Impact of climate change on schedule irrigation events for organic tomato production

by

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Abstract

This study aimed to evaluate the use of irrigation scheduling strategies to enhance irrigation management in organic tomato production, and to analyze the effect of climate change on tomato crops in Alabama through the use of crop modeling. Field experiments were conducted on the organic unit at E.V. Smith Research and Extension Center from Auburn University, located in Shorter, AL in 2022 and 2023. Three irrigation scheduling treatments were tested: systematic irrigation (SYS), crop water demand (CWD), and soil water status method (SWS). Results indicated that SWS had a higher biomass accumulation, consequently increased yield compared to the two other treatments. Furthermore, irrigation water savings were the highest for the SWS treatment, resulting in 72% water savings compared to SYS and 54% to CWD in 2022. In 2023, SWS used 65% less water than SYS, and 55% less than CWD. Data from the field was populated into the CSM-CROPGRO Tomato model, in which crop simulation performance was acceptable with the lowest R^2 being expressed for leaf dry weight (0.91), while the highest was for the soil water content (0.99). A seasonal analysis presented the impact of air temperature and rainfall events indicated a significant decrease in fruit production as temperature increases. Under the worst-case scenario (i.e., 6 ^{o}C temperature increase) of this study, tomato production decreases by roughly 87% for SWS and 73% for SYS irrigation treatment, while water use for SWS increases 2.7 times for the same scenario. In conclusion, climate change may negatively affect tomato production due to high-temperature plant exposure. In contrast, due to the high biomass production under higher temperatures, irrigation water volume may increase, making the crop production cost rise for growers, and consequently increasing consumer prices.

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Chapter 1

Literature review

TOMATO PRODUCTION

Tomato is considered one of the most economically important vegetable crops. Globally cultivated, tomato is the fourth most consumed vegetable in the world, according to F.A.O. (2020). In 2020, a total of 186,821 million tons of tomatoes were produced, representing a total increase of 3.35% compared to the previous year. Among the largest producers, China leads the rank with a total production of 64,768 million tons followed by India, Turkey, United States (U.S.), and the European Union. These top five tomato producers supply about 70% of the global production.

In the U.S., roughly 13 million tons of tomatoes were produced in 2020 with the total value crop reaching $1.66 billion, representing an increase of 4% when compared with the previous year. However, tomato yield in U.S. declined by 4 million tons since 2016, which represents a reduction of 25% (USDA-NASS. 2020). Such vertiginous drops can be explained by many reasons: 1) the banning of methyl bromide. Particularly, Florida used to be the largest producer of fresh tomatoes, and methyl bromide was the most used soil fumigant to control pests during the tomato season. After the banishing of methyl bromide, Florida growers reduced cultivate acreage drastically. 2) the U.S. and Mexico trade agreements. The North American Trade Agreement (NAFTA) signed in 1994, was responsible for the increase of imports of different products in the U.S. coming from Canada and Mexico. Consequently, Mexico became the major exporter of fresh tomato to the U.S. with Canada standing as the second. Compared to 1994, the volume of imported fresh tomatoes from Mexico immediately jumped from 400,000 tons to 650,000 tons in 1995, representing a 50% increase. Imports of fresh tomatoes from Mexico have continually growth in the last decades and reached 1.9 million tons in 2020, which accounts for 90.7% of U.S. total imports of tomatoes. (US-DOC, 2020).

Weather conditions also contributes as an important aspect of tomato production in Mexico, in which most of tomato fields are grown in arid climate conditions, classified as BWh (Arid Desert Hot Arid) and BSk (Arid Steppe Clod Arid), where average temperatures range between 27.5 C to 32.5 C during the summer and 22.5 C to 18.5 C in the winter (Rubel, F., and M. Kottek, 2010). Therefore, growers can produce tomato all year long. Such advantages combined with different and potentially less rigorous work regulations, put Mexico as an important player and competitor in the international market, and may in some cases be considered an unfair competitor against tomato growers in the U.S.

In U.S., as many other vegetable crops, tomato production is still highly concentrated in few states. California ranks first place when it comes to the production of fresh vegetables with an enormous concertation of approximately 42% of all vegetable production. California is then followed by Florida, Idaho, and Washington (NASS-USDA, 2017). Regarding tomato production, California and Florida account for about two-thirds of the national fresh tomato production, while California alone accounts for roughly 95% of the processed tomato production (Wu, Guan, and Suh 2017). Due to economic and social factors, the State of Alabama has not accomplished high positions in the top 10 states with the highest vegetable sales, ranked 33rd among all U.S. states.

Alabama vegetable industry reached 59.2 million in total sales, representing only 1% of the total agricultural market value in the state. However, Alabama is one of the largest states by land area in the U.S. with a rich and privileged location regarding natural resources and weather with abundant rainfall periods and moderate temperature. This conditions can allow growers to increase acreage and production of vegetable crops, including tomatoes (Reeder et al., 2020, Duzy et al., 2013). While research is required to guide growers on decision making, mainly related to crop management practices and the impact of weather variability in crop production.

VEGETABLE ORGANIC PRODUCTION

Organic food production can be classified as an agricultural system that uses ecologically based pest controls and biological fertilizers derived largely from animal and plant wastes. It emphasizes the use of renewable resources and the conservation of soil and water to enhance environmental quality for future generations. Usually implemented by small and medium farms the organic production can be strongly implemented in Alabama to push not only the national organic production but the vegetable production in the state, as aforementioned. A great portion of farms in the state are classified as small and medium-sized, with roughly 40% of all farms sizing less than 49 acres (Census of Agriculture-Alabama State, 2017). The organic production would perfectly fit with the profile of the vegetable growers in Alabama since many growers in the state have opted in the past decades to direct their products to the customers, meaning farmers' markets, objectifying higher returns with the elimination of intermediaries, the higher prices of organic products would provide a great incentive for growers to englobe a huge range of products of animal and vegetal origin. Furthermore,

Overall, there is a considerable increase in the price of organic products compared to non-organic products, total sales of organic products rose to $9.93 billion in 2019, an increase of $2.37 billion from 2016. However, organic products are mostly sold to direct consumers and local markets, and $2.04 billion is generated from direct sales to retail markets, institutions, and local/regional food hubs (Census Agriculture-Organic Survey, 2019).

The large range of returns between organic and non-organic products is the most attractive aspect for growers, which allows them to increase their revenue without the need to increase production area. Considering the current organic production in Alabama, only 11 farms are considered certified organic farms with a total area of approximately 2.220 acres in operation. Compared with the entire country, Alabama ranked only 48th among all U.S. states. Such numbers expose the urgent need to increase the development of organic vegetable production in Alabama (Census Agriculture-Organic Survey, 2019).

IRRIGATION MANAGEMENT FOR VEGETABLE PRODUCTION

Regardless of the growing system (i.e., organic, or conventional), many factors must be considered for growers to achieve potential crop yields. Among several factors, irrigation management is one of the most important crop management practices. The selection of an irrigation system is key and drip irrigation is prominently one of the most important systems for water saving, being the most efficient in terms of resource use and yield increase. (EEA, 2009, CA, 2007, World Bank, 2006). According to Postel (2000), drip irrigation has the potential to at least double crop yield per unit of water. Typically, there is a water use reductions of 30 - 60% and yield increases of 20 - 50% for a variety of crops, including cotton, sugarcane, grapes, tomatoes, and bananas, with drip irrigation when compared to overhead water application (Indian National Committee, 1994, Sivanappan, 1994). Irrigation scheduling is also an important aspect of managing irrigation events of a field. Several irrigation scheduling strategies have been developed to help growers choose the best moment for irrigating and the amount of water to apply in the field during the irrigation process (Dukes et al., 2005, Zotarelli et al., 2009).

Among these methods the systematic irrigation scheduling (SYS) stands as one of the most used among vegetable growers. The SYS is a method of irrigation that involves the application of water automatically or manually for the same frequency and duration every day (da Silva et al., 2022). In short, water is applied at the same volume every day regardless of weather and soil conditions or crop growth stages. Because of that, there is a high likelihood of under or over-irrigated crops (Jones, 1990). Particularly, over-irrigation is commonly reported in fields under SYS, which leads to water and nutrient leaching and consequently, negative impacts on crop yield (Zotarelli et al., 2006; da Silva et al., 2018).

The crop evapotranspiration method is another method and one of the most useful to determine the correct amount of water to be applied. Considering the combination of two separate processes, the water lost by the plant transpiration (Kc) and the evaporation from the soil surface (ETo), the crop evapotranspiration considers many climatic and crop parameters into a mathematical equation (1) that results in an estimated value of the total volume of water to be applied during the irrigation process. (Allen et al., 2006).

$$ET_c = K_c \times ET_o$$

Another strategy that helps growers to determine the volume of water to be applied during irrigation events is using soil moisture sensors. Designated to measure or estimate the soil volumetric water content (VWC) in different layers of the soil, soil moisture sensors are a good alternative for growers who are looking for more control and precision in thermos of water management. When this method is applied, the soil field capacity (FC) must be known, to be used as a parameter of when start and end an irrigation event (da Silva et al 2018). Soil moisture sensors can be classified as stationary or portable, such as handheld probes. Stationary sensors are placed at pre-determined locations and depths in the field, whereas portable soil moisture probes can measure soil moisture at several locations, considering crop height and field topography during the process of installation in the field. (Sharma, 2019).

Overall, the use of soil moisture sensors or crop evapotranspiration asana irrigation strategy are more accurate methods when compared to the SYS. In a study comparing the use of soil moisture sensors against SYS irrigation scheduling on corn, Ko et al., (2006) mentioned that using soil moisture sensor has proven to be a more efficient water delivery that requires less water input during critical growth stages, resulting in higher grain yield. However, the adoption of these methods is still limited for vegetable production and there is a need to better understand the response of vegetable crops to such methods in specials under organic crop management practices.

GLOBAL WARMING AND FUTURE SCENARIOS

Global warming has become a subject of extreme importance in crop production, and it has been extensively discussed around the world. Climate change is an important factor during the process of creating policies and programs for certain areas of the global economy (Diffenbaugh and Burke, 2019). However, little information about the historical process of global warming on the earth is discussed, and for many people around the world the global warming process that we have seen nowadays, is still unclear which means that a large portion of our society still does not give the real importance for such subject.

Historically, daily air temperature variation is a normal process present in the earth's history. Such process has been extremely important and although of the difficult to prove the real cause of all episodes, the climate change caused by global warming reverberates as the most reasonable and sensate explanation responsible for life development and evolution.

Understanding the cause and the consequences of global warming with ancient episodes is extremely significant since increases in daily air temperatures on earth will not only affect the human population, but crop and animal growth and development. Consequently, changes in the daily air temperature can affect food production, since minimal increase in air temperatures could cause a huge negative effect on crop development and yield, making the area unproductive for some crops. In the United States agriculture is extremely diverse in the range of crop grown which has turned some regions highly dependent of good climate conditions and with advanced of climate change in the country it has pronounced the most common effects of global warming which is the increases of heavy rainfall periods. Precipitation has become less frequent but more intense, and this pattern is projected to continue across the United States (Kunkel et al., 2008). One consequence of excessive rainfall is delayed spring planting, jeopardizing profits for farmers paid a premium for early season production of high-value crops such as melon, sweet corn, and tomatoes. Field flooding during the growing season causes crop losses due to low oxygen levels in the soil, increased susceptibility to root diseases, and increased soil compaction due to the use of heavy farm equipment on wet soils (Karl et al., 2009).

