

Effects of Soil Warming and Residue Retention on Soil Carbon Dynamics and Crop
Yield in Irrigated and Dryland Cotton

by

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ABSTRACT

The Great Plains region is an economically important area that produces around 30-35% of the cotton produced in the United States. However, the region is facing challenges to sustain agricultural production due to frequent extreme climate events. Droughts have become more common and severe during growing seasons, and rainfall events have become more unpredictable. These environmental changes have major ramifications, especially for agricultural soil health. Soil health is defined as the capacity of soil to function as a vital living system that supports plant and animal productivity, maintains, or improves water and air quality, and promotes plant and animal health. Soil health has been severely affected by climate variability, particularly in dry soils. Several land management approaches have been identified that have the potential to reduce the negative environmental effects of climate change while also promoting a variety of physical, chemical, and biological soil attributes that improve soil health. For example, adding plant residue as mulch on the soil surface has the potential to increase soil health, thereby mitigating the negative effects of a warmer world. We conducted a passive warming experiment with open top chambers and residue treatment in dryland (unirrigated) and irrigated cotton fields in the semi-arid agroecosystem of Lubbock, Texas to evaluate the interactive effects of warming, residue, and irrigation on soil organic matter, microbial biomass carbon, soil CO₂ flux, seed cotton yield, and aboveground belowground biomass production. We hypothesized that warming triggered by open top chambers (OTCs) would (i) increase microbial biomass carbon, soil CO₂ flux, soil organic matter, and cotton production in irrigated soils, but would reduce microbial biomass carbon, soil CO₂ flux, soil organic matter, and cotton production in dryland soils and (ii) residue would increase soil moisture and lower soil temperature, mitigating warming effects, and thus increase soil organic matter content, cotton yield and biomass production.

OTCs did not result a significant change in soil temperature, but they increased air temperature by 2 °C. Residue and irrigation decreased soil temperature by 0.5 °C and 0.7 °C, respectively. Open top chambers decreased volumetric water content in dryland by 11.56% but volumetric water content in irrigated was unaffected. Interestingly, irrigation

did not affect volumetric water content, likely because the growing season received rainfall 54.58 % higher than irrigation water applied. Residue addition decreased volumetric water content by 10.69% in control, but in OTC plots residue increased water content by 1.43% in our study. OTCs and residue did not affect soil organic matter, but irrigation increased soil organic matter by 36.79%. OTCs increased microbial biomass by 34.85% under residue applied condition, but without residue OTCs decreased microbial biomass by 14.1 %. Nitrogen availability is positively correlated with microbial biomass, but P is negatively correlated. Additionally, OTCs and residue increased soil respiration rate by 20.72% and 103.12 % respectively. Similarly, in irrigated plots we observed 37.17%, 149.17%, and 128.60% higher seed cotton yield, aboveground biomass, and belowground biomass, respectively than dryland. OTCs and residue did not affect cotton yield and biomass production.

Our findings suggested that irrigation increased on soil carbon stocks and crop production amid simulated climate change and indicated that moisture stress, rather than heat stress, limits soil health and agricultural performance in the Southern High Plains of Texas. Therefore, adopting suitable moisture conservation measures that improves agricultural water use efficiency and hence minimize irrigation water demand is vital to long term sustainability of cotton cultivation in the Southern High Plains.

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BACKGROUND

Climate Change and Agriculture

Climate change is defined as long-term alterations in temperature and weather patterns. In recent decades, the fast rate at which the climate has changed has been a major concern for human society. The climate over land has been warming faster than the global average; between 2006 and 2015, the average temperature over land was 1.53 °C higher than it was at the end of the twentieth century (Arneth et al., 2019). Climate change has worsened the loss of land and freshwater resources, increased desertification, land degradation, and biodiversity loss, which exacerbate societal vulnerabilities, particularly in areas where the economy is heavily reliant on the natural resources (FAO et al., 2018). Agricultural land accounts for around 4.8 billion hectares, which makes 37 percent of the total land area (FAO 2021). Agricultural productivity is sensitive to changing climatic conditions. Changes in climatic elements like temperature and precipitation and the frequency and severity of extreme occurrences like droughts, floods, and windstorms directly impact agricultural and livestock production. Even though increased concentrations of carbon dioxide can boost agroecosystem productivity, increased temperatures combined with more unpredictable precipitation can diminish crop yield, thereby outweighing the benefits of increased carbon dioxide (Walthall et al., 2012).

Soil and water are key resources for agricultural production that constantly interact with the climatic elements. Healthy soils have adequate nutrients to support plant growth, moderately high levels of organic matter, a soil structure with good aggregation, optimum pH levels, and higher microbial activity. Climate change can directly and indirectly affect soil health by changing soil biological activity and carbon storage (Bardgett et al., 2008; Karmakar et al., 2016). The direct effects include temperature-driven carbon loss through soil organic matter decomposition, and hence, increased carbon dioxide production, and changes to soil microbial community composition (Bardgett et al., 2008). Indirectly, climate change affects soils through plant productivity and vegetation structure changes. Increased CO₂ concentration and temperature enhance plant growth and increase carbon input, thereby changing net carbon turnover (Van Veen

et al., 1991; Allen et al., 1996), but can also increase decomposition rates (van Groenigen et al., 2014), counteracting soil carbon storage. In addition, soil moisture, aggregation, and soil particle distribution are extremely important in determining carbon reserves. Increased moisture has a positive effect on carbon storage (Xiong et al., 2018). Soil carbon is usually protected within the well-aggregated soil because soil aggregates protect the carbon from microbial breakdown and mineralization (Razafimbelo et al., 2008; Wang et al., 2019). The finer the aggregates, the better the protection of soil carbon, hence fine-textured soil (high in silt and clay) hold more carbon than coarse-textured soils (Saha et al. 2010). A recent study demonstrated that the reduction in soil carbon storage with temperature was more than three times greater in coarse-textured soils, with limited soil aggregation by organic matter, than in fine-textured soils with greater aggregation capacities (Hartley et al., 2021). Therefore, it is critical to consider the reliance of soil carbon dynamics on key environmental and soil variables and their interaction while estimating soil carbon stocks.

Research Objectives

Due to large variations in intra-annual and interannual temperature and precipitation patterns, the Great Plains region, an economically important region that contributes around 30-35% of the cotton produced in the United States (USDA-NASS, 2020), is facing challenges in sustaining crop production (Steiner et al., 2018). The soil quality and crop yield in this region has been declining due to higher mean temperatures, droughts, and extreme rainfall events (Steiner et al., 2018). Follet et al. (2012) also reported that higher temperature and soil disturbance due to agriculture had reduced the existing soil carbon content in the US Great Plains. Increased water availability and conservation soil management practices may help offset these losses either by increasing soil carbon input from increased microbes and plant productivity or by decreasing carbon loss from the soil (Follet et al., 2012; Srinivasarao et al., 2014). However, water is a main limiting factor in US Great Plains since this region has a semi-arid climate with high summer temperatures and low annual precipitation. Agriculture in this region is reliant on irrigation water extracted from the Ogallala aquifer, but the aquifer's water level is decreasing due to increased water harvesting and lower recharge rates (Ouapo et

al., 2013). Here, I examined the effects of passive climate warming and its interaction with crop management practices (i.e., residue and irrigation) on soil carbon dynamics, including CO₂ flux through respiration and cotton production in a semi-arid agroecosystem. The specific objective of this study was to assess the effects of warming and residue retention on soil organic matter, microbial biomass, soil respiration, seed cotton yield, and aboveground belowground cotton biomass production in irrigated and dryland cotton. In my thesis, the impacts of warming and residue retention in irrigated and dryland cotton on soil carbon dynamics and cotton production are discussed in two chapters.

Chapter 1: Warming accelerates carbon loss in soil by enhancing soil respiration.

Chapter 2: Upland cotton production under experimental warming in Texas High Plains.

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CHAPTER I

WARMING ACCELERATES CARBON LOSS IN SOIL BY ENHANCING SOIL RESPIRATION

INTRODUCTION

Soils are the largest carbon reservoir in terrestrial ecosystems, storing around 62% of terrestrial carbon (Lal 2004). As such, soils contain roughly four times as much carbon as in the atmosphere (Jobbágy and Jackson, 2000). Soil organic matter is the major source of organic carbon in the soil, but carbon content in organic matter is dynamic and exhibits great variability across soil type, depth, land use, and climatic conditions. On an average, organic matter contains 58-60 % carbon (Pribyl, 2010) with the remainder comprised of other elements such as nitrogen, phosphorus, and sulfur. Organic matter has several benefits to the soil and plant growth. It promotes plant nutrient availability, improves soil aggregate formation (Hoyle, 2013), improves water retention (Rawls et al., 2003), and supports soil biological activity (Benbi et al., 2018) in the soil. Therefore, it is critical to explore potential influencing elements and determine the key driving forces influencing soil organic carbon and carbon loss via CO₂ exchange for agricultural sustainability and ecosystem balance.

Soil organic carbon content is determined by the balance of input and output of carbon in the soil. Land use is a key component that influences carbon input and release from the soil; forest and grassland typically have larger carbon inputs than the cultivated agricultural soil (Luo et al., 2010). However, depending on the extent of soil manipulation and farming technique used, cultivation can positively or negatively impact soil organic carbon storage and release (Godde et al., 2016). For instance, Luo et al. (2010) showed that soil organic carbon at 10 cm below the surface in cultivated land was 51 percent lower than a natural ecosystem after five decades of farming, indicating that farming decreases organic matter in the soil. However, studies have reported organic matter in the cultivated soil can be increased by using conservation agriculture methods such as no-tillage, irrigation, residue management, cover cropping, and crop rotation (Mandal et al. 2007; Page et al., 2020).

Temperature and precipitation are two major environmental factors that considerably impact soil carbon. Zeng et al. (2021) revealed that mean annual precipitation (MAP) accounted for 81.8 percent and 13.8 percent of the variance in chemical and physical fraction of soil carbon, respectively. In contrast, mean annual temperature (MAT) contributed 1.5 percent and 34.7 percent, respectively. Hence, climate change, particularly global warming and precipitation change, is known to affect soil carbon content, although whether warming causes net carbon loss or net increases soil carbon stocks is still debated (Knorr et al., 2005; Davidson and Janssens, 2006; van Gestel et al., 2018). Warming stimulates soil respiration, organic matter decomposition, and nutrient mineralization (Rustad et al., 2001), thereby releasing more carbon from the soil as CO₂ (Zhang et al., 2015; van Gestel et al., 2018). Warming also increases carbon input to the soil due to enhanced plant production and carbon sequestration, mainly in high latitude regions (Piao et al., 2006; Liu et al., 2020; Keenan and Riley, 2018). The net change, expressed as the difference between increased carbon loss and increased net primary production in response to warming, determines whether carbon is stored or released from the soil in a warmer world (Luo et al., 2007; Liu et al., 2020).

Soil respiration accounts for nearly two-thirds of carbon loss from cultivated soils globally while the remaining one-third of carbon loss is due to land degradation and erosion (Lal, 2004). Total soil respiration is comprised of autotrophic respiration by plant roots and heterotrophic respiration by microbial decomposition. Both autotrophic and heterotrophic respiration release carbon from soil into the atmosphere, with temperature having a significant impact on both (Wang et al., 2014). Soil respiration increases when the temperature rises, (Lefevre et al., 2014); nevertheless, soil respiration's temperature sensitivity tends to attenuate with time (Luo et al., 2001; Rustad et al., 2001) or could show a cyclical pattern. For instance, in a 26-year field warming study Melillo et al. (2017) found that the mean annual CO₂ flux from warmed plots was higher than control plots in the first few years, but steadily dropped to the level in control plots after 6-7 years and then again showed an increasing trend. Further, increases in respiration rates with soil temperature are limited until a temperature threshold of 25 °C is reached, after which they begin to decline as the temperature rises (Carey et al., 2016).

