção e de pós-colheita*; Haber, L. L., Ecole, C. C., Bowen, W., Resende, F. V., Eds.; EMBRAPA: Brasília, 2015; pp. 21–31, 978-85-7035-515-7.
5. Henggeler, J. C.; Dukes, M. D.; Mecham, B. Q. Irrigation scheduling. In *Irrigation*, 6th ed.; Mecham, B. Q., Rochester, E. A., Ross, G. A., Sneed, R. E., Vinchesi, B. E., Eds.; Irrigation Association: Falls Church, USA, 2011; pp. 491–564, 978-1-935324-50-8.
6. Patane, C.; Tringali, S.; Sortino, O. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. *Sci. Hortic*. **2011**, 129, 590–596, 10.1016/j.scienta.2011.04.030.
7. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration—Guidelines for Computing Crop Water Requirements—FAO Irrigation and Drainage Paper 56*; FAO: Rome, Italy, 1998.
8. Marouelli, W. A.; Silva, W. L. C.; Silva, H. R. *Irrigação por Aspersão em Hortaliças: Qualidade da Água, Aspectos do Sistema e Métodos Práticos de Manejo*; 2nd ed.; Embrapa Informação Tecnológica: Brasília, Brazil, 2008; 978-85-7383-428-4.
9. Fraisse, C.; Breuer, N.; Zierden, D.; Bellow, J.; Paz, J.; Cabrera, V.; Garcia y Garcia, A.; Ingram, K.; Hatch, U.; Hoogenboom, G.; Jones, J.; O' Brien, J. AgClimate: A climate forecast information system for agricultural risk management in the southeastern USA. *Comput. Electron. Agric*. **2006**, 53, 13–27.
10. Ropelewski, C. F.; Halpert, M. S. Global and regional scale precipitation patterns associated with the El Niño-Southern Oscillation. *Mon. Weather Rev*. **1987**, 115, 1606–1626.

Peer-reviewed version available at *Water* **2018**, *10*, 1820; doi:10.3390/w10121820

11. Gelcer, E.; Fraisse, C.; Dzotsi, K.; Hu, Z.; Mendes, R.; Zotarelli, L. Effects of El Niño Southern Oscillation on the space–time variability of Agricultural Reference Index for Drought in midlatitudes. *Agric. For. Meteorol.* **2013**, 174–175, 110–128, 10.1016/j.agrformet.2013.02.006.
12. Stige, L. C.; Stave, J.; Chan, K.-S.; Ciannelli, L.; Pettorelli, N.; Glantz, M.; Herren, H. R.; Stenseth, N. C. The effect of climate variation on agro-pastoral production in Africa. *Proc. Natl. Acad. Sci.* U.S.A. **2006**, 103, 3049–3053, 10.1073/pnas.0600057103.
13. Gaughan, A. E.; Staub, C. G.; Hoell, A.; Weaver, A.; Waylen, P. R. Inter- and Intra-annual precipitation variability and associated relationships to ENSO and the IOD in southern Africa. *Int.l J. Climatol.* **2015**, 36, 1643-1656, 10.1002/joc.4448.
14. Lobo, J. Contribuição para o estudo da variabilidade climática em Moçambique: A influência do ENSO, B.S., Universidade Eduardo Mondlane, Maputo, July 1999.
15. Mavie, A. Variabilidade climática inter-annual de Moçambique e sua relação com o fenómeno El-Niño-Oscilação Autral - Parte-II, B.S., Universidade Eduardo Mondlane, Maputo, October 1999.
16. Gelcer, E.; Fraisse, C. W.; Zotarelli, L. Sistema de monitoramento climático: AgroClimate Moçambique. In *Horticultura em Moçambique: Características, tecnologias de produção e de pós-colheita*; Haber, L. L., Ecole, C. C., Bowen, W., Resende, F. V., Eds.; EMBRAPA: Brasília, 2015; pp. 213–218, 978-85-7035-515-7.
17. Tadross, M.; Suarez, P.; Lotsch, A.; Hachigonta, S.; Mdoka, M.; Unganai, L.; Lucio, F.; Kamdonyo, D.; Muchinda, M. Growing-season rainfall and scenarios of future change in southeast Africa: implications for cultivating maize. *Clim. Res.* **2009**, 40, 147–161, 10.3354/cr00821.
18. Fraisse, C.; Zierden, D.; Breuer, N.; Jackson, J.; Brown, C. Climate forecast and decision making in agriculture. *Coop. Ext. Serv. Circ*. **2004**, ABE252.