However, due to the global effect of temperature increases, other regions in the world have also experienced the effects of climate change. Particularly, effects of climate change have already been noted in some regions of the African continent, countries lying around the Nile Basin witnessed an elevated temperature of between 0.2 and 0.3 ^{o}C per decade since the second half of the century, while in Ruanda, the temperature had increased from 0.7 to 0.9 ^{o}C (Eriksen et al., 2008). In Sudan and Ethiopia for example, the Mean annual Diurnal Temperature Range (DTR) has decreased between 0.5 and 1 ^{o}C since the 1950s, and a similar amount of rise in temperature has been experienced in Zimbabwe since then (Hulme et al., 2001). According to New et al., (2006), between 1961 and 2000, there was an increase in the number of warm days over Southern and Western Africa and a decrease in the number of exceedingly cold days. For the whole of the Southern Africa region, Hulme (1996) observed that the six warmest years in this century have all occurred since 1980 with the warmest decade being 1986 - 1995. Proving that although these trends appear to be widespread over the continent, the temperature changes are not always uniform. They vary considerably between and within regions and countries (Kotir, 2011).

Climate change has played a major role in the annual food production in many countries around the world. Some events caused by weather variability including occasional El Niño Southern Oscillation (ENSO) events in the tropical Pacific have resulted in frequent extreme weather events such as droughts and floods which reduce agricultural outputs leading to severe food shortages and economic crises around the world (Conway et al., 2007; Dore 2005; Haile 2005). Only in USA agricultures losses caused by rising temperatures cost in farm subsidies approximately $27 billion over the past three decades, including almost half of the $18.6 billion in losses in 2012, during the super El Niño (Diffenbaugh et al., 2021). Further, the frequency of extreme conditions such as those that occurred in 2012 are projected to at least double within the 2 °C warming target (Diffenbaugh et al., 2012), suggesting that financial damages from crop losses are likely to grow substantially.

CROP MODELING AND GLOBAL WARMING

The need to increase crop yield per growing area has directly been influenced by changes in daily air temperature and rainfall precipitation. In general, national climatology agencies pointed out a considerable increase in world temperature since 1980 (FAO, 2008).

The rapid increase of the world temperature stands as a flag for researchers around the world since the high dependence on good climate conditions for food production could put at risk billions of people soon if the current speed of climate change continues. According to some climate agencies, it is projected that the mean annual global surface temperature will increase by 1.2 to 6°C from 1990 to 2100, with changes in the spatial and temporal patterns of precipitation (Yano et al., 2007). Such scenarios could lead to immeasurable climate effects around the world leading to uncountable losses annually in the agricultural field, deteriorating, even more, the global hunger situation and the food access to poor countries and communities around the world.

Facing such challenges, global leaders around the world have developed policies focusing on delaying or even preventing the deterioration of the climate promoting the preservation of natural resources and biodiversity, and since the First World Climate Conference made in 1979, many climate issues have been discussed with the climate change topic been present in many agreements and policies created by the U.S since then in the wide range of the economic, including agriculture. (Gupta, Joyeeta, 2010). However, to the achievement of solid results special in agriculture production, new technologies must be implemented during the process of food production, focusing on the preservation with a remarkable reduction of crop inputs (fertilizers, irrigation water, etc.).

To promote such development, crop modeling should be present among the new technologies to be strongly introduced, which may assist growers and researchers on different fronts of agriculture development. Due to its great versatility, crop modeling can be present in different areas helping to mitigate the triple challenge of sustainable agriculture, such as climate change, environmental degradation, and food security, by predicting crop growth, development, and yield, which are information used to determine irrigation, fertilizer, and pesticides application in different crop production systems (Choudhury, A. T. M. A., and Kennedy, I. R., 2005). The use of crop modeling goes beyond the field and crop yield predictions. Crop modeling can also be applied to the evaluation of the climate impacts on certain crops, assisting during the development of appropriate management for each scenario.

As an example of how crop modeling can be used for climate studies, Ludwig and Asseng (2006) conducted crop model research in Western Australia to assess the impact of global warming on wheat production using various climate scenarios. The scenarios included temperature elevations of 2, 4, and 6°C, CO2 concentrations of 525 and 700 ppm, and five distinct rainfall regimes. The study revealed that despite the potential positive effect of CO2 on crop yield, a reduction in rainfall by 15% and a temperature increase of over 2°C (a likely scenario for 2050 in the area) could result in a significant decline in total yield, specifically a 20% reduction in clay soil regions. However, for a probable 2100 scenario, the warming could lead to a further decrease in rainfall by 30% and a temperature rise by 4°C. This would result in a total yield loss of approximately 20% in sand and duplex soils, with clay soils suffering even greater losses of up to 50%. This alarming outcome could have significant implications for global food security, as food production losses on this scale would exacerbate the existing problem of food scarcity in many regions of the world.

As an important factor during crop production, different models have been used over the years to understand the real influence that different types of soil exercise during crop development and yield under distinct climate scenarios, Ludwig, F. et al., (2009). Such studies have not only aided with the development of new management strategies over the crop season but also provided a huge knowledge about soil physics and behavior when placed under different climate scenarios. Proving that climate variability not only impacts crop development as an isolated factor to be affected, but it has a direct interaction with all factors related to crop development (Soil, Climate, Plant, etc.).

Such researchers show the fundamental work that modeling has had in the field of climatology and agriculture, making it possible for the entire agriculture chain to be a step ahead of the climate change challenger.

IRRIGATION MODELS UNDER FUTURE SCENARIOS

Irrigation agriculture is at the forefront of global food security. With the potential to provide crop yields more than two times as large as dryland agriculture (FAO, 2002, Kukal, M. S. and Irmak, S. 2019) irrigation agriculture currently produces approximately 40% of all food consumed worldwide in just 20% of the total cultivated land (UNESCO, 2012). Due to the rapid human population increase, it is generally expected that irrigated agriculture will have to be considerably extended in the future to feed growing populations. However, it is not yet known whether there will be enough water available for the necessary extension. As it is very likely that water demands of the domestic and industrial sectors will increase in the future, even regions that do not have water scarcity problems today will be restricted in their agricultural development and thus possibly their food security by a lack of water availability (Döll, P, and Siebert, S, 2002).

For an assessment of the future water and food situation, it is, therefore, necessary to understand the effects that climate change may have on the water requirement of irrigated agriculture. For that, crop modeling may be a useful tool enabling the creation not only of different future scenarios but also evaluating past scenarios and comparing the influence that different irrigation management could have during food production. Modeling today’s irrigation water requirements as a function of irrigated areas, climate, and crops provides the basis for evaluating the future impact of climate change as well as demographic, socio-economic, and technological changes. It does not only help to find sustainable development paths for the future, but, for some regions, it also improves the knowledge about the current water use situation, since existing information on current and historic water use is generally poor, and modeling brings together various types of information that are not combined otherwise (Döll, P, and Siebert, S, 2002).

In a study evaluating the effect of climate change on irrigation requirements, Döll (2002) used a global irrigation model to present the first global analysis of the impact of climate change and climate variability on irrigation water requirements by computing the effect of long-term average irrigation requirements under the climatic conditions of the 2020s and the 2070s. Provided by two climate models, the results present a considerable increase in water use by 3 - 5% until the 2020s and by 5 - 8% until the 2070s, considering that no increase in the irrigated area will happen. The increase in water use was due to the increased temperature and the strong spatial heterogeneity of precipitation increases and decreases, but due to climate change, in most areas, it leads to a shift in the optimal growing period, often by a month or more into the winter season and may sometimes even cause a change in the cropping pattern, controlling the further increase of the water necessity.

Such information is extremely important, presenting the future necessity of adaptation by growers in crop management to new climatic patterns, especially to water availability. According to, Odegard, I. Y. R., and E. Van der Voet, (2014) water availability will be a huge problem in the future, indicating that many countries around the world will experience some level of water stress, affecting the food availability for the global population, proving that food production allied with the efficient use of resources might be a great challenge for the future generations.

OBJECTIVES

The main goal of this research dissertation was to address the impact of irrigation events on tomato crop production under organic management practices and the effect of climate change on both tomato crop development and irrigation management.

The specific objective of this study was:

1) to identify the impact of different irrigation scheduling on water use, tomato crop development, yield, and fruit quality.
2) to evaluate the effect
3) of different climate scenarios of global warming on tomato production and irrigation management.

Chapter 2

Irrigation scheduling strategies for organic tomato production in Alabama

Introduction

During the last two decades, the use of water for agriculture practices has increased over 30% in Alabama, while the irrigated area jumped from 136,000 acres in 2005 to 189,000 acres in 2015 (Harper et al., 2015). Part of this increase can be accounted for the development of new vegetables production areas in the state, which have increased of 60% between 2016 to 2018. (NASS, 2018) Such an increase also boosted organic vegetable production in the state, which increased from 4 to 18 certified operations in a period of 10 years (NASS, 2022). Due to this increase of new organic farms, several research studies have been focusing on the benefits of the organic production in the state (Wood et al., 1992, Nyakatawa et al., 2006 and Gardner et al., 2011). However, while many studies have focused on the benefits of organic systems, few were developed to focuse on improving organic crop management practices. There is a need to better understand the response of vegetable crops to different methods of management under an organic system.

Irrigation management is an important aspect to be considered for vegetable production due to the high demand of water for these crops. Drip irrigation has been widely utilized in agriculture, mainly due to the capability to provide water and nutrients directly to the plant's root system, resulting in a water use reduction and increased yields for vegetable crops (Indian National Committee, 1994; Sivanappan, 1994). Although drip irrigation can be very efficient, it requires precise management practices to avoid under or over-irrigation and excessive nutrient losses through leaching.

Irrigation scheduling is an important aspect in crop irrigation management. Currently the most common method used for growers is the systematic irrigation method, which involves the application of water automatically or manually for the same frequency and duration every day (da Silva, 2022). However, the use of continuous water application without considering the plant water uptake, evaporation and soil water content has shown negative impacts on plant development and production (Zotarelli et al., 2009). Thus, using a decision support technology during irrigation management can provide critical information for correct irrigation timing, increasing water savings and reducing nutrient losses through leaching and positively affecting plant production.

Over recent decades, sensor technology has enabled continuous soil water status monitoring and has become widely available to commercial growers. The use of soil moisture sensors that measure volumetric soil water content can be a useful tool to avoid over-irrigation by addressing specific crop water requirements(Cardenas-Lailhacar et al., 2010). By employing SMS-based irrigation systems, it is possible to regulate soil water status within specific upper and lower limits, which are determined based on the soil type and crop. This approach prevents over-irrigation, conserves water, and ensures optimal water management on the farm (Dukes and Scholberg, 2005; Munoz-Carpena et al., 2005). Particularly, the use of SMS-based irrigation management has been shown to reduce irrigation water use 34 to 60% in tomatoes, and consequently increasing 65% of total yield compared to daily fixed irrigation management (Dukes et al., 2007). Likewise, the use of surface and sub-surface drip irrigation controlled by soil moisture sensors resulted in a reduction of 7 to 51% in irrigation water use compared to fixed irrigation management, respectively, leading to an increase in yield of about 11 to 26%, respectively (Zotarelli et al., 2009).

Although the use of SMS has been successfully demonstrated in conventional agriculture, few studies have evaluated the performance of this technology in organic production systems. Therefore, the objective of this study was to: (1) investigate the effect of different irrigation methods for organic tomato production in Alabama, evaluating the performance of crop vegetative growth, yield, water saving, and the water efficiency of each method. (2) provide valuable knowledge and practical recommendations for organic growers focusing on the optimization of irrigation practices improving the sustainable model of the organic system in the region.

Material and Methods

Site description

Field experiments were conducted in 2022 and 2023 at the E.V. Smith Research and Extension Center (32°26'48.5"N 85°53'45.5"W) in the Organic Unit at Auburn University, Shorter, AL. The region is classified as a humid subtropical climate (Cfa) with dry winters and wet summers (Köppen, 1928). The soil is classified as a Cahaba sandy loam soil (a fine-loamy, siliceous, semiactive, thermic Typic Hapludults) (USDA, 2023). The soil water holding capacity ranges between 0.25 to 0.40 $m^3 m^{-3}$.