Temperature is not the sole factor that influences soil organic matter decomposition and soil respiration; availability and accessibility of soil microbes to the substrate, microbial abundance, precipitation, enzyme activity, and soil properties all play a crucial role. Soil organic matter decomposition and soil respiration both increase with temperature if all other factors remain constant (Davidson and Janssens, 2006), but in a natural setting temperature interacts with other variables in the soil (Jia et al., 2020). For example, warming can reduce soil water availability by increasing evapotranspiration and decreasing soil moisture (Dolschak et al., 2019), thereby lowering the rate of organic matter decomposition, even to the point at which soil respiration no longer responds to warming (Wang et al., 2014). These findings support the theory that the breakdown of organic matter and soil respiration are sensitive to fluctuations in temperature and moisture because of their effects on microbial growth and activity. Therefore, it is imperative to study how variations in soil temperature and moisture affect the organic carbon pool and carbon loss in the soil to better understand the effects of future climate change on soil carbon dynamics.

Residue retention is an important agronomic practice which contributes to soil health directly by providing carbon input and plant nutrients in the soil, and indirectly by regulating soil temperature and moisture. Several studies have shown incorporating crop residue in the soil can increase the soil organic matter content (Potter et al., 2007; Luo et al., 2016). On the other hand, increased active soil organic matter stocks from residue could lead to increased carbon loss as CO₂ flux (Zhao et al., 2013). Residue also has effects on the soil environment. The addition of residue reduces evaporation and enhances water retention rate of the soil, minimizing moisture loss due to excessive evaporation at higher temperatures (Russel 1939). Therefore, residue may be a viable strategy for reducing temperature and moisture changes in the soil profile and minimizing soil health degradation during climate extremes.

Soil microorganisms influence the terrestrial carbon cycle either by driving plant litter decomposition and soil organic matter formation or contributing directly to the soil carbon pool (Bardgett et al., 2008). Warming alters soil temperature and moisture, plant growth and biomass production, and root-derived carbon via root exudates stimulating soil microbial growth and activity (Yin et al., 2013; Carlyle et al., 2011). Microbial

biomass carbon is highly correlated with plant-derived carbon via root exudation and decomposition (Eisenhauer et al., 2017). Warming may increase (Bell et al., 2010), decrease (Mandal et al., 2007; Qi et al., 2016), or have no effects (Zhou et al., 2013) on microbial biomass. The precipitation regime, which may govern soil moisture and substrate availability, influences the response of soil microbial activity and biomass to warming. In drier environments, microbial growth and biomass production is negatively correlated with warming, as indicated by Liu et al. (2016) who showed that, after four years of warming in desert steppe, warming lowered microbial biomass and microbial respiration when soil moisture was a limiting factor, but not under abundant moisture conditions.

The South Texas Plain has a semi-arid climate where plant growth and agricultural production is limited by high temperature and low water availability. Increased climate extremes such as increased temperature, and more frequent and severe drought driven by unpredictable precipitation pattern, has further exacerbated the agricultural soil degradation in this region. As a result, the physical, chemical, and biological aspect of soils have been severely affected, especially in dry soils. Specifically, we are losing organic matter and soil microbes at a faster rate from the soil, which are considered key indicators of the soil health. Furthermore, groundwater, which is the region's main source of irrigation, is depleting at a quicker rate than before, thus farmers have already started to switch to dryland cultivation. Many researchers have proposed conservation agricultural practices such as no tillage, residue retention, and cover cropping as potential climate change mitigation approaches in agriculture as these practices are believed to stabilize soil microenvironment, thereby maintain better soil conditions for plant and microbial activity. Nevertheless, a little is known about the how well these practices alleviate climate change in moisture-limited arid and semi-arid environments. This study evaluated the effects of passive warming and residue application on soil organic carbon pool, microbial biomass carbon, and soil respiration rate in irrigated and dryland soils of semi-arid Texas High Plains. We used an open-top chambers (OTC) to passively raise soil and air temperatures, and multispecies grass residue (Bermuda (*Cynodon dactylon* (L.) Pers.), blue grama (*Bouteloua gracilis* (Kunth) Lag. ex Griffiths), and fescue grasses (*Festuca arundinacea* Schreb.)) was used as a

residue source. We hypothesized that (i) in irrigated soils, warming triggered by OTC would increase microbial biomass carbon, soil CO₂ flux, and soil organic matter content because greater moisture availability would stimulate microbial growth, soil respiration, and increase carbon input through improved plant productivity regardless of soil higher temperature; (ii) in dryland soils, warming would reduce microbial biomass carbon, soil CO₂ flux, and soil organic matter content because limited moisture availability in dryland would intensify the negative effects of warming on microbial growth, soil respiration, and soil carbon stocks; (iii) irrigation and residue would raise the moisture content of the soil, decrease the soil temperature, and lower daily temperature fluctuations, and (iv) increased soil moisture and added carbon biomass due to residue application would have positive impacts on soil microbial growth and activity, resulting in higher soil organic matter content, microbial biomass carbon, and soil CO₂ flux in both irrigated and dryland regions.

MATERIALS AND METHODS

Site Characteristics

The research was carried out during the growing season of 2021 (May – October) at the Texas Tech Quaker Avenue Research Farm, Lubbock, Texas (33° 41' 36.4596" N, -101° 54' 18.612 "W, 992 m a.s.l.). The study site was located in a semi-arid climate with a mean annual precipitation of 472 mm and a mean annual temperature of 15.9 °C. The hottest month is July, with an average monthly temperature of 33.8 °C, and the coolest month is January, with an average monthly temperature of 3.3 °C. A weather station installed in the center of the research field was used to record field-level weather data such as temperature, precipitation, relative humidity, and wind speed. During the growing season of 2021 the average temperature was 24.2 °C (the hottest month was June, with an average monthly temperature of 27.3 °C, and the coolest month was October with an average monthly temperature of 18.21 °C). During our study period the field received an average rainfall of 337 mm. The mean soil pH was 8.49. The soil had 1.042 ± 0.10 % organic matter and a bulk density of 1.29 g/cm³ at 0-10 cm depth. The soil has a sandy clay loam texture with 61.45 % sand, 15 % silt, and 23.55 % clay. The soil is classified as

Amarillo-Acuff sandy clay loam (Fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) (Pilon et al., 2015)

Experimental Design

The field experiment was conducted in two adjacent fields that had a drip irrigation system installed. Prior to this experiment, both fields were operating under irrigated cotton monocropping system. During our experiment period, irrigation was applied in one field (irrigated) in addition to rainfall, and the other field received rainfall as the sole water source (i.e., dryland). The passive warming treatment consisted of 1m × 1m × 1m open-top chambers (OTC) composed of aluminum rods and clear polycarbonate sheets during the growing season. We set up the OTCs in the field immediately after sowing cotton seeds, using stakes and zip ties to secure them to the ground. The radiation level in control and OTC plots were monitored continuously. In the plots with residue treatments, multispecies grass residue (*Bermuda (Cynodon dactylon (L.) Pers.)*, blue grama (*Bouteloua gracilis (Kunth) Lag. ex Griffiths*), and fescue grasses (*Festuca arundinacea Schreb.*)) was added to the soil surface at the rate of 3 kg residue/m². OTCs and residue were applied at the plot level, nested within the irrigation treatment. To limit the variation in data caused by the spatial heterogeneity in the field, the field was divided into six blocks, three blocks in irrigated and three blocks in dryland (Figure 1.2). For the growing season, 218 mm of irrigation water was provided via drip lines, and there was a 4 m buffer zone between the irrigated and dryland field. There were eight 1m × 1m plots in each block. Therefore, each block contained two replicates of four treatment combinations (control, OTC, residue, and OTC plus residue) administered randomly to a plot. The plots were 1 m apart from one another. Each treatment was replicated six times, resulting in a total of 48 plots. Cotton was planted in early June continuously in a row and harvested in late October. Each plot had a single crop row with 7-8 cotton plants in it.

Measurement of Environmental Variables

5TM sensors linked to EM50 data loggers (Meter Group, Inc., Pullman, Washington, USA) were used to record soil temperature (°C) and volumetric moisture

content (m^3/m^3) every 30 minutes at 10 cm soil depth in each plot. In addition, we used ibuttons (Maxim Integrated, California, USA) to record air temperature ($^{\circ}\text{C}$) and relative humidity (%) at 50cm above the ground surface every four hours. The ibuttons were covered by the radiation shields to prevent heating of sensors from direct solar radiation. We constructed the radiation shields by overlapping two perforated plastic funnels in such a way that the holes in one funnel didn't line up with the holes in the other. The amount of light intercepted at the leaf canopy (lux) was monitored with HOBO Pendant Temperature/light data loggers (Onset Computer Corp., Massachusetts, USA). The HOBO loggers were installed approximately 10 cm above the ibuttons but was not covered with radiation shield.

Soil Sample Collection and Laboratory Analysis

Soil samples were collected from each plot shortly after crop harvest in late October. We took samples from 0-15 cm deep with a soil core (3 cm diameter). Two soil samples were obtained per plot, one from each side of the crop row in a plot. For each soil sample, the soil was taken from three random sites within a side of crop row in the plot and mixed to create one composite sample. As a result, the field yielded a total of 96 soil samples from 48 plots. The soil samples were transferred to the laboratory in a refrigerated container. The samples were kept at 4 $^{\circ}\text{C}$ after passing through a 2-mm sieve to remove bigger plant roots, debris, and stones and analyzed by Waters Agricultural Laboratories Inc. for physicochemical analyses (soil macro- and micronutrients, soil organic matter, pH, and cation exchange capacity).

Microbial biomass was measured using the chloroform fumigation extraction procedure (Vance et al., 1987). Four 5 g dry weight equivalent soil samples were weighed in the glass beaker, two of which were fumigated for 48 hours with 25 ml of chloroform and the other left unfumigated. Extractable carbon was extracted from fumigated and non-fumigated samples using 50 ml of 0.5 M K_2SO_4 and filtered through filter paper. We measured the extracts at 280 nm wavelength using a spectrophotometer (GENESYS 1XX, ThermoFisher Scientific, Madison, USA). The difference in absorbance between the fumigated and unfumigated samples was used to calculate soil microbial biomass (mg/kg) (Nunan et al., 1998).

Soil Respiration Measurement

We used the LI-8100A soil CO₂ flux system to measure soil respiration rate ($\mu\text{mol CO}_2 \text{ m}^{-2}\text{s}^{-1}$) (LI-COR Inc, Nebraska, USA). At the beginning of the experiment, each plot had a 20 cm diameter soil collar installed 2-3 cm deep into the soil in the middle of the plot, 10 cm apart from the crop row. Throughout the growing season, we measured soil respiration from each soil collar three times. Plant structures inside the soil collar were periodically removed to exclude the aboveground plant tissue respiration. The measurement time was set to 2 minutes for each measurement. All measurements were taken during the same time window, from 8:30 AM to 11:30 AM, to eliminate measurement errors due to temperature differences.