19. Battilani, A.; Bussières, P.; Dumas, Y. IRRIGERE: an improved version of an irrigation scheduling model for the processing tomato crop. *Acta Hortic*. **2000**, 537, 519–526.
20. Muñoz-Carpena, R.; Dukes, M. D.; Li, Y. C.; Klassen, W. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. *Horttechnology.* **2005**, 15, 584–590.
21. Davis, S. L.; Dukes, M. D.; Miller, G. L. Landscape irrigation by evapotranspiration-based irrigation controllers under dry conditions in Southwest Florida. *Agric. Water Manag.* **2009**, 96, 1828–1836, 10.1016/j.agwat.2009.08.005.
22. Migliaccio, K. W.; Morgan, K. T.; Fraisse, C.; Vellidis, G.; Andreis, J. H. Performance evaluation of urban turf irrigation smartphone app. *Comput. Electron. Agric.* **2015**, 118, 136–142, 10.1016/j.compag.2015.08.015.
23. Vellidis, G.; Liakos, V.; Andreis, J. H.; Perry, C. D.; Porter, W. M.; Barnes, E. M.; Morgan, K. T.; Fraisse, C.; Migliaccio, K. W. Development and assessment of a smartphone application for irrigation scheduling in cotton. *Comput. Electron. Agric.* **2016**, 127, 248–259, 10.1016/j.compag.2016.06.021.
24. Saetre, R.; Silva, R. P. *The marine fish resources of Mozambique — Reports on surveys with R/V Dr. Fritjof Nansen.* Serviço de Investigações Pesqueiras: Maputo, Mozambique and Institute of Marine Research: Bergen, Norway, 1979.
25. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger climate classification updated. *Meteorol. Zeitschrift*. **2006**, 15, 259–263, 10.1127/0941-2948/2006/0130.
26. Hoguane, A. Perfil diagnóstico da Zona Costeira de Moçambique. *Rev. Gestão Cost. Integ*. **2007**, 7, 69–82.
27. Doorenbos, J.; Kassam, A. H. *Yield response to water—FAO Irrigation and Drainage Paper* 33; FAO: Rome, Italy, 1979.
28. Hargreaves, G. H.; Samani, Z. A. Reference crop evapotranspiration from temperature. *Appl. Eng. Agric.* **1985**, 1, 96–99.
29. Farmer, W.; Strzepek, K.; Schlosser, C. A.; Droogers, P.; Xiang, G. A. *Method for Calculating Reference Evapotranspiration on Daily Time Scales Report 195*. MIT Joint Program on the Science and Policy of Global Change: Cambridge, USA, 2011.
30. Droogers, P.; Allen, R. G. Estimating reference evapotranspiration under inaccurate data conditions. *Irrig. Drain. Syst.* **2002**, 16, 33–45.
31. Saha, S.; Moorthi, S.; Pan, H.-L.; Wu, X.; Wang, J.; Nadiga, S.; Tripp, P.; Kistler, R.; Woollen, J.; Behringer, D.; Liu, H.; Stokes, D.; Grumbine, R.; Gayno, G.; Wang, J.; Hou, Y.-T.; Chuang, H.; Juang, H.-M. H.; Sela, J.; Iredell, M.; Treadon, R.; Kleist, D.; Van Delst, P.; Keyser, D.; Derber, J.; Ek, M.; Meng, J.; Wei, H.; Yang, R.; Lord, S.; van den Dool, H.; Kumar, A.; Wang, W.; Long, C.; Chelliah, M.; Xue, Y.; Huang, B.; Schemm, J.-K.; Ebisuzaki, W.; Lin, R.; Xie, P.; Chen, M.; Zhou, S.; Higgins, W.; Zou, C.-Z.; Liu, Q.; Chen, Y.; Han, Y.;

Cucurull, L.; Reynolds, R. W.; Rutledge, G.; Goldberg, M. The NCEP Climate Forecast System Reanalysis. *Bull. Am. Meteorol. Soc.* **2010**, 91, 1015–1058, 10.1175/2010BAMS3001.1.

32. Marouelli, W. A.; Silva, W. L. C.; Silva, H. R. *Manejo de irrigação em hortaliças*; 5th ed.; Embrapa Centro Nacional de Pesquisa de Hortaliças: Brasília, Brazil, 1996; 85-85007-27-3.
33. Woli, P.; Jones, J. W.; Ingram, K. T.; Fraisse, C. W. Agricultural Reference Index for Drought (ARID). *Agron. J.* **2012**, 104, 287–300, 10.2134/agronj2011.0286.