Crop management

Tomato seeds, c.v. Patsy (Bejo Seeds Inc., Ocean, CA), were planted in 200 cell trays filled with soilless media (Miracle Grow Performance Organics, Marysville, OH), and greenhouse grown until transplanting. During seedling production, a 5-3-3 organic fertilizer was applied twice at a rate of 100 g per tray (Espoma Organic, Plant-tone, Millville, NJ). Seedlings were irrigated twice daily, while greenhouse temperatures were maintained at 25 °C during the day and 20 °C during the night. Seedlings were later transplanted on 15 cm raised beds spaced 2 m center to center with an in-row spacing of 0.45 m. Raised beds were placed using a white-on-black polyethylene mulch (Total Blockade; Berry Global Inc., Evansville, IN) with a drip line irrigation system (30.48 cm emitter spacing, 1.89 L per min per 30.48 m at 68.95 kPa; Chapin DLX; Jain USA, Haines City, FL) installed under the plastic mulch in the center of each bed. Before laying plastic mulch, fertilizer was applied at 56 kg of N/ha using a 5N-4P-3K (Harmony; Environmental Products, Roanoke, VA). After transplanting, plants received 15 lb of N/week/acre using 7N-7P-7K (Nature Safe; Darling Ingredients, Irving, TX). For pest control, 11.2 g/L of Dipel DF (Valent;

San Roman, CA) was applied twice a month during crop development, but no fungicide was applied during the entire season in both years.

Experimental design

Field experiments were arranged in a one factor experimental design of irrigation scheduling strategies in both years. Treatments were randomized complete block design with four replications. Each block was divided into 3 plot sections of 10 m each, of which 9 m were used as planting field and the remaining as a border between adjacent plots. In total 20 plants were transplanted per plot, in plant spacing of 0.45 m After transplanting, irrigation events supplied 3.62 mm of water daily in the entire field to ensure the establishment of tomato transplants. Irrigation treatments were then initiated 25 days after transplanting (DAT) and consisted of a 1) systematic irrigation (SYS) where the volume of water applied daily during the crop season supplied 6.34 mm of water a day mimicking growers standard practices; 2) the crop water demand (CWD) method of irrigation scheduling where the tomato crop evapotranspiration (ETc) was daily calculated as the product of the daily reference evapotranspiration (ETo) and the crop coefficient to determined irrigation events (Allen et al., 1999), and 3) the soil water status (SWS) method of irrigation scheduling, which consisted of the use of a soil moisture sensor to determine the irrigation event.

In the CWD treatment, rainfall events and ETo were daily monitored using an on-site weather station (WatchDog Wireless Station, WD Wireless ET Weather Station, LTE-M 50500102), allowing the weekly calculation of the ETc by multiplying the daily ETo by the tomato Kc (Allen et al., 1998). In the SWS, soil hydraulic proprieties were initialy determined using an undisturbed soil core sample collected at the 15 cm soil depth at pre-planting, in which the soil water retention curve (SWRC) was estimated using an adaptation of the evaporation method

(Schindler and Müller, 2006). Using the SWRC, the soil saturation was identified at 0.46 m^3 m^{-3}, soil field capacity assumed at 0.36 m^3 m^{-3} using the matric potential of -6 kPa, and permanent wilting point assumed to be 0.12 m^3 m^{-3} at -1500 kPa. To monitor the soil water content, a soil moisture sensor (Sentek Probe© 2023 Sentek Technologies BMP Logic, Trenton, FL) was installed vertically between two plants below the drip tape, measuring the soil water content in the top 0.45 m of the bed. The sensor was connected to a data logger (YDOC Data Logger version ML-017 BMP Logic, Trenton, FL), which was set to monitor the soil water content every 30 minutes. Irrigation events were then manually started once soil moisture levels were below 0.28 m^3 m^{-3} of the soil volumetric water content (VWC), which represents 80% of the soil available water. An additional soil moisture sensor was also installed in the SYS and CWD treatment, which monitored the soil volumetric water content for all irrigation scheduling treatments in both seasons.

Plant growth and development

Plant growth and development were weekly monitored. Plant tissue samples were collected five times during the growing season to evaluate the tomato leaf area index (LAI) dry leaf biomass, dry stem biomass and total aboveground dry biomass accumulation. Samples were collected during the transplanting establishment, at foliar development, at foliage expansion, at flowering, and at harvesting, which occurred at 31, 38, 45, 52, 59 DAT in 2022 and 37, 46, 52, 62, 79 DAT in 2023. Dry biomass samples consisted of two representative plants from each plot dried at 65 ^{o}C until constant weight.

Tomato yield and fruit quality

Tomato fruit were harvested at maturity from 10 plants in the middle of each plot. Fruit were weighed and graded as small (25 to 47 mm diameter), medium (47 to 67 mm diameter), large (67 to 88 mm diameter), and extra-large (higher than 88 mm diameter) (USDA, 1991). Total marketable? yield was then calculated as the sum of the yield of all sizes, and the irrigation water productivity (IWP) was calculated as the ratio between yield per unit of irrigation water use (IWP, kg m^{-3}) (Expósito et al., 2019).

Statistical Analysis

Statistical analyses were performed using the SAS PROC GLIMMIX (SAS/STAT 14.2; SAS Institute Inc., Cary, NC). Year, irrigation scheduling treatment, sampling time (i.e., growth stage), and their interaction were used as fixed effects for the analysis of LAI, dry stem biomass, and dry leaf biomass. Year, irrigation scheduling treatment, and their interactions were used as fixed effects for the analysis of yield of fruit sizes, total yield, and IWP. Block was used as a random effect for all analysis. When the F-value of the ANOVA was significant, least-square mean comparisons using the Tukey were performed at a p-value of <0.05.

Results

Weather conditions and soil volumetric water content

Figure 1 shows the daily air temperature and rainfall event for both tomato growing seasons, 2022 and 2023. In general, the average daily air temperatures for 2022 and 2023 were 27 and 23 °C with an accumulated rainfall of 178 and 404 mm, respectively.

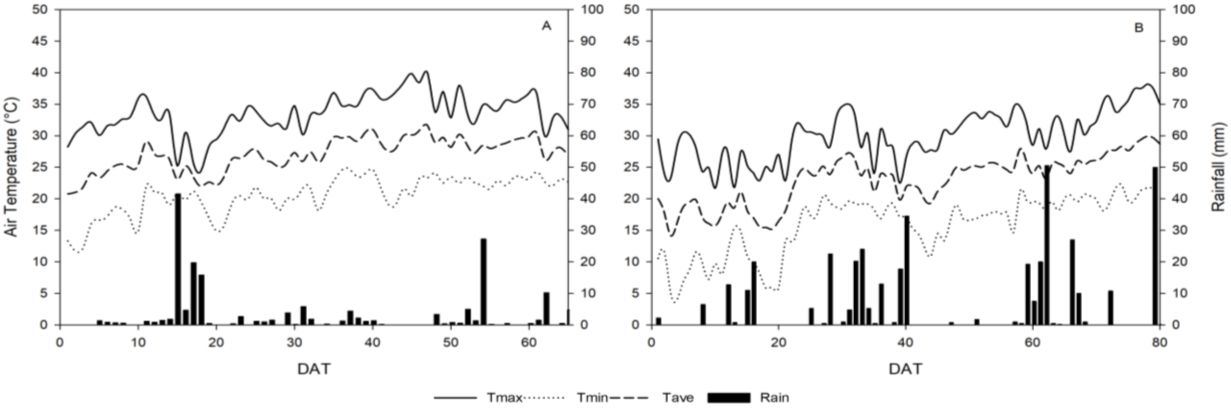

Figure 1. Weather conditions of tomato seasons (April to July), including maximum, minimum, and average air temperature and rainfall events of 2022 (A) and 2023 (B) in Shorter, AL.

In 2022, the daily irrigation events supplied 63.5, 51.3, and 23.3 m^3 per hectare for the SYS, CWD, and SWS treatments, while irrigation events supplied 63.5, 41.03, and 19.2 m^3 per hectare of water in 2023 for the SYS, CWD, and SWS treatments, respectively. Particularly, there was a reduction in the volume of water applied of 17% to 20% from 2022 to 2023 for the CWD and SWS irrigation methods, respectively.

Regardless of the year, the SWS maintained the soil volumetric water content within the pre-determined irrigation threshold of 0.28 $m^3\ m^{-3}$ and soil field capacity of 0.36 $m^3\ m^{-3}$. In 2022, the CWD and SYS irrigation treatments had no significant differences for the soil volumetric water content, particularly after 20 days of treatment (Fig. 2A). While, in 2023, CWD and SYS treatments had a significant difference due to the influence of rainfall events (Fig. 2B). Soil volumetric water content in the SYS treatment remained below soil field capacity (0.36 $m^3\ m^{-3}$) in 2022 and in periods with no rainfall events in 2023. After heavy rainfall events, particularly during the crop season of 2023, the soil volumetric water content in the SYS treatment exceeded field capacity and was at saturation . In the CWD treatment regardless of the year, the soil volumetric water content was maintained within the irrigation threshold and field capacity.

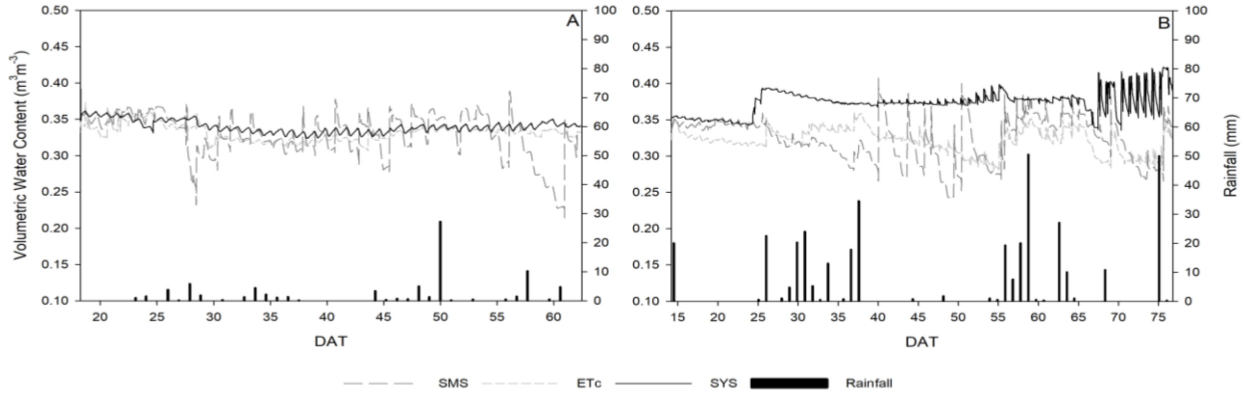

Figure 2. Rainfall events and volumetric soil water content for the tomato seasons of 2022 (A) and 2023 (B) in Shorter, AL.

Plant growth stages and biomass accumulation

The main effect of irrigation scheduling and the interaction between growth stage and year was significant for LAI, dry leaf biomass, and dry stem biomass (Table 1).

Table 1. Analysis of variance summary for plant Leaf area index, dry stem, and dry leaf.

Effect	Leaf area index	Dry leaf	Dry stem
Year	ns	ns	ns
Irri. Sched.	*	*	*
Year Irri. Sched.*	ns	ns	ns
Growth Stage.	***	***	***
*Year*Growth Stage.*	***	***	***
Irri. Sched. Growth Sta.*	ns	ns	ns
Year Irri. Sched.*Growth Sta.*	ns	ns	ns

ns—not significant according to the ANOVA; *p<0.05; **p<0.01; ***p<0.001.