Statistical Analysis

We evaluated the interaction between warming, residue, and irrigation treatments on environmental variables such as soil temperature, air temperature, volumetric soil moisture content, and light using a linear mixed effects models in R (R core team, 2022). Soil organic matter, microbial biomass, and soil respiration rate were evaluated using generalized linear mixed effects models. For these variables, the residuals showed non-normal error distribution, and hence we chose generalized linear mixed effects models with an inverse gaussian distribution that was log-linked. The use of this family of distribution improved behavior of residuals and had lower AIC value. We used ‘lmer’ and ‘glmer’ function in ‘lme4’ package (Bates et al., 2015) for linear mixed effects, and generalized linear mixed effects models, respectively. Block was used as a random effect in the models. For time series data (soil temperature, air temperature, volumetric water content, and soil respiration rate), we first calculated monthly averages for each plot, then included month as an additional random effect variable. To avoid collinearity between continuous predictors and our treatments, we fit two separate models for each response variable: the first included only the treatments (warming, residue, and irrigation) and their interaction as fixed effects, while the second included the continuous predictor variables as fixed effects. We performed backward model selection for the first model to assess interaction among treatments to be included in the final model using AIC values. We used ‘car’ package (Fox and Weisberg, 2019) to generate the ANOVA tables and p

values for fixed effect predictors. Following that, post hoc analysis was performed using Tukey's HSD with a 95% confidence interval to determine if there were significant difference between treatments. We used emmeans package (Searle et al., 1980) for post hoc analysis. The 'ggplot2' package (Wickham, 2016) was used to visualize the data and R^2 values were calculated using 'MuMIn' package (Barton, K. (2009)).

RESULTS

We observed a strong temporal variation in soil and air temperature throughout the growing season (Figure 1.3, Figure 1.6). The random effects (block and months) accounted for majority of the variation in the soil (R^2 marginal = 0.024; R^2 conditional = 0.938) and air temperature (R^2 marginal = 0.069; R^2 conditional = 0.984). Soil temperatures were not affected by the OTCs but were affected by residue ($\chi^2 = 29.09$, $P < 0.0001$; Table 1.1a) and irrigation ($\chi^2 = 25.56$, $P < 0.0001$; Table 1.1a). Residue decreased mean soil temperature by 0.6 °C, while irrigation decreased mean soil temperature by 0.7 °C compared to dryland (Figure 1.5). OTCs ($\chi^2 = 826.9$, $P < 0.0001$; Table 1.3a), and irrigation ($\chi^2 = 7.21$, $P = 0.007$; Table 1.3a) had significant main effects on air temperature. We also observed a significant interaction between OTCs and residue on air temperature ($\chi^2 = 3.99$, $P = 0.045$; Table 1.3a). OTCs increased mean air temperature by 2.3 °C in dryland while they increased air temperature by 2.0 °C in irrigated condition (Figure 1.7). OTCs also decreased light intensity by 5.8 % ($\chi^2 = 17.54$, $P < 0.0001$).

Volumetric water content also showed a temporal fluctuation (~5%) throughout the growing season (Fig 1.9). Random effects (block and months) accounted for majority of the variation in the volumetric water content (R^2 marginal = 0.073; R^2 conditional = 0.589). OTCs and irrigation did not have significant main effect on volumetric water content, but we observed a significant reduction in average volumetric water content when residue was applied ($\chi^2 = 7.59$, $P = 0.006$; Table 1.2a). Also, there was a significant interaction between OTC and irrigation ($\chi^2 = 5.82$, $P = 0.015$; Table 1.2a), and OTC and residue ($\chi^2 = 5.39$, $P = 0.02$; Table 1.2a). OTCs reduced volumetric water content in dryland by 11.7 % but it did not change volumetric water content in irrigated field (Fig 1.10). Similarly, with residue OTCs increased volumetric water content by 1.4 %, but

without residue OTCs decreased water content by 10.7 % (Figure 1.10). Our results also showed a significant three-way interaction between OTC, residue, and irrigation ($\chi^2 = 5.23$, $P = 0.022$; Table 1.2a).

OTCs and residue did not affect soil organic matter content. However, there was a significant main effect of irrigation on soil organic matter ($\chi^2 = 10.12$, $P = 0.0014$; Table 1.4a), with dryland soils having 36.8 % lower soil organic matter compared to irrigated soils (Figure 1.11). Soil organic matter was also negatively correlated with soil temperature ($\chi^2 = 4.49$, $P = 0.033$; Table 1.4b; Figure 1.12). Microbial biomass was not affected by OTCs alone, but there was a significant interaction between OTC and residue ($\chi^2 = 5.96$, $P = 0.014$; Table 1.5a). OTCs increased microbial biomass by 34.9 % under residue application, but with no residue OTCs decreased microbial biomass by 14.1 % (Figure 1.13). Residue, without considering interaction, increased ($\chi^2 = 10.37$, $P = 0.0001$; Table 1.5a; Figure 1.13) microbial biomass by 37.3 % and irrigated soil had 26.8 % higher microbial biomass carbon ($\chi^2 = 7.17$, $P = 0.007$; Table 1.6a; Figure 1.13) than dryland soils. Similarly, available soil nitrate ($\chi^2 = 20.61$, $P < 0.0001$; Table 1.5b; Figure 1.14) was positively related to microbial biomass, while phosphorus ($\chi^2 = 6.41$, $P = 0.011$; Table 1.5b; Figure 1.15) and ammonium ($\chi^2 = 4.66$, $P = 0.03$; Table 1.5b) availability were negatively correlated. Soil CO₂ flux was significantly affected by OTCs ($\chi^2 = 4.94$, $P = 0.026$; Table 1.6a) and residue ($\chi^2 = 71.08$, $P < 0.0001$; Table 1.6a), but it was not affected by irrigation. OTCs and residue increased CO₂ flux by 20.7 % and 102.1 % respectively (Figure 1.16).

DISCUSSION

The soil carbon in agricultural soils is declining because of unsustainable land management practices in agriculture and increasing extreme climate events; agricultural soils have lost 25-75% of their soil organic carbon pool (Lal et al., 2015). Soil conservation practices such as residue retention, cover cropping, irrigation, and others have been shown to help mitigate carbon loss from the soil due to soil warming in previous studies (Follet et al., 2012; Srinivasarao et al., 2014), but results vary, depending on climate and soil microenvironmental conditions (Page et al., 2020). It is generally expected that water-limited ecosystems will be particularly susceptible to increase in

temperature, which is why we sought to investigate how covering the semi-arid soils with multispecies grass residue would affect soil organic matter pools and microbial in a warmer world.

Effects of OTCs, Residue, and Irrigation on Soil Environment

OTCs are a simple, cost-effective technique to simulate global warming in field studies, particularly in areas with no access to power for active warming (Arnonon & McNulty, 2009). However, their efficiency varies depending on the vegetation structure and environment of the study area. Previous warming studies in high latitude regions suggested that OTCs could efficiently raise air temperature, but not necessarily soil temperatures (Welshofer et al., 2018; Hollister et al., 2006). On the other hand, OTCs have successfully elevated both air and soil temperatures in semi-arid regions (Escolar et al., 2012; León-Sánchez et al., 2017). In our study open top chambers increased air temperature, but not soil temperature which contrasts with the earlier OTC warming experiments in semi-arid soils. OTCs also reduced the light by 5.8% as compared to control.

Residue lowered soil temperature in our study which is consistent with Turmel et al. (2015). Covering soils with residue insulates the surface or reflects sunlight, limiting heat absorption and resulting in lower soil temperatures than uncovered soils (Li et al., 2013). The observed lower temperature in irrigated condition might be due to moisture effects and larger vegetation cover. Soil moisture regulates heat flow and conductivity in the soil profile. Soil has a lower specific heat capacity, but the moisture increases the specific heat capacity of soil as well as the conductivity. Hence, the surface of dry soils warms more quickly during the day and cools more promptly at night (Gassar, 1975; Licht and Al-Kaisi, 2005). As a result, dryland soils showed more rapid temperature fluctuations than irrigated soil.

We observed a significant interaction between OTC and irrigation on volumetric water content, although OTCs and irrigation alone did not influence volumetric water content. OTCs reduced volumetric water content in dryland, but it did not change volumetric water content in irrigated field. Higher mean soil temperature and greater diurnal temperature fluctuation in dryland than irrigated fields may have increased

evaporation rate from the soil surface (Irmak, 2016; Ma et al., 2020), speeding up moisture loss and resulting in a greater reduction in water content in dryland compared to the irrigated field. Irrigation alone did not increase volumetric water content compared to dryland, perhaps because the total precipitation received during the growing season of 2021 (337 mm) was enough to sustain soil moisture even in dryland without supplemental irrigation.

Residue cover offers shade and prevents soil moisture loss by lowering soil temperature and reducing evaporation (Iqbal et al., 2020). Therefore, we expected that soils covered with residue would be moister. Unexpectedly, our results showed that residue covered soils were drier than when left uncovered. Surface residue may have impeded the rainwater infiltration, acting as barrier, resulting a reduction in water content in the soil. Furthermore, we observed a significant increase in root biomass with residue application, which could have increased plant water intake, lowering volumetric water content in residue plots compared to plots without residue. We noticed a significant three-way interaction between OTC, residue, and irrigation treatment. In OTC plots in dryland, application of residue increased volumetric water content, indicating that application of residue in dryland farming may have potential to increase soil moisture in warmer world.

Effects of OTCs, Residue, and Irrigation on Soil Carbon Dynamics

Warming has been shown to enhance microbial activity and speed up the decomposition of soil organic matter, thereby releasing more CO₂ in previous studies (Qin et al., 2019; Lloyd and Taylor, 1994; Bond-Lamberty and Thompson, 2010; Li et al., 2019). When the soil was warmed by 4 °C, Hicks Pries et al. (2017) found that soil respiration increased by 34 to 37 percent, and organic carbon stocks declined. Our data, on the other hand, demonstrated that OTCs had no influence on soil organic matter stocks. However, we observed a significantly higher soil CO₂ flux from OTC plots, which was consistent with earlier warming experiments. Though OTCs did not have the expected warming effect on soil temperature at a depth of 10 cm, they may have increased temperature at the soil surface, increasing microbial activity and CO₂ flux. Further, soil organic matter stocks respond to on longer time scale but soil respiration changes even in very short time scales. A study in desert steppe showed that short term

warming did not change soil organic matter, but soil organic matter decreased with long term warming (Yu et al., 2020); however, soil respiration changed under both short-term and long-term warming. Our experiment ran only for one growing season, that might be a reason for not observing a change in soil organic matter, but in soil respiration rate. In accordance with our results, Schnecker et al. (2016) reported no difference in organic soil carbon between warming and control treatments but an increase in CO₂ emission.

Residue treatment was intended to increase soil organic matter by adding plant biomass in the form of residue, but that was not the case; nevertheless, it did increase microbial biomass and CO₂ flux as expected. The interaction between residue and OTC was synergistic on microbial biomass; OTCs increased microbial biomass in residue applied plots, but with no residue OTCs decreased microbial biomass. Irrigation, on the other hand, increased soil organic matter and microbial biomass while having minimal influence on CO₂ flux in the soil. The storage and release of organic carbon via CO₂ flux in response to temperature is a complex process driven by substrate quality, moisture availability, microbial carbon use efficiency, and enzyme activities (Conant et al., 2011; Chen et al., 2020). The direction of soil carbon sequestration is determined by the balance between carbon input from plant litter, roots, and microbial compounds and carbon release from organic matter breakdown and soil respiration (Tajik et al., 2020, Allison et al., 2010). Furthermore, soil organic matter chemistry affects carbon transport; unstable carbon has a fast turnover rate and consequently a short residence period in the soil (Schnecker et al., 2016). Residue applied in our study consisted of dry grasses, which have a low C: N ratio (approximately 18:1) (Hamido et al., 2016). Substrates with low C:N ratio favors microbial decomposition and increase microbial carbon use efficiency (Argen & Bosatta, 1987). However, microbial carbon use efficiency, which is a ratio of carbon taken up by microbes to carbon allocated for their growth, largely depends on availability and nutrients composition of substrate, and soil microclimate (Sinsabaugh et al., 2013). We believe the carbon released to the soil in our study via residue was more labile, decomposing at a quicker rate, and was constantly replaced by fresh carbon into the soil. Therefore, increased accessibility of microbes to fresh easily degradable carbon might have boosted carbon use efficiency, increasing carbon allocated for microbial growth, and hence increased microbial biomass under residue application. We also

suspect that most of the organic matter pool in our study site consisted of carbon derived from microbial tissue.