34. Hengl, T.; de Jesus, J. M.; MacMillan, R. A.; Batjes, N. H.; Heuvelink, G. B. M.; Ribeiro, E.; Samuel-Rosa, A.; Kempen, B.; Leenaars, J. G. B.; Walsh, M. G.; Gonzalez, M. R. SoilGrids1km — Global Soil Information Based on Automated Mapping. *PLoS ONE.* **2014**, 9, 10.1371/journal.pone.0105992.
35. Rawls, W. J.; Brakensiek, D. L.; Saxton, K. E. Estimation of Soil Water Properties. *Transactions of the ASAE* **1982**, 25, 1316–1320 & 1328.
36. Dukes, M. D.; Zotarelli, L.; Morgan, K. T. Use of irrigation technologies for vegetable crops in Florida. *Horttechnology.* **2010**, 20, 133–142.
37. Pilgrim, M. *HTML5: Up and Running*; O'Reilly Media, Sebastopol, USA, 2010; 978-0-596-80602-6.
38. Meyer, E. A. *CSS: The Definitive Guide*; 3rd ed.; O'Reilly Media, Sebastopol, USA, 2006; 978-0-596-52733-4.
39. Flanagan, D. *JavaScript: the definitive guide*; 5th ed.; O'Reilly Media, Sebastopol, USA; 2006, 978-0-596-80552-4.
40. Florida Automated Weather Network. Available online: https://fawn.ifas.ufl.edu/ (accessed on November 25 2015).
41. Bonachela, S.; Gonzalez, A. M.; Fernandez, M. D. Irrigation scheduling of plastic greenhouse vegetable crops based on historical weather data. *Irrig. Sci.* **2006**, 25, 53–62, 10.1007/s00271-006-0034-z.
42. Amayreh, J.; Al-Abed, N. Developing crop coefficients for field-grown tomato (*Lycopersicon esculentum* Mill.) under drip irrigation with black plastic mulch. *Agric. Water Manag.* **2005**, 73, 247–254, 10.1016/j.agwat.2004.10.008.
43. Mbabazi, D.; Migliaccio, K. W.; Crane, J. H.; Fraisse, C.; Zotarelli, L.; Morgan, K. T.; Kiggundu, N. An irrigation schedule testing model for optimization of the Smartirrigation avocado app. *Agric. Water Manag.* **2017**, 179, 390–400, 10.1016/j.agwat.2016.09.006.
44. Zotarelli, L.; Scholberg, J. M.; Dukes, M. D.; Muñoz-Carpena, R.; Icerman, J. Tomato yield, biomass accumulation, root distribution and irrigation water use efficiency on a sandy soil, as affected by nitrogen rate and irrigation scheduling. *Agric. Water Manag.* **2009**, 96, 23–34, 10.1016/j.agwat.2008.06.007.
45. Wang, D.; Kang, Y.; Wan, S. Effect of soil matric potential on tomato yield and water use under drip irrigation condition. *Agric. Water Manag.* **2007**, 87, 180–186, 10.1016/j.agwat.2006.06.021.
46. Marouelli, W. A.; Silva, W. L. C. *Tomateiro para processamento industrial: irrigacao e fertirrigação por gotejamento – Circular Técnica 30*, Embrapa Hortaliças: Brasilia, Brazil.
47. Brito, M. E. B.; Soares, L. A. A.; Lima, G. S.; Sá, F. V. S.; Araujo, T. T.; Silva, E. C. B. Crescimento e formação de fitomassa do tomateiro sob estresse hídrico nas fases fenológicas. *Irriga.* **2015**, 20, 139–153, 10.15809/irriga.2015v20n1p139.
48. May, D. M. Moisture stress to maximize processing tomato yield and fruit quality. *Acta Hortic.* **1993**, 335, 547–552.
49. FAO/IIASA/ISRIC/ISSCAS/JRC Harmonized World Soil Database (version 1.2); FAO: Rome, Italy and IIASA, Laxenburg, Austria, 2012;
50. EMBRAPA Hortaliças Cultivo de Tomate para Industrialização. Available online: https://sistemasdeproducao.cnptia.embrapa.br/FontesHTML/Tomate/TomateIndustrial_2ed/index.htm (accessed on 14 May 2017). (In Portuguese)
51. Johane, S. Comportamento de preços de algumas hortícolas no mercado central de Maputo (1998-2004) , B.S., Universidade Eduardo Mondlane, Maputo, June 2007.
52. Saji, N. H.; Yamagata, T. Possible impacts of Indian Ocean Dipole mode events on global climate. *Clim. Res.* **2003**, 25, 151–169, 10.3354/cr025151.
53. Climate Prediction Center (CPC) Cold & warm episodes by season. Available online: http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml. (accessed on 8 Feb 2017).