The LAI, dry leaf, and dry stem had no significant differences among irrigation scheduling treatment at crop establishment, foliar development, and leaf expansion. However, as the crop developed to the flowering and harvesting stages, there was a significant difference among irrigation scheduling treatments (Fig. 3). The LAI under SWS treatment was 0.97 and 0.91 m^3 at flowering and harvesting growth stages, respectively. While the CWD averaged 0.81 m^3 at flowering and 0.84 m^3 at harvesting. The SYS had the lowest LAI and averaged 0.76 m^3 at flowering and 0.69 m^3 at harvesting. The dry leaf biomass under the SWS was significantly higher than the CWD and SYS treatments. In general, the dry leaf biomass for the SWS treatment was 759 and 735 kg ha^{-1} at flowering and harvesting, respectively. While plants in grown with CWD and SYS irrigation treatments had a dry leaf biomass of 651 and 628 kg ha^{-1} and 574 and 507 kg ha^{-1} at flowering and harvesting, respectively (Fig. 3B). Similar results were measured for the dry stem biomass, the SWS had a higher dry stem biomass than CWD and SYS. Particularly, plants receiving the SWS treatment averaged a dry stem yield of 1788 kg ha^{-1} at harvest, while for CWD and SYS irrigation scheduling, plants averaged a dry stem yield of 1552 and 1368 kg ha^{-1}, respectively (Fig. 3C).

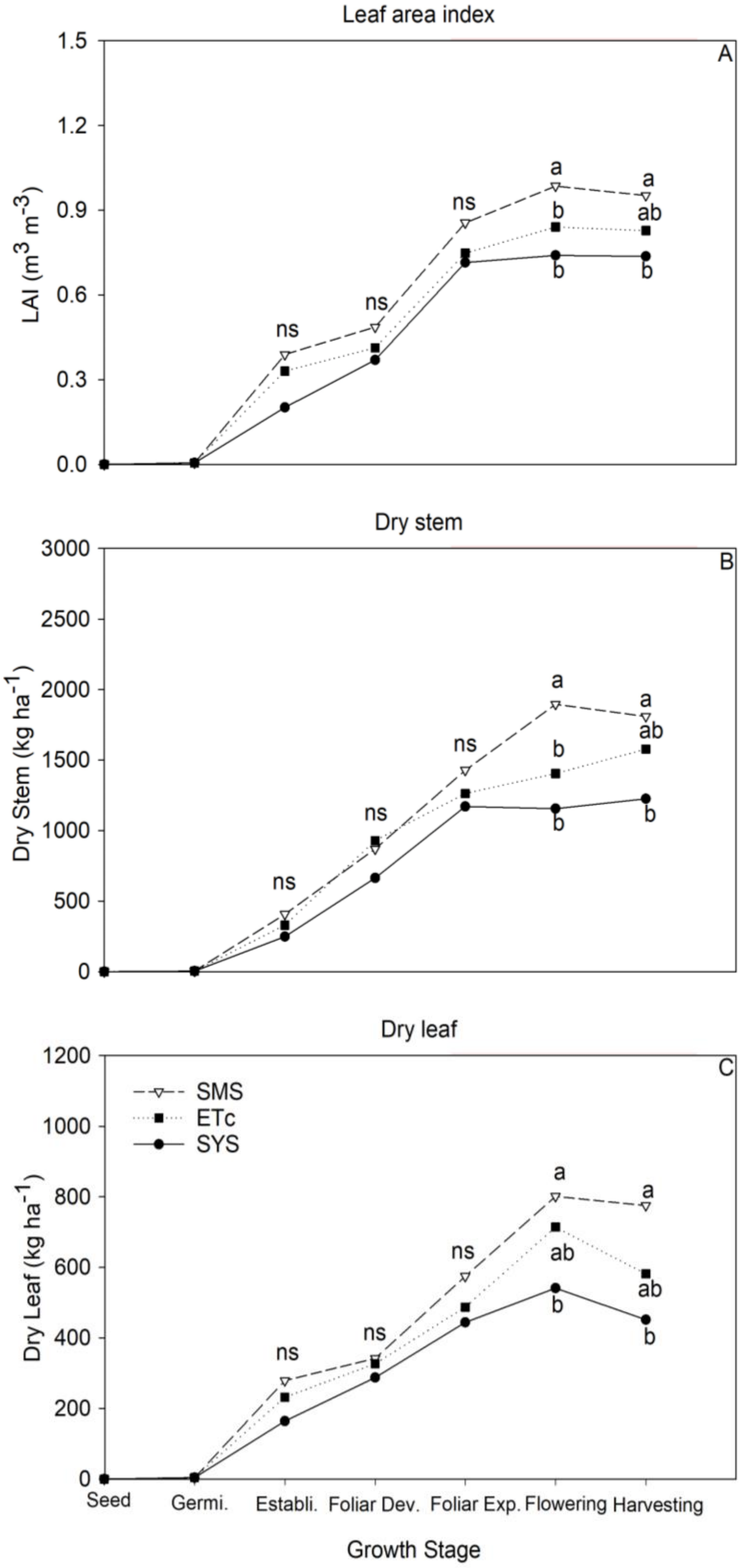

Figure 3. Leaf area index (LAI), total steam and leaf dry matter accumulation over the crop growth stage during the tomato season of 2022 and 2023.

Yield and irrigation water productivity

The effect of year, irrigation scheduling, and their interaction on tomato fruit size yield, total yield, and IWP are presented in Table 2.

The main effect of the year had a significant impact on the yield of small fruit. Particularly, there was a significant increase in yield from 2022 (3,581 kg ha^{-1}) to 2023 (5.802 kg ha^{-1}). However, the main effect of irrigation scheduling treatment had no significant impact on the yield of small fruit size. For the yield of medium-sized fruit, the impact of year was not significant, while the main effect of irrigation scheduling indicated that the SWS (8,110 kg ha^{-1}) and CWD (8,780 kg ha^{-1}) had a significantly higher yields than SYS (5,137 kg ha^{-1}). The yields of large and extra-large fruits were significantly affected by year. In general, 2023 had a significantly higher yield of large (10,987) and extra-large (9,044 kg ha^{-1}) fruit than 2022, which yielded 8,104 and 3,470 kg ha^{-1}, for large and extra-large fruit, respectively. For the main effect of irrigation scheduling on the yield of large and extra-large tomatoes, the SWS treatment had the highest yields with 11,798 and 8,256 kg ha^{-1} for large and extra-large, respectively. The CWD and SYS irrigation did not affect yields of large and extra-large fruit, producing 9,135 and 5,337 kg ha^{-1}, respectively, for large fruit and 8,304 and 5,177 kg ha^{-1}, respectively, for extra-large fruit. Tomato total yield was also affected by the main effects of year and irrigation scheduling treatments (Table 2). Total yield was 11,409 kg ha^{-1} higher in 2023 than the 2022. The SWS treatment had the highest total yield with an average of 32,542 kg ha^{-1}; however, SWS was not significantly different than CWD, which had a total yield of 27,768 kg ha^{-1}. The lowest total yield was measured for SYS (23,388 kg ha^{-1}). For the main effect of irrigation scheduling, total yield was significantly affected by the different irrigation regimes.

The IWP was responsive to both volume of water applied and tomato total yield. Particularly, there was a significant difference on IWP between 2022 (20.22 kg m^{-3}) and 2023 (15.66 kg m^{-3}), while the SWS had the highest IWP (32.82 kg m^{-3}), followed by CWD (13.2 kg m^{-3}) and SYS (7.74 kg m^{-3}).

Table 2. The main effect of year and irrigation scheduling on tomato categorized yield, total yield, and irrigation water productivity.

Effect	Small	Medium	Large	X-Large	Total yield	IWP
Year			*kg ha^{-1}*			*kg m^{-3}*
2022	3,581 b	6,977	8,104 b	3,470 b	22,133 b	20.22 a
2023	5,802 a	7,708	10,987.a	9,044 a	33,542 a	15.66 b
p-value	**	ns	*	***	***	*
Irri. Sched.						
SWS	4,599	8,110 a	11,198 a	8,256 a	32,357 a	32.82 a
CWD	4,897	8,780 a	9,135 b	5,337 b	27,768 ab	13.2 b
SYS	4,578	5,137 b	8,304 b	5,177 b	23,388 b	7.74 c
p-value	ns	**	*	*	*	***
*Year*Irri. Sched.*						
p-value	ns	ns	ns	ns	ns	ns

ns—not significant according to the ANOVA; *$p<0.1$; **$p<0.01$; ***$p<0.001$.

Discussion

Due to erratic weather patterns resulting from climate change, irrigation events need to be properly managed, focusing on weather inputs and outputs to supply crop production (Chartzoulakis and Bertaki, 2015). In the present study, the spring of 2022 was a drier and warm season, while during 2023 a favorable weather conditions was present during most of the growing season in 2023. These weather conditions affected the total volume of water applied in the CWD and SWS treatments; consequently, plant development and yield (Zotarelli et al., 2010, Dukes and Scholberg 2005). According to Zhou et al., (2017), the performance of irrigation scheduling treatments can be highly affected by rainfall. Due to fewer rainfall events in 2022, soil moisture levels in the SWS, CWD, and SYS treatments remained below the soil field capacity during the entire growing season (Fig. 2A). However, as the rainfall events increased in 2023, the saturation point was reached several times in the SYS irrigation schedule during periods of rainfall, possibly increasing nutrient leaching. Growers must keep in mind that proper irrigation scheduling can directly minimize costs with water pumps, and indirectly reduce fertilizer waste (Haley and Dukes, 2012).

Despite no significant differences among treatments during most crop growth stages, plant biomass accumulation at the end of the season was significantly greater in the SWS treatment compared to the CWD and SYS regimes. This may be related to increased nitrogen availability, as excessive irrigation in the CWD and SYS treatments may result in nitrogen leaching (Zotarelli et al., 2008). The importance of effective irrigation scheduling strategies to optimize vegetable productivity has been previously reported in the literature and corroborate with results of this study (Locascio, 2005; da Silva et al., 2018; Schattman et al., 2023).

The warmer 2022 season resulted in premature blooming and fruit development. In 2022 there were more days with air temperatures that surpassed 28.8 °C (which has a detrimental effect on fruit production) compared to 2023. This resulted in a reduction in yield in 2022 compared to 2023. Likewise, Peet et al., (1997) noted considerable reductions in fruit weight and quantity as daily average temperatures rose from 25 to 29.8 °C. These changes were linked to impacts on ovule development and subsequent post-pollen production processes. Zotarelli et al., (2009) also reported a similar trend as tomato yield and dry biomass increases during cooler temperatures. Differences in yield between both seasons can also be attributed to differences in the age of transplants (Leskovar et al., 1991). In 2022, seedlings were transplanted at 8 weeks old, while in 2023, seedlings were transplanted at 5weeks of age. The use of older transplants often results in earlier yields because of an advanced physiological age (Nicklow and Minges, 1962). However, this may also negatively affect individual fruit weight and number of fruit per plant (Weston and Zandstra, 1989).

The SWS treatment had a consistently higher yield for large and extra-large fruits than CWD and SYS irrigation scheduling, consequently increasing total yields. In an experiment comparing the performance of SWS and fixed irrigation in tomato production, Dukes et al., (2007) reported a yield increase between 21% and 43% for SWS compared to the SYS irrigation treatment. The difference between treatments may be related to nitrogen leaching below the root zone for SYS irrigation scheduling. In the present study, nitrogen uptake was not evaluated; however, the saturated conditions observed during 2022 and 2023 for SYS and CWD treatments likely led to soil nitrogen leaching, which is commonly reported in coarse-textured soils of southeastern U.S. (da Silva et al., 2018; da Silva et al., 2022). Consequently, the lower yields of SYS and CWD compared to SWS can be associated with waterlogging conditions and lack of soil nitrogen availability in the crop root zone.

The ratio between the overall yield and the volume of water utilized during irrigation events indicates the amount harvested relative to the water used (Expósito et al., 2019). In this study, the SWS presented a significant increase in the IWP, representing a better performance of the soil moisture sensor to convert water into yield, corroborating the results of Zotarelli et al., (2009).

The appropriate irrigation scheduling should combine crop water demand according to crop growth stage, soil moisture status, and proper frequency of application (Dukes et al., 2010), which is relatively easy to achieve with the correct use of soil moisture sensors. Research findings of this study considered the concept of optimum irrigation management, the method that accounts for the climate inputs and outputs combined with the crop necessity during the season. Nevertheless, understanding of how each irrigation management practice might impact soil properties (both physical and chemical) and nutrient availability, which were not addressed in this study, would enhance the ability to assess the advantages and disadvantages of each irrigation method employed in this research.