We observed a higher microbial biomass in the irrigated field than dryland, which was in accordance with Yu et al. (2021). In dry soils, moisture rather than temperature limits microbial development and activity (Li et al., 2019). Soil water facilitates microbial movement in the soil, maintains osmotic equilibrium in microbial cells, and improves metabolic efficiency, all of which contribute to improved microbial growth and development (Schimel, 2018). When microorganisms are stressed by water, they synthesize osmolytes to maintain osmotic equilibrium, which takes a lot of energy, and reduces the amount of carbon available for microbial growth (Schimel et al., 2007). Therefore, a more stable soil moisture content, either due to irrigation or residue, in our experiment may have contributed to increased microbial biomass carbon levels by enhancing microbial carbon use efficiency and growth.

Summary

In a semi-arid agroecosystem, OTCs and residue resulted in variation in soil temperature and moisture, thereby affecting several biochemical processes in the soil and carbon movement to and from the soil. Our data suggest that soil organic matter is more sensitive to moisture than temperature fluctuations in a dry environment. OTCs enhanced carbon output from the soil via CO₂ flux and irrigation improved both total soil organic matter and microbial biomass carbon. Meanwhile, residue stabilized soil temperature regime and increased microbial biomass. Hence, we concluded that suitable soil conservation such as residue retention, could help to compensate carbon loss and improve microbial growth, thereby mitigating soil health degradation in dry regions despite climate extremes.

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TABLES

Table 1.1: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for soil temperature. The bolded and italicized values are significant at $P < 0.05$. R²_m: Marginal r-square value; R²_c: Conditional r-squared value.

a)

Categorical fixed effect predictors	χ^2	Df	<i>P</i>	<i>R²_m/R²_c</i>
OTC	0.279	1	0.597	0.024/0.938
Reside	29.09	1	<i>< 0.0001</i>	
Irrigation	25.56	1	<i>< 0.0001</i>	

b)

Continuous fixed effect predictors	χ^2	Df	<i>P</i>	<i>R²_m/R²_c</i>
Volumetric water content	1.357	1	0.244	0.00095/0.931

Table 1.2: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for soil moisture. The bolded and italicized values are significant at $P < 0.05$. R^2m : Marginal r-square value; R^2c : Conditional r-squared value.

a)

Categorical fixed effect predictors	χ^2	Df	P	R^2m/R^2c
OTC	3.197	1	0.073	0.073/0.589
Reside	7.599	1	<i>0.006</i>	
Irrigation	1.671	1	0.196	
OTC: Residue	5.394	1	<i>0.020</i>	
OTC: Irrigation	5.824	1	<i>0.015</i>	
Residue: Irrigation	0.416	1	0.518	
OTC: Residue: Irrigation	5.228	1	<i>0.022</i>	

b)

Continuous fixed effect predictors	χ^2	Df	P	R^2m/R^2c
Temperature	0.861	1	0.354	0.022/0.572

Table 1.3: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for air temperature. The bolded and italicized values are significant at $P < 0.05$. R^2_m : Marginal r-square value; R^2_c : Conditional r-squared value.

a)

Fixed effect predictors	χ^2	Df	P	R^2_m/R^2_c
OTC	398.64	1	< 0.0001	0.069/0.984
Reside	0.458	1	0.498	
Irrigation	10.99	1	0.0009	
OTC: Irrigation	3.990	1	0.045	

b)

Continuous fixed effect predictors	χ^2	Df	P	R^2_m/R^2_c
Light	0.608	1	0.435	0.0013/0.907

Table 1.4: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for soil organic matter. The bolded and italicized values are significant at $P < 0.05$.

a)

Fixed effect predictors	χ^2	Df	<i>P</i>
OTC	0.681	1	0.409
Reside	3.203	1	0.073
Irrigation	10.13	1	<i>0.0014</i>

b)

Continuous fixed effect predictors	χ^2	Df	<i>P</i>
Volumetric water content	0.406	1	0.524
Temperature	4.495	1	<i>0.033</i>

Table 1.5: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for microbial biomass. The bolded and italicized values are significant at $P < 0.05$.

a)

Fixed effect predictors	χ^2	Df	<i>P</i>
OTC	1.046	1	0.306
Reside	10.37	1	<i>0.0001</i>
Irrigation	7.175	1	<i>0.007</i>
OTC: Residue	5.967	1	<i>0.014</i>

b)

Continuous fixed effect predictors	χ^2	Df	<i>P</i>
Organic matter	0.812	1	0.367
Temperature	1.250	1	0.229
pH	1.445	1	0.263
NO ₃ ⁻	20.61	1	<i>< 0.0001</i>
P	6.416	1	<i>0.011</i>

Table 1.6: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for microbial biomass. The bolded and italicized values are significant at $P < 0.05$.

a)

Fixed effect predictors	χ^2	Df	P
OTC	4.945	1	<i>0.026</i>
Reside	71.08	1	<i>< 0.0001</i>
Irrigation	1.313	1	0.251
Residue: Irrigation	1.765	1	0.184

b)

Continuous fixed effect predictors	χ^2	Df	P
Volumetric water content	1.61	1	0.253
Temperature	1.13	1	0.204

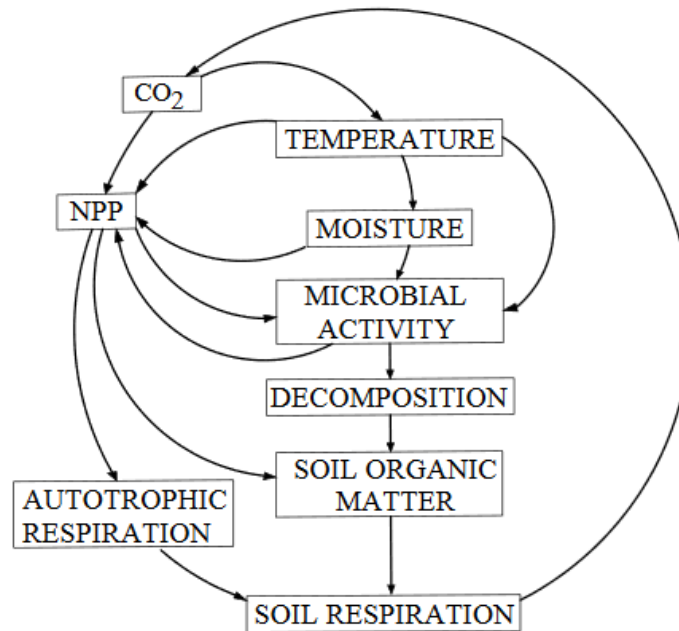
FIGURES

Figure 1.1: Visual illustration of climate-carbon feedback. Soil organic matter can have both positive and negative feedback due to climate change. Increased soil temperature as a result of climate change reduces soil moisture, impacting microbial activity and organic matter decomposition in the soil. Higher temperatures typically accelerate organic matter decomposition, resulting in carbon loss from the soil to the atmosphere in the form of CO₂. Warming causes increased microbial and autotrophic respiration, which adds to soil carbon loss. Climate change's positive feedback is linked to enhanced primary productivity because of the carbon fertilization effect. Increased CO₂ levels in the atmosphere may stimulate photosynthesis and plant productivity, resulting in more carbon being buried in the soil from plant litter.

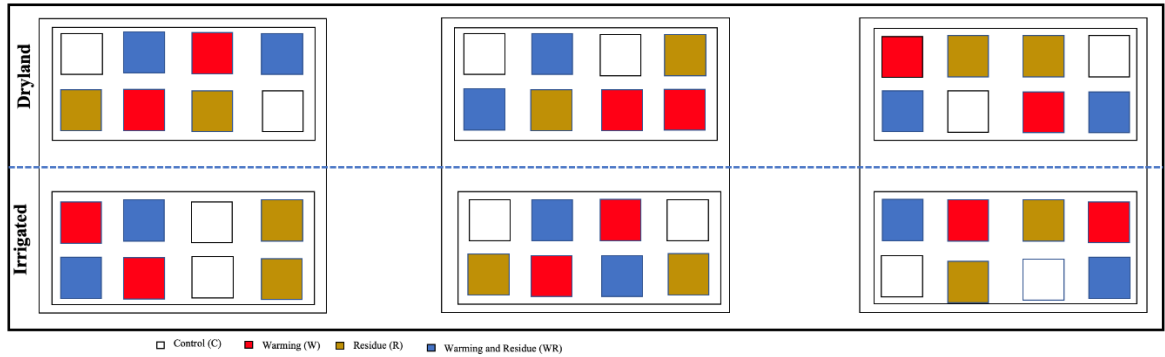


Figure 1.2: Diagrammatic representation of our experimental design. The experiment has a full factorial nested block design. Each field was divided into three blocks, with each block in the irrigated field paired with a block in the dryland field. Each block contained eight plots with two replicates of residue and OTC treatment combinations randomly assigned to a plot.

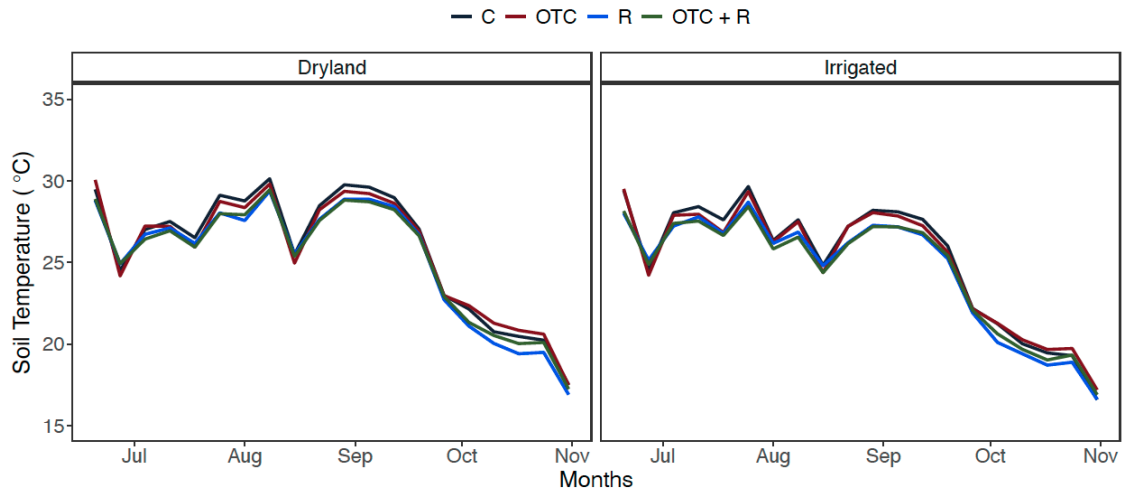


Figure 1.3: Weekly average soil temperatures measured at 10 cm depth across control (C), open top chamber (OTC), residue (R), and OTC plus residue (OTC + R) treatments in irrigated and dryland cotton.

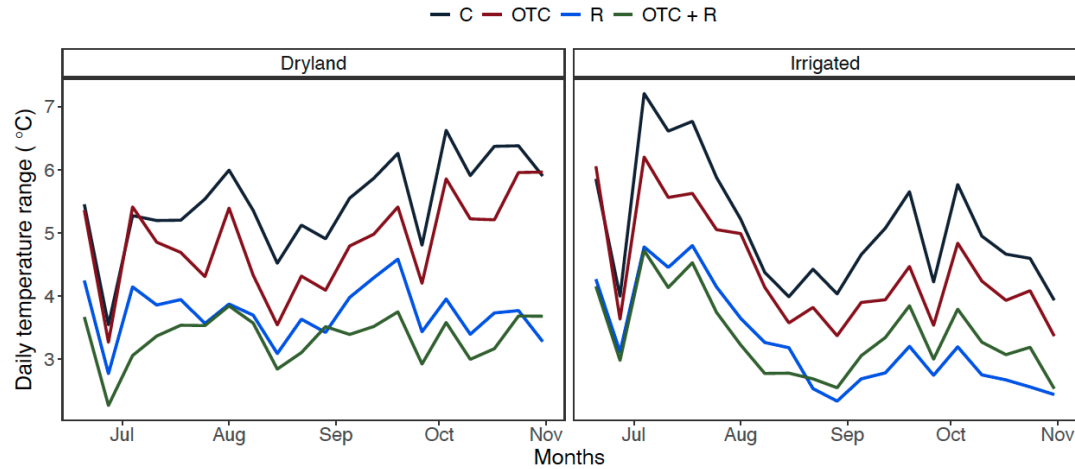


Figure 1.4: Weekly average of daily soil temperature range measured at 10 cm depth across control (C), open top chamber (OTC), residue (R), and OTC plus residue (OTC + R) treatments in irrigated and dryland cotton

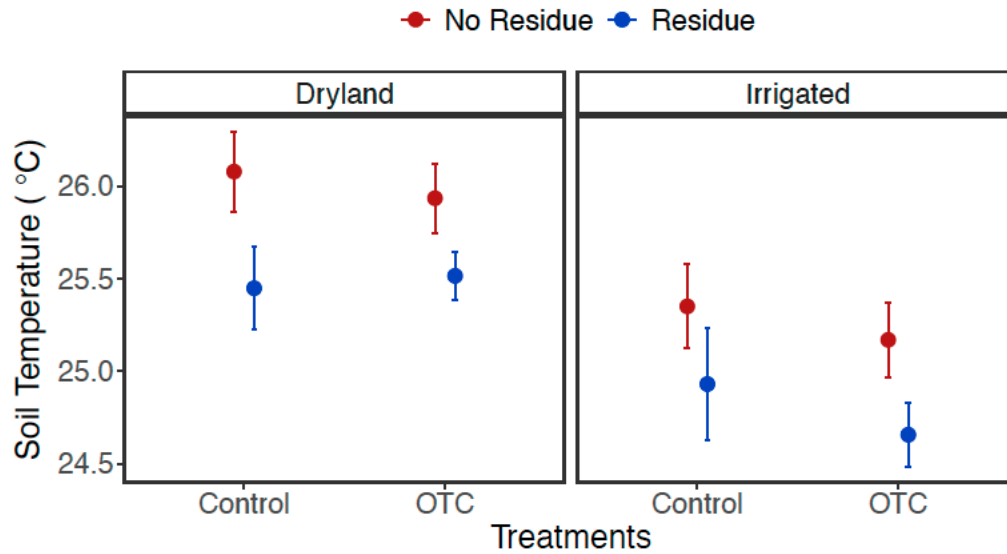


Figure 1.5: Growing season's average soil temperatures measured at 10 cm depth across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), n = 5-7 plots per treatment.

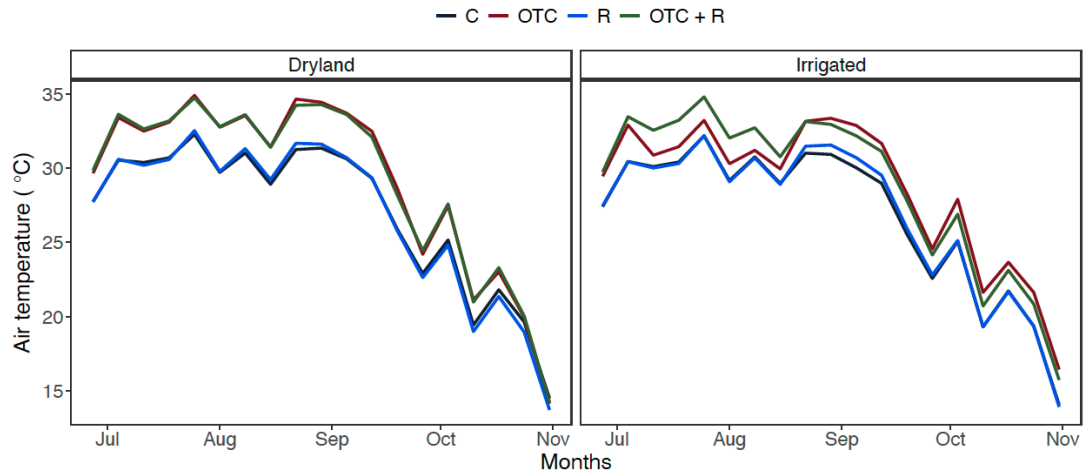


Figure 1.6: Weekly average air temperatures across control (C), open top chamber (OTC), residue (R), and OTC plus residue (OTC + R) treatments in irrigated and dryland cotton.

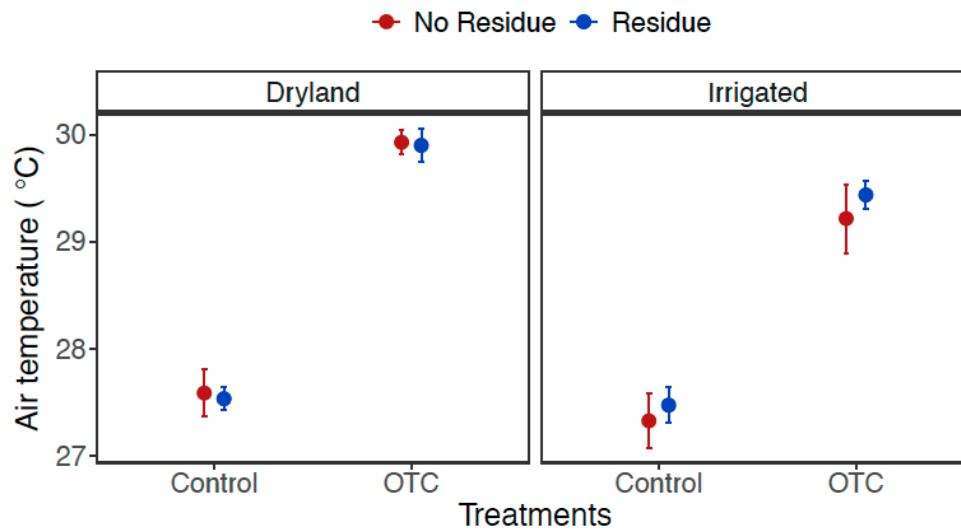


Figure 1.7: Growing season's average air temperature across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), $n = 5-7$ plots per treatment.

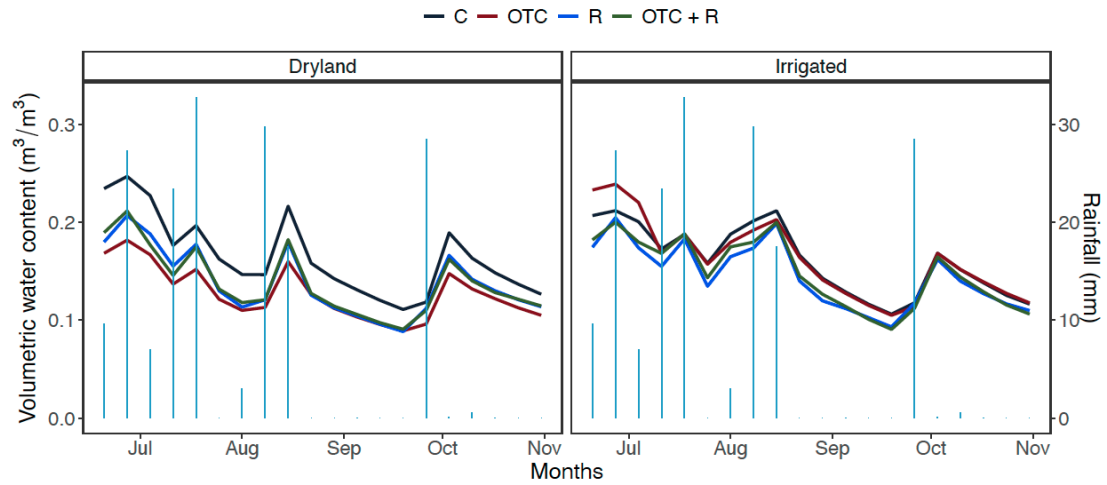


Figure 1.8: Weekly average volumetric water content (VWC) measured at 10 cm depth across control (C), open top chamber (OTC), residue (R), and OTC plus residue (OTC + R) treatments in irrigated and dryland cotton. The vertical lines show total weekly precipitation.

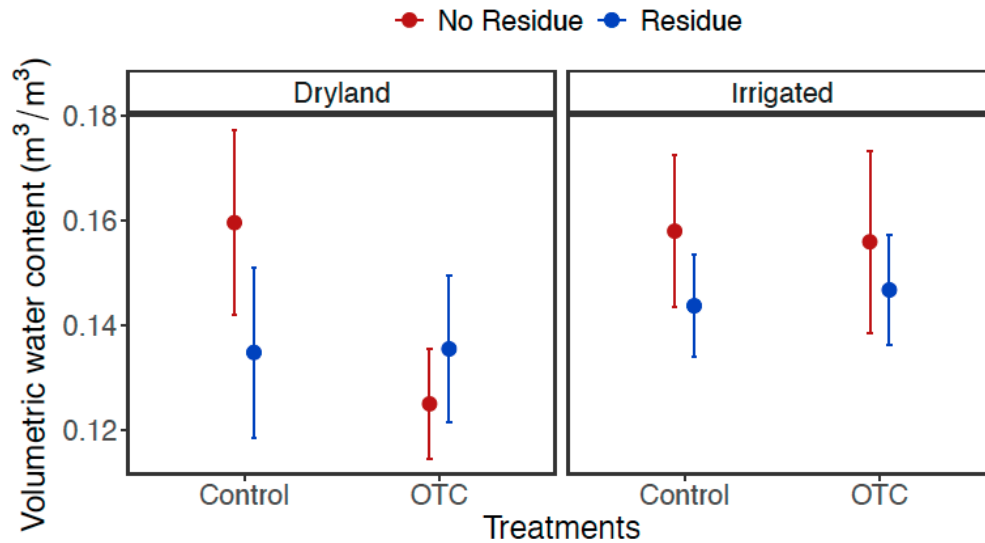


Figure 1.9: Growing season's average volumetric water content (VWC) measured at 10 cm depth across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), $n = 5-7$ plots per treatment.