Conclusion

In general, weather conditions directly influenced the growth and development of organic-grown tomatoes. Temperature played a crucial role in determining the duration of the tomato crop season from transplanting to harvest. Additionally, rainfall events had an impact on the strategies used for irrigation. Among the various irrigation scheduling methods tested, the SWS approach exhibited better results in terms of fruit growth, biomass accumulation, and overall yield when compared to CWD and SYS methods. Considering the global need for sustainable practices, the SWS treatment emerges as one of the best alternatives in terms of water saving. This indicates that embracing irrigation scheduling based on soil moisture sensors could offer a feasible option for growers in the southeastern U.S. to improve tomato yields under different weather conditions.

Chapter 3

Climate change evaluation using CROPGRO-Tomato model for different irrigation scheduling in Alabama

Introduction

Climate change stands as the greatest challenge currently faced in agriculture. Historical weather observations indicate that global warming is occurring (Peters, R. L. 1985, Westerling, A. L et al., 2006), and many agricultural production regions will experience increasing average temperatures (Batibeniz et al., 2020). In addition, climate change has shown a more intense and widespread precipitation extremes (Rastogi et al., 2020) and changes in rainfall and temperature patterns directly affect crop development, as well as impacting the hydrological cycle and increasing the risk of water and heat stress. (Liu et al., 2016).

Heat stress is an abiotic stress that occurs when daily air temperatures are above those that are optimal for crop development, negatively impacting plant production (Van Herwaarden et al., 1998). Initially, heat stress increases water demand due to increases in the crop transpiration rates, while in extreme conditions, it will restrict plant growth due to insufficient photosynthetic capacity (Zhou et al., 2015; Lu et al., 2017). Ultimately, heat stress will affect crop yields, the impact of which will vary among species. Particularly, plants that have an optimum range of cooler temperatures might present a significant reduction in total production as daily air temperature rises (Backlund et al., 2008). In general, the exposure to elevated temperatures can adversely influence seed germination, leaf abscission and senescence, decrease in shoot and root growth or a decrease in flower number, pollen tube growth and viability, and fruit damage, ultimately leading to devastating loss of crop yield (Teixeira et al., 2013; Hemantaranjan et al., 2014).

Water is imperative for plant growth and development. Water stress, temporally or permanently, affects plant growth and production. Since plants absorb water from the soil, many of the impacts of climate and soil characteristics are impact plants through water availability in soil (Stephenson, 1990). Plants exposed to water stress have limited access to the resources required for photosynthesis due to stomatal closure and the reduction of internal water transport (Breda et al., 2006). As such, water stress impairs normal plant functionality and further induces morphological, physiological, and biochemical changes to compensate for water limitations (Lee et al., 2016). Plants that experience early season drought may present a reduction in germination and stand establishment principally due to reduced water uptake during the imbibition phase of germination, reduced energy supply, and impaired enzyme activities (Okcu et al., 2005; Taiz and Zeiger 2010). When drought occurs during the critical during flowering periods it may increase pollen sterility, resulting in flower and fruit abortion (Farooq et al., 2012).

Overall, the impacts of climate change on crop production are difficult to predict, yet assessing these impacts is needed for both farm management and policy-making purposes (Kenny et al., 1995). Numerous crop models have been developed over previous decades with the objective to predict the global climate change effect on food production. Among the various models employed to evaluate the influence of climate change on crops, the CSM-CROPGRO-Tomato (Scholberg et al., 1997) model has been shown as an essential tool that addresses the significant challenges of crop productivity and sustainability linked with the current scenario of weather variability (Ventrella et al., 2012., Cammarano et al., 2020). Particularly, most of the studies currently available are focused on wheat, maize, rice, and potato, while for horticulture crops only a few studies have been addressing the impact of climate change (Cammarano et al., 2022), despite the high importance that those crops have to the world population in terms of nutritional value (Kalmpourtzidou et al., 2020) and economic sector (Rubatzky & Yamaguchi 2012).

Thus, the objective of this study was to evaluate the performance of the CSM-CROPGRO-Tomato under two different irrigation strategies using historical weather data and to evaluate the impact of different climate change scenarios on organic tomato production.

Material and Methods

Field experiments and site description

Field experiments were conducted to assess the impact of two irrigation scheduling treatments on tomato growth and yield under organic production growing practices. Irrigation scheduling strategies consisted of a systematic irrigation (SYS), which mimics farmers' practices and supplied 6.34 mm of water a day, and a soil water status based irrigation (SWS), which considered the soil volumetric water content for each irrigation event. Chapter 2 contains a description of each irrigation scheduling treatment.

Field experiments were conducted during the spring of 2022 and 2023 at the Organic Unit in the E.V. Smith Research and Extension Center from Auburn University, Shorter, AL. Climate conditions of the region is classified as a humid subtropical climate (Cfa) with cold and dry winters followed by a wet and warm to hot summers (Köppen, 1928). The soil is classified as Cahaba sandy loam soil (fine-loamy, siliceous, semiactive, thermic Typic Hapludults) (USDA, 2023). Soil organic matter content in the 0-15 cm depth was 9.4g kg^{-1}. Soil bulk density in the 0-15 and 15-30 cm of soil depth layers was 1.34 and 1.82 g cm^{-3}, respectively. Soil hydraulic proprieties, permanent wilting point, field capacity, and saturation were 0.12, 0.40, and 0.46 m^3 m^{-3} for the 0-15 cm soil depth and at 0.16, 0.29, and 0.36 m^3 m^{-3} for the 15-30 cm soil depth, respectively. Soil bulk density, permanent wilting point, saturation, and field capacity were measured using an adaptation of the evaporation method (Schindler and Müller, 2006).

Tomato seeds of cultivar Patsy (Bejo Seeds, Ocean, CA) were used in both years and seedlings were greenhouse grown until transplant April 15, 2022, and May 15, 2023. The genetic coefficients of the standard cultivar (Table 1) were used for the proper parameterization. Table 1 presents the adjustable genetic coefficients in the calibration, the genetic coefficient of the standard cultivar (Sunny SD) and the genetic information of cultivar Patsy.

Table 3. Genetic coefficients of tomato (var. Patsy) calibrated in DSSAT (Decision Support System of Agriculture Transfer) against previously calibrated Sunny SD tomato cultivar.

Code	Description	Sunny SD	Patsy
EM-FL	Time between plant emergence and flower appearance (R1) (photothermal days)	24.4	24.4
FL-SH	Time between first flower and first pod (R3) (photothermal days)	3	2.2
FL-SD	Time between first flower and first seed (R5) (photothermal days)	19	25
SD-PM	Time between first seed (R5) and physiological maturity (R7) (photothermal days)	45.2	45.2
FL-LF	Time between first flower (R1) and end of leaf expansion (photothermal days)	52	47
LFMAX	Maximum leaf photosynthesis rate at 30 °C, 350 vpm CO2 , and high light (mg CO2 /m2 s)	1.36	1.36
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm2 /g)	300	300
SIZLF	Maximum size of full leaf (three leaflets) (cm2	300	300
XFRT	Maximum fraction of daily growth that is partitioned to seed + shell	0.73	0.78
WTPSD	Maximum weight per seed (g)	0.004	0.004
SFDUR	Seed filling duration for pod cohort at standard growth conditions (photothermal days)	26	26
SDPDV	Average seed per pod under standard growing conditions (#/pod)	300	300
PODUR	Time required for cultivar to reach final pod load under optimal conditions (photothermal days)	58	56
THRSH	Threshing percentage. The maximum ratio of (seed/(seed/shell)) at maturity. Causes seed to stop growing as their dry weight increases until the shells are filled in a cohort	8.5	8.5
SDPRO	Fraction protein in seeds (g(protein)/g(seed))	0.3	0.3
SDLIP	Fraction oil in seeds (g(oil)/g(seed))	0.5	0.5

Data collection

During both growing seasons, daily air temperature, solar radiation, and rainfall events were monitored using an on-site weather station (WatchDog Wireless Station, WD Wireless ET Weather Station, LTE-M 50500102). Soil moisture sensors (Sentek Probe© 2023 Sentek Technologies, BMP Logic, Trenton, FL) were installed in the field to monitor the soil volumetric water content in the top 0-0.45 m of soil. Soil volumetric water content was monitored every 15 minutes and data storage in data loggers (YDOC Data Logger version ML-017, BMP Logic, Trenton, FL).

Weekly field inspections monitored the tomato crop development and allowed for determination of the crop phenological stages (i.e., vegetative stage, flowering, fruit formation, and maturity). Table 2 shows the field activities in each year. In each growth stage, aboveground plant tissue samples were collected, leaves separated from the stems, and both oven-dried to a constant weight. Total dry biomass was calculated as the sum of leaf dry weight and stem dry weight. Tomato fruits were harvested at maturity on 50, 57 and 64 days after transplanting (DAT) in 2022 and 66, 73 and 79 DAT in 2023. A sub-sample of 200 g of fruit were separated after harvesting and oven-dried to constant weight. The water content in each fruit was then multiplied by the total fresh fruit yield and fruit total dry mass estimated.

Table 4. Field activities for tomato crop season of 2022 and 2023.

Crop season 2022				Crop season 2023			
Date	Activities	Rate	Amount	Date	Activities	Rate	Amount
03/11/2022	Planting day			03/11/2023	Planting day		
04/13/2022	Fertilization G/H	5.3.3	100 g / tray	04/10/2023	Fertilization G/H	5.3.3	100g / tray
05/09/2022	Transplanting field			04/15/2023	Transplanting field		
05/12/2022	Fertilization Field	5.3.3	103 kg ha^{-1}	05/02/2023	Fert irrigation	3.3.3	375 l ha^{-1}
05/27/2022	Fertilization Field	5.3.3	103 kg ha^{-1}	05/10/2023	Start treatment		
06/03/2022	Start treatment			05/11/2023	Irrigation SMS	4 h	74.4 m^3 m^{-3}
06/06/2022	Irrigations SMS	4 h	74.4 m^3 m^{-3}	05/15/2023	Irrigation SMS	4 h	74.4 m^3 m^{-3}
06/09/2022	Irrigations SMS	4 h	74.4 m^3 m^{-3}	05/15/2023	Fert irrigation	5.1.1	336 l ha^{-1}
06/09/2022	Plant evaluation			05/22/2023	Plant evaluation		
06/10/2022	Fert irrigation	7.7.7	212 kg ha^{-1}	05/26/2023	Insect Control	Xentari	1.85 kg ha^{-1}
06/10/2022	Insect Control	Xentari	1.85 kg ha^{-1}	05/27/2023	Fert irrigation	5.1.1	187 l ha^{-1}
06/12/2022	Irrigations SMS	5 h	93 m^3 m^{-3}	05/27/2023	Fert irrigation	1.7.5	187 l ha^{-1}
06/13/2022	Fert irrigation	7.7.7	212 kg ha^{-1}	05/27/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/16/2022	Plant evaluation			05/31/2023	Plant evaluation		
06/17/2022	Fert irrigation	7.7.7	212 kg ha^{-1}	06/01/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/17/2022	Irrigations SMS	5h	93 m^3 m^{-3}	06/02/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/18/2022	Irrigations SMS	5h	93 m^3 m^{-3}	06/03/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/20/2022	Irrigations SMS	5h	93 m^3 m^{-3}	06/04/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/22/2022	Irrigations SMS	5h	93 m^3 m^{-3}	06/06/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/23/2022	Fert irrigation	7.7.7	212 kg ha^{-1}	06/06/2023	Plant evaluation		55.8 m^3 m^{-3}
06/23/2022	Plant evaluation			06/08/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/24/2022	Insect Control	Xentari	1.85 kg ha^{-1}	06/10/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/25/2022	Irrigations SMS	4 h	74.4 m^3 m^{-3}	06/12/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/27/2022	Irrigations SMS	4 h	74.4 m^3 m^{-3}	06/16/2023	Plant evaluation		
06/28/2022	Harvest			06/17/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
06/30/2022	Plant evaluation			06/19/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
07/03/2022	Irrigations SMS	4 h	74.4 m^3 m^{-3}	06/20/2023	Harvest		
07/05/2022	Harvest			06/21/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
07/06/2022	Irrigations SMS	4 h	74.4 m^3 m^{-3}	06/24/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
07/07/2022	Plant evaluation			06/27/2023	Harvest		
07/12/2022	Harvest			06/30/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
				07/01/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
				07/03/2023	Irrigation SMS	3 h	55.8 m^3 m^{-3}
				07/03/2023	Harvest		
				07/03/2023	Plant evaluation		

CSM-CROPGRO-Tomato model evaluation

Tomato genetic coefficients (Table 1), experimental data, soil data, and weather data were used during the process of calibration and validation of the CSM-CROPGRO-Tomato model (Scholberg et al., 1997). Calibration was conducted using data from the field experiment of 2022 and validation using data from the field experiment of 2023. During the process of calibration and validation, also called model evaluation, crop evapotranspiration was calculated using the Priestley-Taylor/Ritchie formula, soil water infiltration was calculated using capacity approach method, soil evaporation was estimated by the Suleiman-Ritchie method, and the dynamic of carbon and nitrogen was simulated with the CERES model. These are all pre-defined routines.