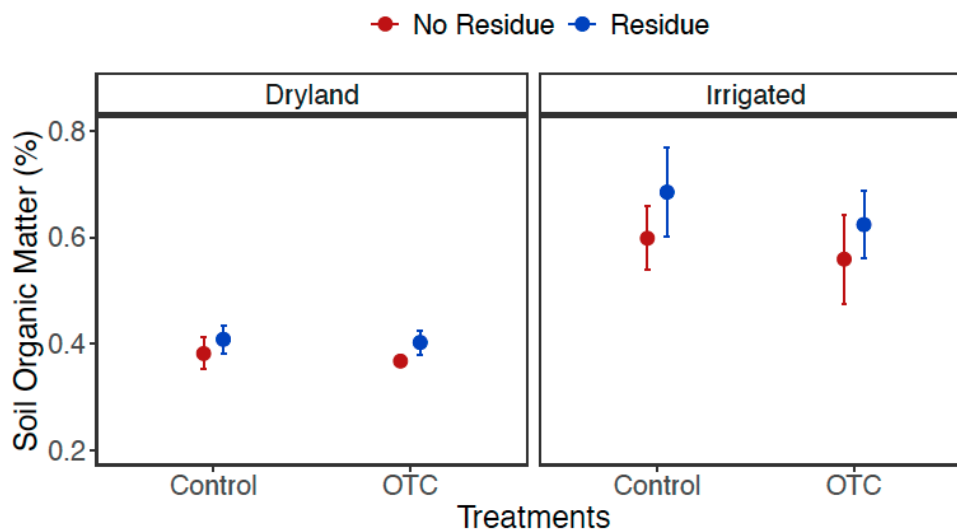


Figure 1.10: Average soil organic matter content across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), $n = 5-7$ plots per treatment.

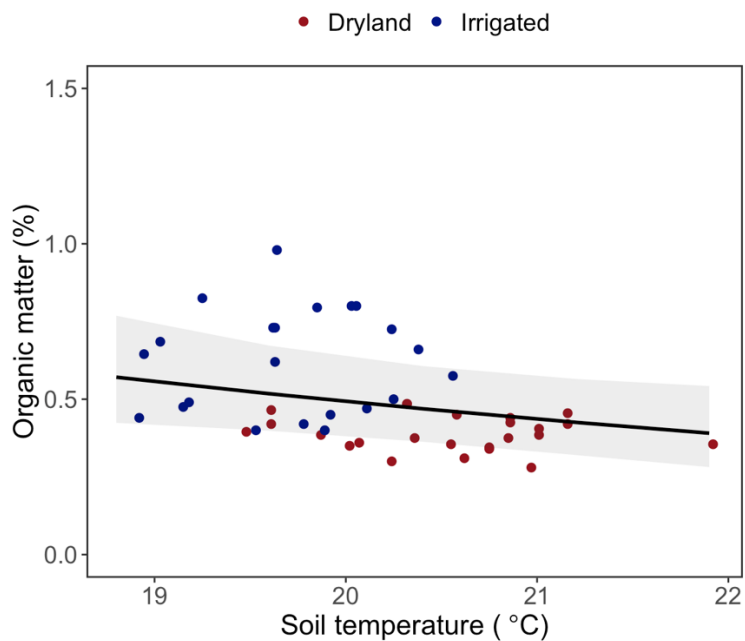


Figure 1.11: Relation between organic matter and soil temperature. Organic matter decreased with increasing soil temperature. The data shown are average of each plot. The regression line was generated from mixed model predicted values.

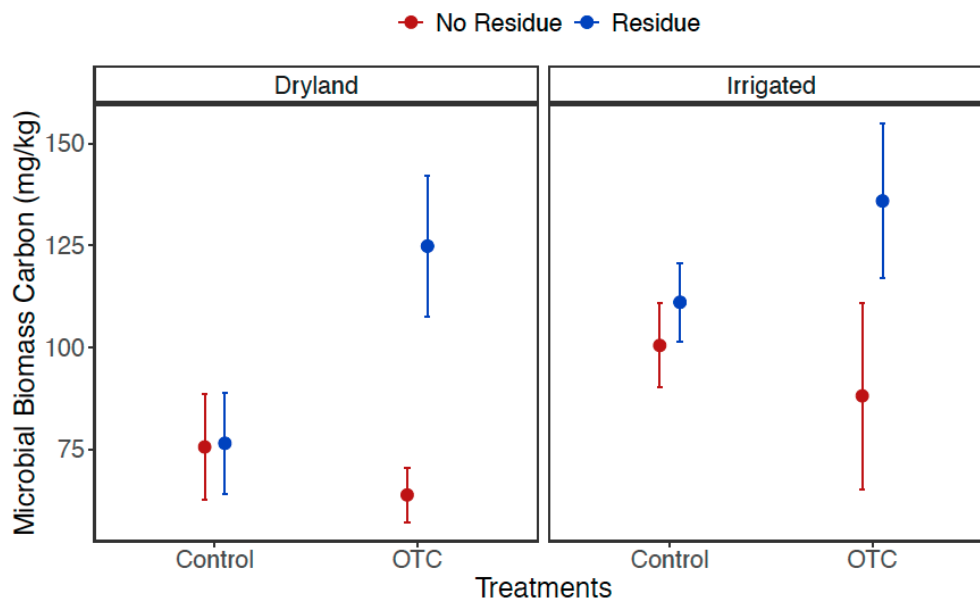


Figure 1.12: Average microbial biomass carbon across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), $n = 5-7$ plots per treatment.

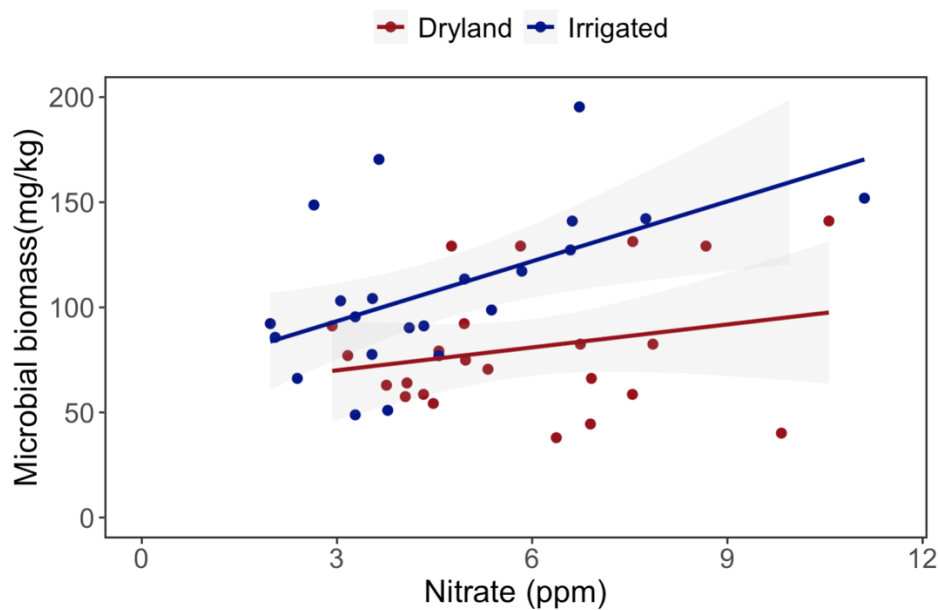


Figure 1.13: Relation between microbial biomass and available nitrate. Microbial biomass increased with increasing nitrate in the soil. The data shown are average of each plot. Regression lines generated from simple linear regression.

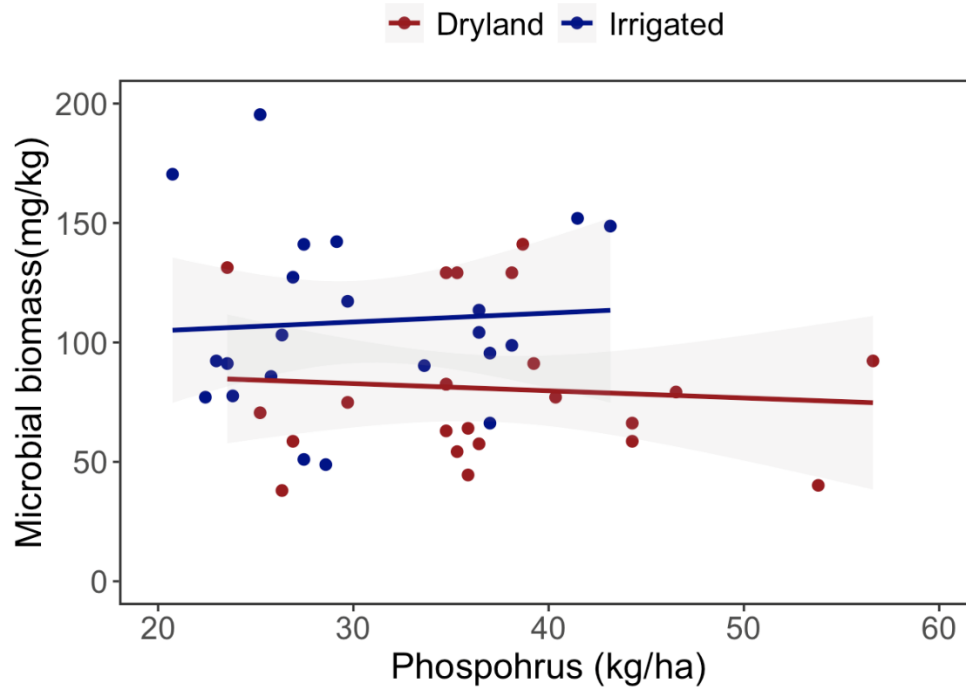


Figure 1.14: Relation between microbial biomass and available phosphorus. The data shown are average of each plot. Regression lines generated from simple linear regression.

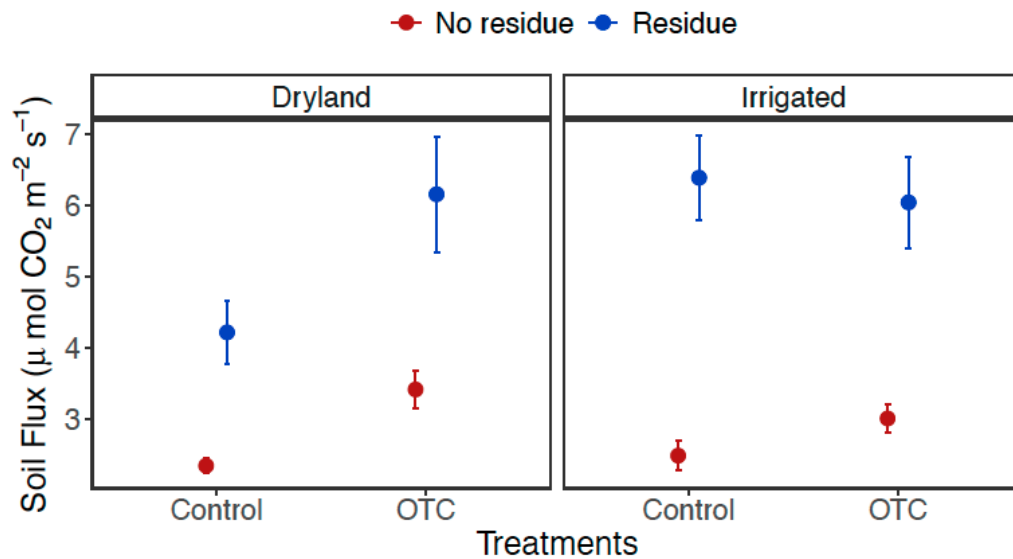


Figure 1.15: Growing season's average soil respiration rate across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), $n = 5-7$ plots per treatment.

CHAPTER II

UPLAND COTTON PRODUCTION UNDER EXPERIMENTAL WARMING IN TEXAS HIGH PLAINS

INTRODUCTION

The quality and quantity of crops grown have been severely impacted by changes in global temperature and precipitation patterns (Rosenzweig et al., 2014). According to (Lobell & Field, 2007), temperature and precipitation alone contribute to 30% or more of the fluctuation in worldwide average yields for the world's most extensively produced crops. As a result, further study into climate change mitigation measures and crop adaptation is critical to ensure long-term agricultural sustainability in the face of climate change.

In the US, the Great Plains region is the most susceptible to changes in precipitation, while the northwestern and north-central states are the most sensitive to changes in temperature (Ramankutty et al. 2002). Cotton production in the United States is centered in the Great Plains; this region produces about 30 to 35 percent of the cotton crop in the United States and 5 to 8% of the world's cotton yield (USDA-NASS, 2020). However, more recent statistics show that while total cotton acreage planted in the Texas High Plains has increased over the years, cotton productivity has decreased (USDA-NASS, 2020). Wet and mild weather during the planting season in May and hot and dry conditions during the critical growth phase in August are major contributing factors, according to the (PCG 2020). Another key barrier for long term-cotton cultivation in the Texas High Plains is moisture stress. Irrigation is used on about 60% of the agricultural land in this region (Brett, 2013). Groundwater withdrawn from the Ogallala aquifer, the world's largest aquifer, is the main irrigation water supply. However, the Ogallala's water level has been dropping in recent years (Ouapo et al., 2013). Because of the region's semi-arid environment, poor groundwater recharge rate, and little rainfall, only 10-20% of the currently irrigated land can be sustainably irrigated (Brett, 2013). Cotton

growers in West Texas are already switching from irrigated to dryland cultivation, which could reduce yields by up to half (Dorminey, 2012). Therefore, to sustain the long-term viability of cotton cultivation in the high plains, it is vital to adopt irrigation management strategies or conservation agriculture methods to conserve soil moisture.

Crop yields can be positively and negatively affected by global warming (Ostberg et al., 2018). On the one hand, it shortens the growing season, creates heat stress, enhances evapotranspiration and moisture stress, and reduces overall crop yield (Zhao et al., 2017; Lobell et al., 2013). On the other hand, increased CO₂ levels in the atmosphere could help crop growth and yield by enhancing water use efficiency and photosynthesis, especially in C₃ plants (Hatfield & Dold, 2019). However, soil and environmental variables such as precipitation, plant nutrient availability, and soil moisture content, limit crop growth and yield interactions with increased CO₂ (Kimbell, 2010). As a result, CO₂ fertilization does not always compensate for increased water demand or the shortening of already short growing seasons for most annual crops (Ostberg et al., 2018). Moreover, different geographical regions may have different sensitivity to climate change. Ramankutty et al. (2002) demonstrated that the regions already on the edge of temperature or precipitation limit for cultivation are most vulnerable to changes in climate.

The rate of cotton growth and development and the amount of lint produced is influenced by the air temperature. Temperature can have both positive and negative influence cotton productivity (Chen et al., 2015). For instance, Li et al. (2020) demonstrated that cotton plant height, seed cotton production, biomass yield, and lint percentage increased as the air temperature increased. In contrast, Oosterhuis and Snider (2011) reported that a prolonged temperature exceeding 35 °C during the initial boll development and flowering stages decreased cotton yield and fiber quality. How cotton plants react to heat is determined by the amount and length of heat stress and the cotton developmental stage at which they are experiencing heat stress (Snider et al., 2009). Huang & Ji (2015) found that increasing air temperature lowered seed cotton yields during the vegetative phase but enhanced seed cotton yields during the reproductive stage. In the early stages of cotton growth, every 1-degree decrease in mean temperature

results in delayed growth and development (Roussopoulos et al. 1998), whereas very high temperatures can harm cotton boll formation, cottonseed yield, and fiber quality, resulting in lower yields (Pettigrew, 2008).

Likewise, moisture stress is another environmental factor that inhibits cotton growth and development. Moisture stress reduces the number of bolls, boll size, and fiber quality, lowering lint yield (Wang et al., 2016). However, depending on how long it lasts, how intense it is, and what stage of development it occurs, the effects may differ (Snowden et al., 2014). Furthermore, stressors such as drought and heat stress occur in tandem. Raising temperature usually amplify the negative effects of drought stress in plants (Gao et al., 2020), but the level of damage depends on their interaction with environmental conditions, soil management, and plant type.

A limited number of studies have examined the effects of temperature and moisture stress in moisture limited semi-arid regions, and these studies had mainly focused on cotton yield and fiber production. In this study, we investigated the effects of climate warming and residue application on seed cotton yield, aboveground biomass, and belowground biomass in dryland and irrigated condition. We simulated climate warming using open-top chambers (OTC), and multispecies grass residue was applied in residue plots. Our hypothesis was: (i) Warming would increase seed cotton yield and biomass production in irrigated conditions since under adequate moisture availability, a rise in temperature up to a particular threshold (35 °C for cotton) would increase photosynthetic rate and crop water use efficiency, resulting in more carbon allocation for cotton growth. (ii) while in dryland soils, due to combined effect of heat and moisture stress, warming might disturb vegetative and reproductive growth in cotton, resulting into decline in yield and biomass production.

MATERIALS AND METHODS

Experimental Design

The research was carried out during the growing season of 2021 (May – October) at the Texas Tech Quaker Avenue Research Farm, Lubbock, Texas. The field experiment was conducted in two adjacent fields that had a drip irrigation system installed. Prior to

this experiment, both fields were operating under irrigated cotton monocropping system. During our experiment period, irrigation was applied in one field (irrigated) in addition to rainfall, and the other field received rainfall as the sole water source (i.e., dryland). The passive warming treatment consisted of $1\text{ m} \times 1\text{ m} \times 1\text{ m}$ open-top chambers (OTC). The radiation level in control and OTC plots were monitored continuously. In the plots with residue treatments, multispecies grass residue (Bermuda (*Cynodon dactylon* (L.) Pers.), blue grama (*Bouteloua gracilis* (Kunth) Lag. ex Griffiths), and fescue grasses (*Festuca arundinacea* Schreb.)) was added to the soil surface at the rate of 3 kg residue/m^2 . OTCs and residue were applied at the plot level, nested within the irrigation treatment. To limit the variation in data caused by the spatial heterogeneity in the field, the field was divided into six blocks, three irrigated and three dryland (Figure 1.2). There were eight $1\text{ m} \times 1\text{ m}$ plots in each block. Therefore, each block contained two replicates of four treatment combinations (control, OTC, residue, and OTC plus residue) administered randomly to a plot (see chapter 1 for more detailed site characteristics and experimental layout).

The soil underwent minimal tillage at the start of the growing season in May. The Phytogen 394 cotton variety was then sown in rows that were 1 meter apart in first week of June. After sowing, but prior to the start of the experiment irrigation was applied to both irrigated and dryland plots to maintain uniform initial soil moisture via subsurface drip lines underlaying each row. Irrigation continued only in the irrigated field after the warming and residue treatment had started, for a total of 218 mm of irrigation water during the growing season. Weeds were cut out using a knife or removed by regularly uprooting to keep the field weed-free.

Harvesting and Measurements

Cotton was harvested in late October when most of the bolls were fully open. Cotton bolls were harvested from all plants in plots of $1\text{ m} \times 1\text{ m}$. Each plot's cotton bolls were hand-picked and placed in a separate plastic bag. The weight of the harvested seed cotton was recorded after it was air-dried for a week. The total number of plants per plot and the number of bolls in each plant were also recorded.

A hand-pruner was used to harvest the aboveground plant components from each plot and air-dried for two weeks before taking dry biomass weight. To collect root

samples, we used soil cores with a diameter of 3 cm and a length of 10 cm. Three plants were chosen at random within each plot, and two soil cores of root samples (one sample from each side of the plant row) were obtained. Root samples were taken at 3-5 cm from the plant stem. As a result, six soil cores root samples were obtained from a plot and collected in a plastic bag. We used a 2 mm sieve to separate roots from the soil. The roots were hand-picked from the sieved sample and air-dried for a few weeks before taking dry root weight.

Statistical Analysis

We evaluated the interaction between warming, residue, and irrigation treatments on cotton yield traits viz. seed cotton yield, the number of bolls per plant, aboveground biomass, and belowground biomass using linear mixed effect model in R (R core team, 2022). Block was used as a random effect in the models. We fit two models for each response variable: the first included only the treatment and their interaction as fixed effects, while the second included the continuous predictor variables as fixed effects. We performed backward model selection for the first model to assess interaction among treatments to be included in the model using AIC values. All the models were fitted using the ‘lme4’ package (Bates et al., 2015). We used ‘car’ package (Fox and Weisberg, 2019) to generate the ANOVA tables and p values for fixed effect predictors. The ‘ggplot2’ package (Wickham, 2016) was used to visualize the data and R^2 values were calculated using ‘MuMIn’ package (Barton, K. (2009)).

RESULTS

Our findings showed that seed cotton yield was not affected by OTCs, but residue ($\chi^2 = 5.012$, $P = 0.025$; Table 2.1a) and irrigation ($\chi^2 = 11.17$, $P = 0.0008$; Table 2.1a) had a significant impact on seed cotton yield. We obtained 37.2 % higher seed cotton from the irrigated field compared to dryland and residue increased seed cotton yield by 15.0 %. (Figure 2.1)

Similarly, OTCs did not change both aboveground biomass and belowground biomass. Residue treatment had no effect on aboveground biomass, but it increased belowground biomass by 23.5 % ($\chi^2 = 3.98$, $P = 0.046$; Table 2.3a; Figure 2.4). Irrigation

increased aboveground biomass by 149.2 % ($\chi^2 = 35.65$, $P < 0.0001$; Table 2.2a; Figure 2.3) and belowground biomass by 128.6 % ($\chi^2 = 13.87$, $P = 0.00019$; Table 2.3a; Figure 2.4) compared to dryland.

DISCUSSION

Cotton production in the Texas High Plains is challenged by the recurrence of extreme weather events. Heat and moisture stress are limiting factors for the vegetative and reproductive growth of cotton in this region, but these stresses can be mitigated via certain agronomic and soil management practices (Komarek et al., 2021; Nouri et al., 2021). In this study, we sought to explore how two key cultivation practices, residue, and irrigation management, interact with climate warming simulated using open-top chambers (OTC), and affect yield and biomass production in upland cotton.

Effects of OTC, and Residue on Irrigated and Dryland Cotton

Warming has been linked to a decline in cotton yield and plant biomass in several studies (Li et al., 2020; Pettigrew, 2008), particularly in dry environments. Warming shortens the growing period of cotton plants while also accelerating flowering, boll opening, boll retention, and boll filling (Arshad, 2021). The increase in temperature promotes vegetative growth, cotton boll development, and boll maturity up to 25 °C, but decreases boll growth rate above 25 °C (Reddy et al., 1999). Cotton bolls can withstand temperatures up to 32°C, albeit their retention rate drops considerably when temperatures exceed 28°C (Reddy et al., 1999) due to heat stress. In addition, increased atmospheric temperature reduces cotton photosynthesis and growth rate (Bibi et al., 2008), thereby reducing carbon that could be allocated to biomass yield and fiber growth. Our findings, however, contradicted the results of those previous warming studies. A 2-degree increase in air temperature caused by OTCs had no effect on seed cotton yield, aboveground biomass, or belowground biomass in our study. Although cotton plants experienced higher (> 30 °C) temperature during early growth period in June to August, later in the season during critical reproductive growth period in September to October temperature started decreasing gradually. Even with the OTC treatments, the daily mean air temperature was within the optimum range (~ 26 °C) during the boll development and

filling stage in late September to early August. This is likely why, unlike prior warming studies, we did not see a decline in cotton yield and biomass with higher temperatures.

In fact, not warming but irrigation had a strong impact on cotton yield and biomass production in our study. Cotton yield is dependent on moisture, more so in water limited arid and semi-arid environments. Hence, rainfed agriculture (dryland) can exacerbate moisture stress in those places, resulting in yield losses. Irrigation substantially increased seed cotton yield, aboveground biomass, and belowground biomass production in our study. Consistent with our findings, DeLaune et al. (2020) and Ale et al. (2020) also observed that irrigation increased seed cotton yield and biomass production while mitigating the detrimental effects of heat stress in upland cotton (Broughton et al., 2017). Irrigation improved the distribution of fine roots within the topsoil surface, allowing the plant to absorb more soil moisture. The higher fine root biomass in the topsoil layer at the late reproductive stage was helpful for increasing aboveground biomass, resulting in enhanced total bolls and seed cotton yield (Wang et al., 2021).