Crop model performance was evaluated by comparing simulated and observed data, which included leaf and stem dry weight (kg ha^{-1}), total biomass accumulation (kg ha^{-1}), total yield (kg ha^{-1}), and daily soil volumetric water content (m^{3} m^{-3}). Statistical indices used consisted on the coefficient of determination (R^{2}), which was forced through the origin (0:0), so the values measured the true deviation of the estimates from the observation (Yang et al., 2014); the slope of a linear regression, which provides an over or underestimation by the model; the root mean square error (RMSE), which provide a measure of the absolute magnitude of the error (Wallach and Goffinet, 1987); and the relative root mean square error (RRMSE).

Seasonal analysis

The analysis of different environmental scenarios was performed after the CSM-CROPGRO-Tomato evaluation using historical weather data from 1998 to 2023 (25 years) collected from the National Oceanic and Atmosphere Administration (NOAA). Weather data consisted of daily total precipitation, wind speed, humidity, and daily maximum (T_{max}) and minimum (T_{min}) air temperatures. Daily solar radiation is also required, and data was collected from the National Solar Radiation Database, which is maintained by the National Renewable Energy Laboratory.

For the seasonal analysis, irrigation strategy treatments were simulated in interaction with different climate scenarios. Climate scenarios were simulated covering the range of predicted changes for the eastern region of the United States (Almazroui, et al., 2021), in which historical daily temperature was adjusted by adding 2 ^{o}C and 2% rainfall precipitation in the first scenario, 4 ^{o}C and 6% rainfall precipitation in the second scenario, and 6 ^{o}C and 10% rainfall precipitation in the third scenario, according to Ludwig and Asseng (2006). Particularly, increases in precipitation only occurred for the latest months of the winter and for the entire spring months (Jan – Apr) (Almazroui, et al., 2021). Rainfall was increased by changing every individual rain event in the period mentioned above. So, the number of rainfall events remains equal, but the intensity of each event changed. Ultimately, the seasonal analysis for each scenario was simulated using 25 years of historical weather data.

Overall, there was a total of 200 simulations from the combination of two irrigation scheduling treatment and 4 weather scenarios using the 25 years. For this analysis, the crop biomass accumulation (kg ha^{-1}), water use (mm/ha) for each irrigation scheduling treatment, and total yield (kg ha^{-1}) were compared among treatments in a cumulative probability distribution (Ngwira et al., 2014).

Results

Tomato crop and model performance

Crop development and irrigation scheduling

The CSM-CROPGRO-Tomato model was evaluated for soil volumetric water content, dry leaf biomass, dry stem biomass, total dry biomass , and total fresh yield. During crop development, there was a rapid increase in the aboveground dry weight after tomato transplanting, which reached its maximum at flowering when total biomass accumulation seceded. Particularly, the SYS treatment had the lowest total dry biomass accumulation during simulations (Fig. 4), reaching a plateau with 1,751 and 1,911kg ha^{-1} in 2022 and 2023, respectively. The SWS irrigation scheduling had a total dry biomass accumulation of 2,470 kg ha^{-1} in 2022 and 2,789 kg ha^{-1} in 2023.

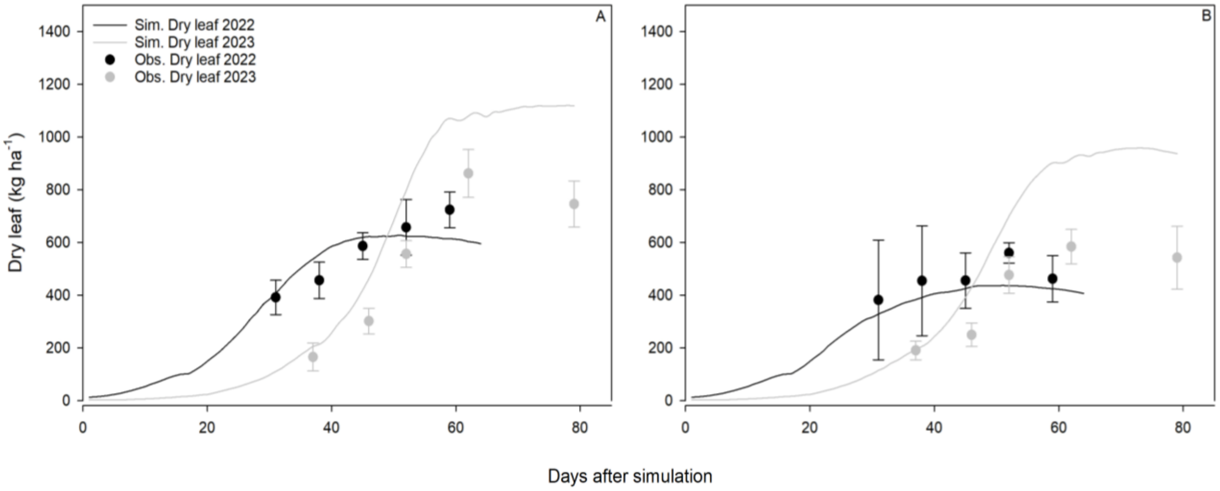

Figure 4. Simulated (lines) and observed (symbols) data of total biomass dry weight (kg ha^{-1}) for SWS (A) and SYS (B) irrigation scheduling in days after simulation started under Central Alabama weather conditions of 2022 and 2023. Error bars indicate the standard deviation of field measurements.

Total dry biomass accumulation was responsive to both leaf and stem dry biomass, which exponentially increased after transplanting. However, total dry leaf biomass reached a plateau 11 days earlier than the stem. The SWS treatment had the highest accumulation for dry stem at harvest with 1,813 and 1,951 kg ha^{-1} while the SYS had 1,256 and 1,385 kg ha^{-1} at the same period (Fig. 6) for 2022 and 2023, respectively. Plants grown with the SWS irrigation system had increased leaf biomass compared to those grown with the SYS. Tomato plants receiving the SWS treatment accumulated 724 and 861 kg ha^{-1} of dry leaf biomass, while tomato plants receiving the SYS irrigation scheduling accumulated 462 and 584 kg ha^{-1} of dry leaf biomass in 2022 and 2023, respectively (Fig. 7).

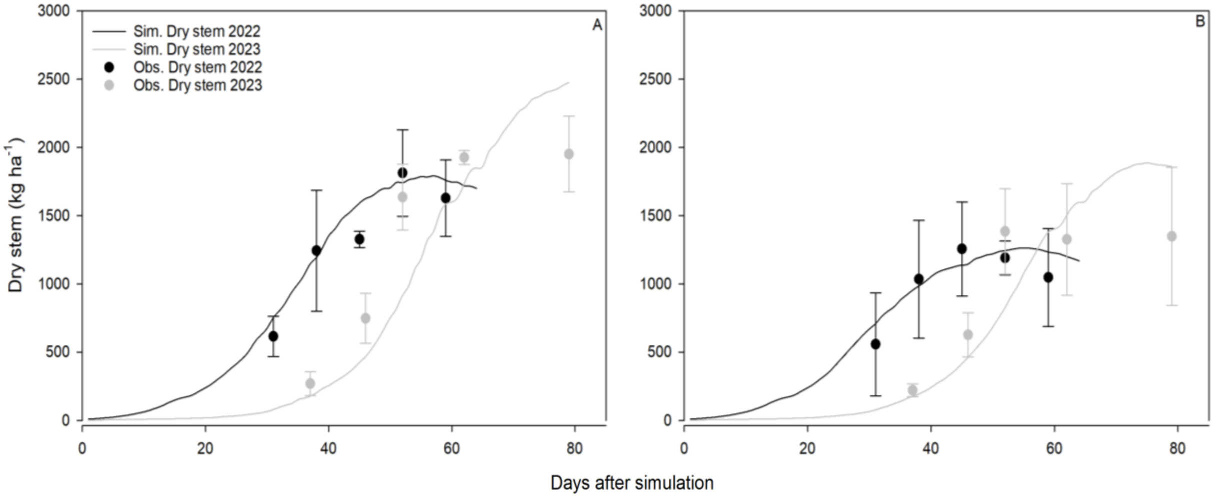

Figure 5. Simulated (lines) and observed (symbols) data of dry stem weight (kg ha^{-1}) for SWS (A) and SYS (B) irrigation scheduling in days after simulation started under Central Alabama weather conditions of 2022 and 2023. Error bars indicate the standard deviation of field measurements.

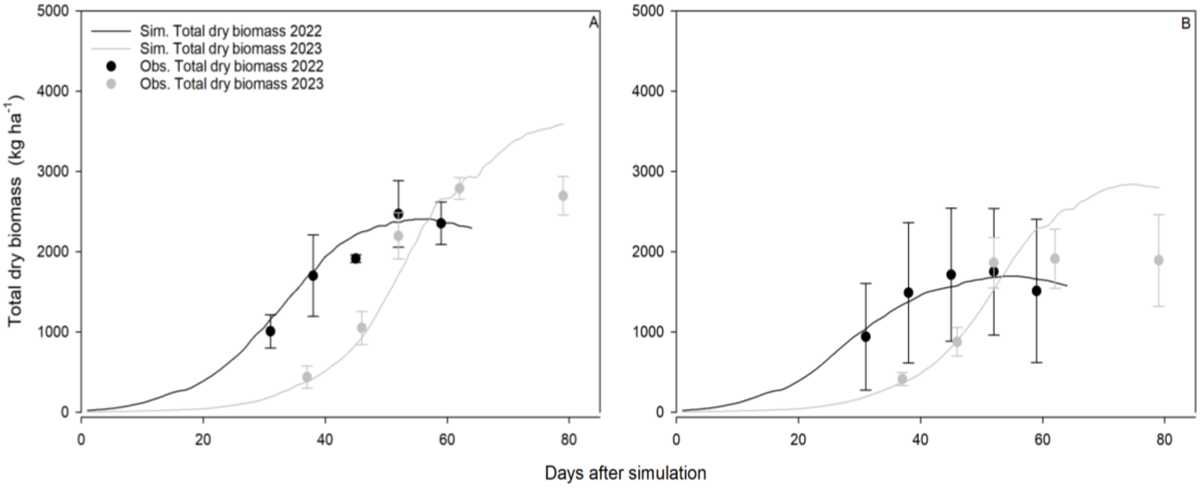

Figure 6. Simulated (lines) and observed (symbols) data of dry leaf weight (kg ha^{-1}) for SWS (A) and SYS (B) irrigation scheduling in days after simulation started under Central Alabama weather conditions of 2022 and 2023. Error bars indicate the standard deviation of field measurements.

Regarding tomato total yield, the SWS had a higher yield than the SYS in both years. Particularly, SWS treatment yielded 25,882 and 39,072 kg ha^{-1} in 2022 and 2023, respectively. While SYS yielded 17,741 and 28,962 kg ha^{-1} in 2022 and 2023, respectively (Fig. 8A and B).

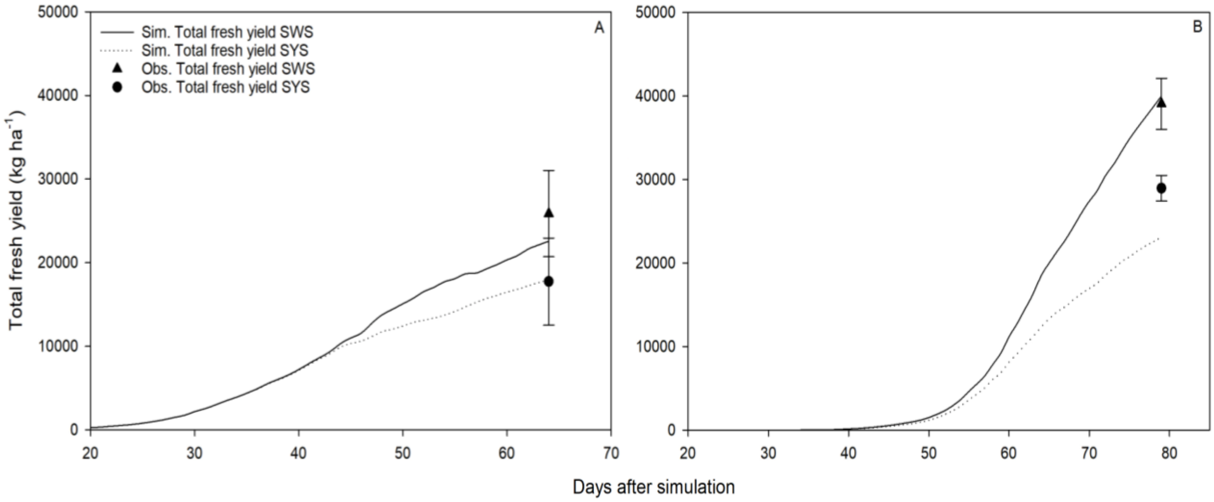

Figure 7. Simulated (lines) and observed (symbols) data of total fresh yield (kg ha^{-1}) for SWS and SYS treatment in the crop season of 2022 (A) and 2023 (B) in days after simulation start under Central Alabama weather conditions.

Figure 8 shows the observed and simulated soil volumetric water content in the 0-15 cm soil depth during the 2022 and 2023 tomato seasons. Overall, for SWS irrigation scheduling, soil moisture content had a peak after each rainfall and irrigation event and the water drainage after those events was faster simulated than that measured (Fig. 8 A and B). For SYS, on the other hand, soil moisture presented a stable water volume, with small difference of moisture after irrigation and rainfall events (Fig. 8 C and D).

The simulated soil moisture content during both years of tomato season in the 0-15 cm soil depth layers had an average of 0.40, and 0.41 cm^3 cm^{-3}, for SWS, and SYS, respectively, while the measured soil moisture content averaged was 0.30, and 0.36 cm^3 cm^{-3} in the same order.

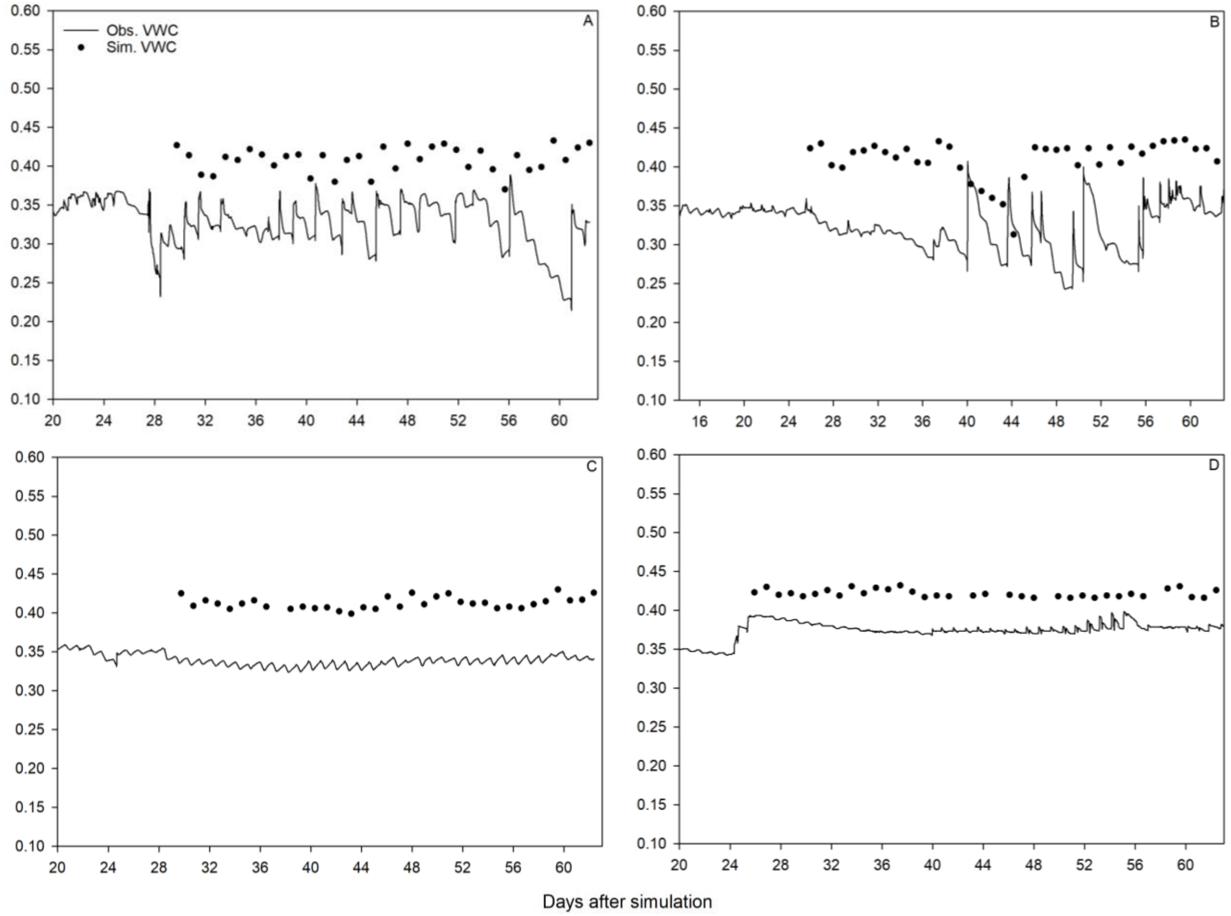

Figure 8. Simulated (symbols) and observed (lines) data of soil moisture content (cm^3 cm^{-3}) at 0-15 cm of soil depth for SWS (A and B) and SYS (C and D) treatment in the crop season of 2022 (A and C) and 2023 (B and D) in days after simulation start (DAS) under Central Alabama weather conditions.

CSM-CROPGRO-Tomato evaluation

The CSM-CROPGRO tomato had an acceptable match between observed and simulated dry leaf biomass, dry stem biomass, and total dry biomass (Table 6). The RMSE for dry leaf biomass and dry stem biomass was 141 and 291 kg ha^{-1}, respectively. Total dry biomass had an RMSE of 352 kg ha^{-1}, respectively. For dry leaf biomass and dry stem biomass, the R^2 was 0.91 and 0.94, respectively, while the R^2 for total dry biomass accumulated was 0.96. Particularly, simulations for SYS, which was the irrigation scheduling treatment that applied fixed amount of water throughout the crop season, had better performance than simulation for the high irrigation rates of SYS. This can be seen in Figure 6, when total dry biomass of the SYS is presented as a better fit by the model than the SWS treatment.

Table 5. CSM-CROPGRO-Tomato model performance when compared to the observed data for field experiments in 2022 and 2023.

Variable	Number of paired data	R^2	Slope	RMSE[a]	RRMSE[b]
Dry leaf weight (kg ha^{-1})	30	0.91	0.41	141	0.45
Dry stem weight (kg ha^{-1})	30	0.94	0.73	291	0.25
Total above ground weight (kg ha^{-1})	30	0.96	0.74	352	0.21
Total fresh yield (kg ha^{-1})		0.98	0.89	4329	0.15
Soil volumetric water content (cm^3 cm^{-3})	268	0.99	0.57	0.07	0.23

[a] Root mean square error

[b] Relative root mean square error (%)

The CSM-CROGRO Tomato also satisfactorily simulated tomato total yield, in which the RMSE was 4,329 kg ha^{-1} with an R^2 of 0.98. While soil volumetric water content was overestimated by the model despite the R^2 of 0.99. The large number of paired data increased the R^2 for observed versus simulated soil volumetric water content, however, the RMSE of 0.07 m^3 m^{-3} and a RRMSE of 0.23 m^3 m^{-3}, as well as data shown in figure 8 indicate the over simulation of soil volumetric water content. This might be due to a slow simulated water drainage after rainfall and irrigation events, which was not observed in the field (Fig. 8).

Seasonal Analysis

Effect of climate change on tomato development and irrigation scheduling

The validated CSM-CROPGRO-Tomato model was employed to assess the interaction effects of irrigation methods and climate scenarios on tomato aboveground biomass accumulation and total yield. Overall, the simulated total volume of irrigation water applied for the 25 years averaged 60 and 331 mm for SWS and SYS, respectively. For the scenario with no effect of global warming, irrigation water volume was 5.5 times higher for the SYS compared to SWS (Table 6). While the SWS treatment had 63% and 75% higher aboveground dry biomass and total yield than the SYS treatment, respectively.

Table 6. Total water used, total yield, and dry weight plant tops at maturity for each irrigation treatment and weather scenario in a 25-year simulation.

Variable	Irrigation treatments							
	SWS				SYS			
	Temperature scenarios				Temperature scenarios			
	0 ^{o}C	2 ^{o}C	4 ^{o}C	6 ^{o}C	0 ^{o}C	2 ^{o}C	4 ^{o}C	6 ^{o}C
Total water used (mm)	60	67	97	164	331	331	331	331
Total yield at harvest (kg DW ha^{-1})	3,152	2,703	1,528	422	785	759	535	211
Weight plant tops at maturity (kg DW ha^{-1})	6,061	6,547	7,181	7,205	2,218	2,556	3,372	4,481

In the climate scenario with temperature increasing 2 ^{o}C and rainfall precipitation increasing 2%, irrigation water volume increases 7 mm on average while for SYS the water volume remained unchanged. Irrigation water volume was approximately 500% higher for the SYS compared to SWS; however, this volume of water did not necessary translate into increased aboveground dry biomass and total yield, which were 60% and 71% higher in the SWS than in the SYS treatment, respectively (Table 6).

In the climate scenario with temperature increasing 4 ^{o}C and rainfall precipitation increasing by 6%, the irrigation water volume applied increased by 37 mm when compared to a scenario with no temperature increase. Overall, irrigation water volume was approximately 3.5 higher for the SYS compared to SWS, while aboveground dry biomass and total yield, was 53% and 64% higher for SWS compared to SYS, respectively (Table 6).

In the climate scenario with temperature increasing 6 ^{o}C and rainfall precipitation increasing 10%, the irrigation water volume for SWS was approximately 50% less than SYS irrigation scheduling. For this scenario, the difference between treatments on water use was the smallest among all scenarios simulated. Differences among treatments also decrease for the aboveground dry biomass and total yield. For the total aboveground dry biomass SWS treatment was 50% higher than SYS while for total yield SWS presented a difference of 37% higher than the SYS treatment, respectively (Table 6).

The overall impact of climate change on tomato production

The effect of temperature in the irrigation scheduling increased the water volume of the SWS treatment, and the total aboveground dry biomass of both treatments, while the total yield progressively decreased as temperature rose (Table 6). The average rainfall accumulation during the tomato season (April to July) for the 25 years studied was 383 mm. The year with the highest volume of rainfall was 2003 with 671 mm, while the lowest volume of rainfall was measured for 2001 (191 mm).