The benefits of residue retention on soil environment and crop production in dryland agriculture was well documented (Jones et al., 1994; Lascano et al., 1994; Klocke et al., 2009); residue had stabilized soil water content, reduced evapotranspiration, and improved water use efficiency in cotton, thereby increasing lint yield in dryland cotton (Lascano et al., 1994). In our study, we observed increased seed cotton yield and belowground biomass with residue application, but aboveground biomass did not change. Perhaps mineralization of residue released important nutrients for utilization by plants and the soil microbial community, resulting in increased microbial growth and crop yield. Increased microbial activity in the soil may have further aided nutrient mineralization and uptake efficiency, especially for immobile plant nutrients like phosphorus, resulting in a considerable increase in cotton yields (Rafique et al., 2012).

Summary

Semi-arid cotton production was more susceptible to moisture than heat stress. We demonstrated that cotton yield could be increased with proper irrigation and residue management regardless of climatic change. However, due to faster depletion of ground the water table, a major source of irrigation water, in Southern High Plains region in recent years. We showed that residue application, a conservation agriculture technique, has the potential to increase cotton productivity in Southern High Plains. Therefore, more research is needed to establish a suitable moisture conservation agriculture strategy for dry environment that improve crop water use efficiency and hence lower irrigation water demand for the long-term viability of cotton farming in the Southern High Plains.

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TABLES

Table 2.1: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for seed cotton yield. The bolded and italicized values are significant at $P < 0.05$. R^2m : Marginal r-square value; R^2c : Conditional r-squared value.

a)

Categorical fixed effect predictors	χ^2	Df	P	R^2m/R^2c
OTC	0.060	1	0.806	0.396/0.494
Reside	5.012	1	<i>0.025</i>	
Irrigation	11.17	1	<i>0.0008</i>	
OTC: Irrigation	3.016	1	0.082	

b)

Continuous fixed effect predictors	χ^2	Df	P	R^2m/R^2c
NO_3^-	1.171	1	0.279	0.088/0.364
P	2.204	1	0.137	
NH_4^+	0.631	1	0.77	
Organic matter	0.085	1	0.426	

Table 2.2: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for aboveground biomass. The bolded and italicized values are significant at $P < 0.05$. R^2_m : Marginal r-square value; R^2_c : Conditional r-squared value.

a)

Categorical fixed effect predictors	χ^2	Df	P	R^2_m/R^2_c
OTC	1.592	1	0.207	0.715/0.810
Reside	0.320	1	0.571	
Irrigation	35.65	1	<i>< 0.0001</i>	

b)

Continuous fixed effect predictors	χ^2	Df	P	R^2_m/R^2_c
NO_3^-	0.447	1	0.503	0.018/0.785
P	0.390	1	0.532	
NH_4^+	0.112	1	0.726	

Table 2.3: Type II ANOVA showing χ^2 , degree of freedom, and p-values from mixed effects model results fit using a) categorical variables as fixed effect predictors b) continuous variables as fixed effect predictors for belowground biomass. The bolded and italicized values are significant at $P < 0.05$. R^2_m : Marginal r-square value; R^2_c : Conditional r-squared value.

a)

Categorical fixed effect predictors	χ^2	Df	P	R^2_m/R^2_c
OTC	1.181	1	0.277	0.458/0.585
Reside	3.981	1	<i>0.046</i>	
Irrigation	13.87	1	<i>0.00019</i>	

b)

Continuous fixed effect predictors	χ^2	Df	P	R^2_m/R^2_c
NO_3^-	2.305	1	0.128	0.087/0.525
P	2.597	1	0.107	
NH_4^+	0.393	1	0.531	

FIGURES

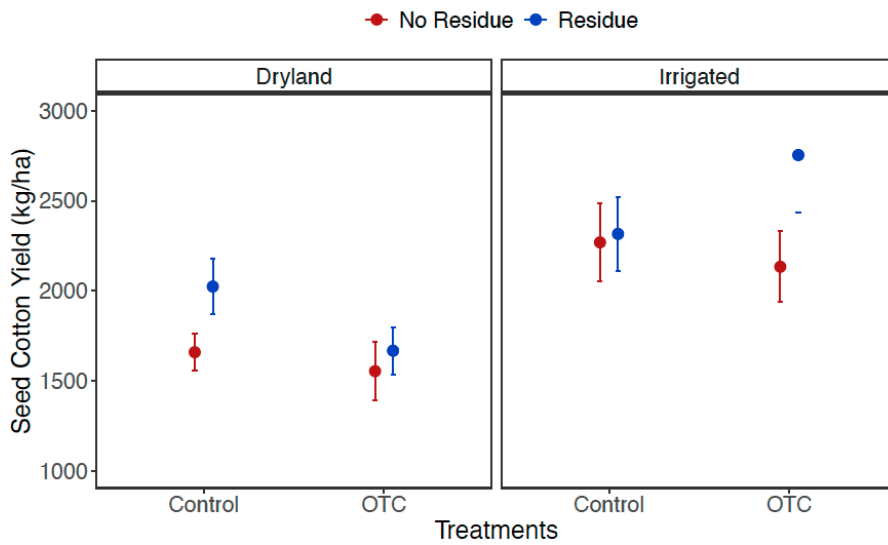


Figure 2.1: Average seed cotton yield across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), n = 5-7 plots per treatment.

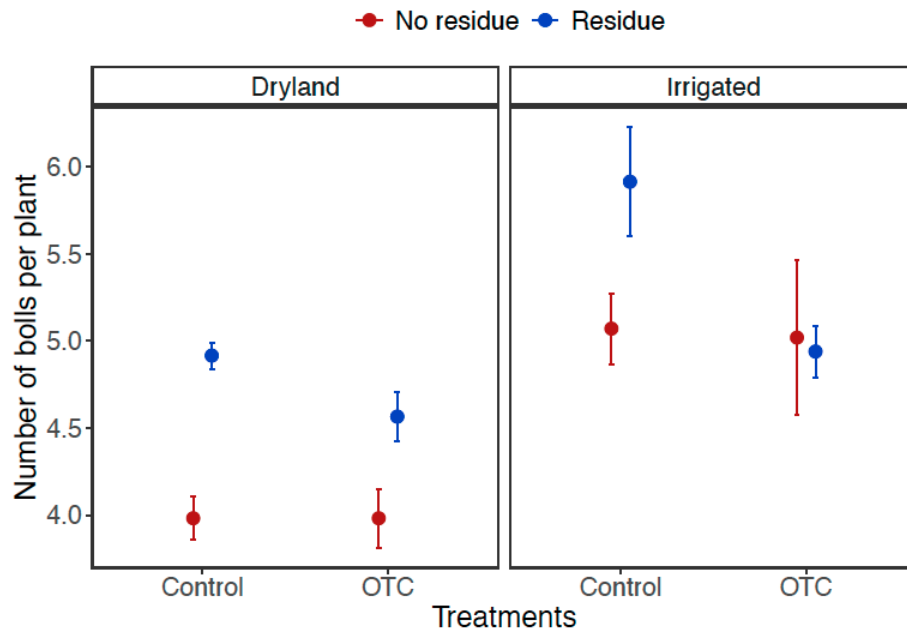


Figure 2.2: Average number of cotton bolls per plant across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), n = 5-7 plots per treatment.

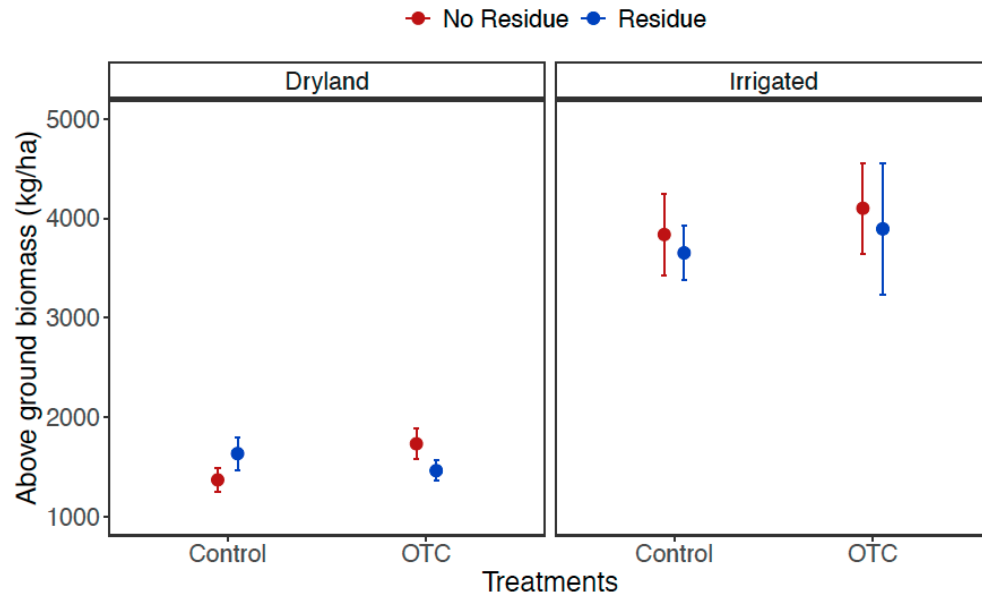


Figure 2.3 Average aboveground biomass across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), n = 5-7 plots per treatment.

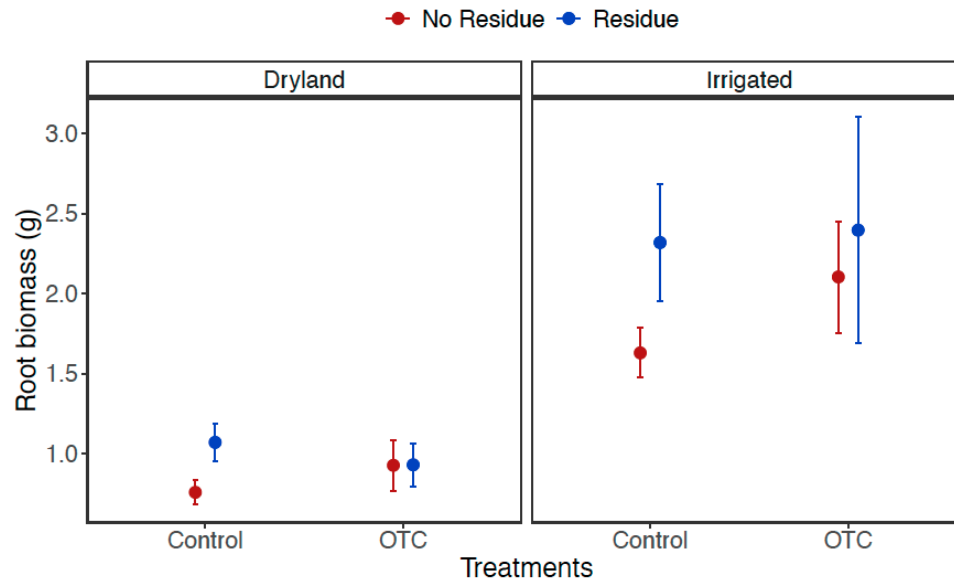


Figure 2.4 Average belowground biomass across OTC and residue treatments in irrigated and dryland cotton. The error bars represent standard error of mean (SEM), n = 5-7 plots per treatment.