Simulated future climate scenarios were applied to the seasonal analysis seeking to understand the future effects of global warming in the tomato crop season. The effects of increased temperatures and rainfall on above-ground dry weight and total yield differed between the irrigation methods (Fig. 9). For the climate scenario where daily air temperature increases 2 ^{o}C and rainfall precipitation increases 2%, aboveground biomass increases by 8% (Fig.9A), while total yield was reduced 15% for treatment SWS (Fig.9C). Similar results were also observed for SYS treatment under the same climate scenario, while aboveground biomass increased 15%, yield had a reduction of 3%, respectively.

In further simulations, as temperature increases, the aboveground biomass of the treatment SWS had a smaller increase than the SYS treatment. In the scenario with a temperature increase of 4 ^{o}C and rainfall increase of 6%, the aboveground biomass of tomato grown with the SWS irrigation scheduling presented an increase of 18% (Fig.9A). While for the treatment SYS the above-ground biomass increases 52%, comparing with the climate scenario that had no effect of temperature and rainfall precipitation increase.(Fig.9B). For total yield on the other hand, SWS treatment had drastic decrease presenting a reduction of 51% (Fig.9C). While SYS presented a reduction of 31% in total yield (Fig.9D).

In the climate scenario with temperature increasing 6 ^{o}C and rainfall precipitation increasing 10%, the aboveground biomass of treatment SWS did not present significant difference between the previous scenario, while plants under SYS treatment more than doubled its above ground biomass, with an increase of 2263 kg ha^{-1} of total dry biomass than no climate change scenario (Fig.9B). However, for total yield both treatments present on average a decrease of 80% in total fruit production (Fig.9C and D).

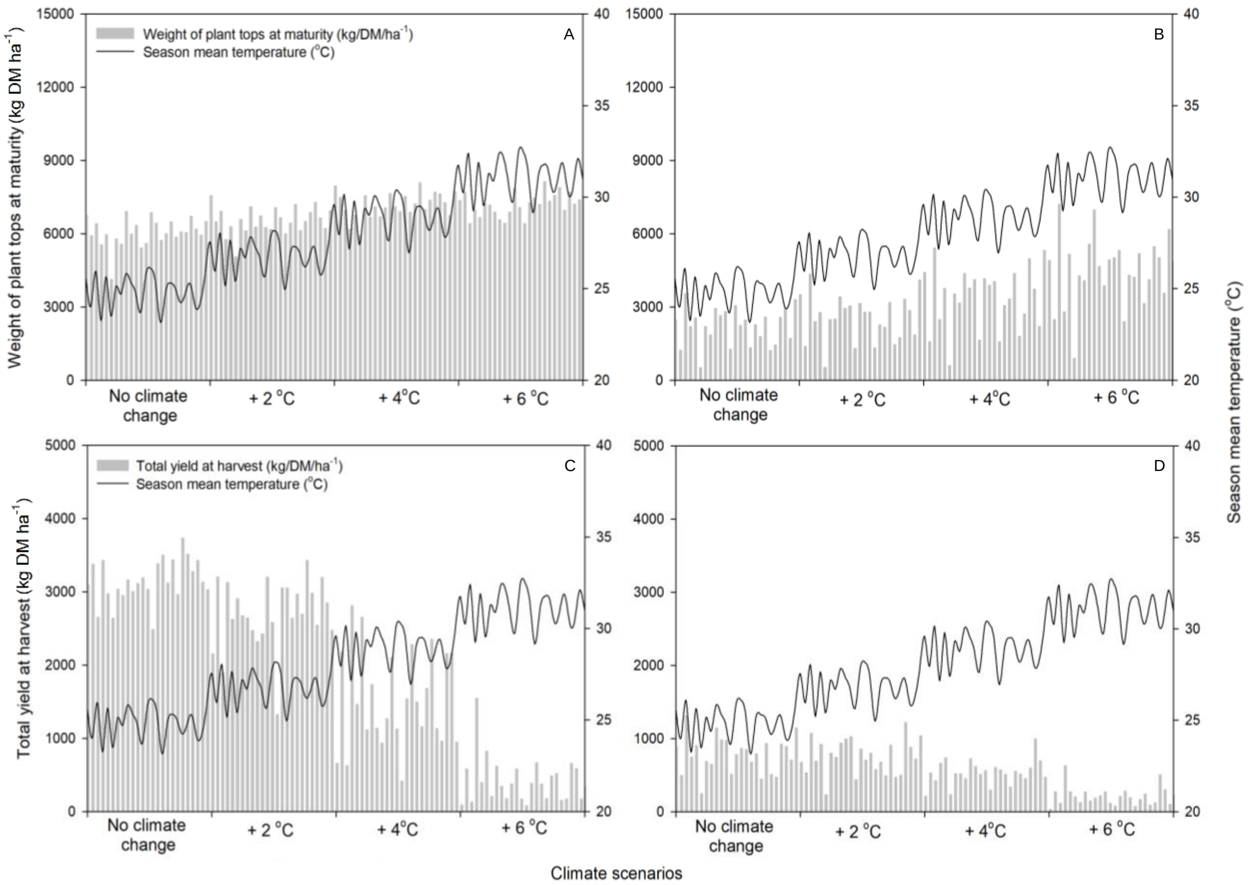

Figure 9. Simulated seasonal (April to July) total dry biomass (kg ha^{-1}), and total dry yield (kg ha^{-1}) for the tomato crop in different climate scenarios. The first scenario with no influence of climate change represents the period of 1998 to 2023. Scenarios with +2 4 and 6 °C are projected scenarios based on the weather history of the non-climate change period.

Effects of the future climate scenarios were also observed in the total volume of water used for irrigation events in the treatment SWS (Table 6). In the climate scenario with temperature increasing 2 °C and rainfall precipitation increasing 2% the total amount of water used during the irrigation events increased by an average of 10%, however with the progressive increase of temperature in other scenarios, the total water volume presented a considerable increase. For example, In the climate scenario with temperature increasing 4 °C and rainfall precipitation increasing 6% the volume of water used during the season increases 38%,while in the climate scenario with temperature increasing 6 °C and rainfall precipitation increasing 10%, the volume of water was 1.7 times higher than no climate change scenario, respectively. The treatment SYS did not change in total irrigation volume over the scenarios (Table 7).

Discussion

Overall, the response of tomato crops to irrigation scheduling treatments was satisfactory simulated by the CSM-CROPGRO-Tomato model. Observed and simulated data of most crop variables presented a good slope, indicating that the model satisfactorily reproduced the observed field data. Similar results were previously reported in the literature, where Ayankojo and Morgan et al., (2012) reported an R^2 of 0.96 and RMSE of 440 kg ha^{-1} for tomato aboveground dry biomass and Elsayed et al., (2012), who reported R^2 values ranging from 0.61 to 1 for tomato total fresh yield. This suggests that the CSM-CROPGRO-Tomato model can be confidently employed to assess tomato production across various cultivation techniques and diverse climatic conditions.

Daily air temperature played a crucial role as an abiotic stress factor in the growth and development of tomatoes (Boote et al., 2012). Our results indicated that due to elevated temperatures in the region during the spring/summer season, tomato crops may not reach their full genetic potential due to the influence of heat stress. This highlights the importance of addressing global warming as a crucial topic for discussion, especially when considering the potential impact, it has on future food production.

Optimum air temperatures for tomato production range from 22 ^{o}C and 27 ^{o}C (Sato et al., 2000), once the daily air temperature increases to levels above the optimum there is a higher portioning of resources (water and nutrients) into vegetative biomass, leading plants under such scenario to have higher development of biomass than plants under low temperature conditions (Patterson, D. T. 1993, Hussey, G 1965). Nevertheless, the increased biomass accumulation will not necessarily translate in higher yield since ideal climate conditions must be observed during crop reproductive stage. Although with minor effects on total yield, tomato plants tend to allocate a large proportion of resources into physiological maintenance processes, when exposed to higher temperatures, which negatively affects the reproductive cycle and may also contribute to the lower yield (Boote et al., 2012). However, for tomato crop when exposed to higher temperatures plants can also present high flower abortion and decreases of pollen viability, and consequently resulting in yield reduction (Sato, et al., 2001). To conclude, depending on the timing, intensity, and duration of exposure the tomato yield can decrease up to 70% under heat stress scenario (Ro et al., 2021), which may result in huge losses for growers.

Changes in soil water content were poorly simulated by the CSM-CROPGRO-Tomato model. Variations between the simulated and observed had been previously reported by Rinaldi et al., (2007). Authors reported an overestimation of 10% of simulated soil moisture, which indicates limitation for the simulation of soil volumetric water content by the CSM-CROPGRO-tomato model. This might be caused by the inaccurate simulation of soil water movement in coarse-textured soils, where water flow is assumed to occur when the soil moisture content is above the saturation threshold (Chen, D. et al., 2019). The total irrigation water volume increases as temperature rises over the different scenarios. The increase in daily air temperatures increased tomato crop evapotranspiration, which consequently increased the crop irrigation demand. Particularly, climate change impacts on irrigation water requirements were previously reported to increase water use in 15 to 20 % by 2050 in Spain (Rodriguez Diaz et al., 2007). In Baojixia, China, temperature was identified as the dominant factor determining irrigation water demand, and for a scenario of a 1 ^{o}C increase, irrigation water demand was expected to double in winter wheat season (Wang et al., 2014). Increased irrigation demand has also been reported in other parts of the world. Ashour and Al-Najar (2013) reported that a temperature increases of 1-2 °C would cause an increase in annual average evapotranspiration of 45–91 mm relative to current climate conditions, leading to an increase in irrigation requirements for overall crops of 3-6% in the middle east. In a worldwide perspective Döll (2002) states a likely increase by 5-8% until the 2070s in the net irrigation requirement due to the temperature and evapotranspiration increase

When considering the likely impacts of future climate change scenarios, and the total efficiency of growers to change or adjust their productions management to a more sustainable way some questions remain unanswered about the real capability of several regions to increase and maintain food production capability, which brings an additional uncertainty about the real scenarios for future agriculture production.

Conclusion

Tomato crop development and yield were well simulated in the CSM-CROPGRO-Tomato model for the central area of Alabama's subtropical environmental conditions. Seasonal analysis performed in the model indicated an increase of plant biomass as temperature rises, while on the other hand, for total yield a drastic reduction on yield turned the crop production impracticable under the highest temperature scenario, regarding the irrigation scheduling the water volume applied during seasons by the SWS treatment was affected by temperature. The total amount of water used for irrigation events increased progressively, more than doubling its volume in some scenarios. To conclude, regardless of the temperature increase scenarios, tomato fruit production will be negatively affected, forcing growers to adjust their management to avoid losses.

Chapter 4

Overall conclusion

The results of this graduate research dissertation highlight the significant impact of irrigation scheduling on organic tomato production under different irrigation scheduling. Over the two growing seasons, rainfall events presented significant differences, with higher rainfall accumulation measured in 2023 compared to 2022. These distinct weather patterns influenced the management of the CWS and SWS irrigation treatment.

In both years SWS treatment exhibited higher biomass compared with CWD and the SYS irrigation scheduling, indicating its resilience to weather-induced waterlogging conditions. The positive correlation between biomass accumulation and tomato yield further highlights the importance of effective irrigation strategies in optimizing crop productivity. Moreover, the SWS method increased IWP, indicating its efficiency in converting irrigation water into fruit weight. Particularly, this study’s findings strongly support the implementation of the SWS approach as an effective irrigation scheduling strategy for maximizing tomato growth and yield under an organic production system.

Ultimately, the modeling simulations presented futuristic scenarios of global warming for tomato production under SWS and SYS irrigation treatment. The project highlighted the negative effect that rising temperature could bring for the crop in Alabama. Consequently, this study strongly supports and highlights the need for future adjustments of the currents or the development of new crop management systems to avoid losses in the crop yield due to high temperatures.

Chapter 5

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