Mitigating Climate-Induced Soil Health Challenges in Semiarid Texas: Residue Addition and Irrigation Strategies to Enhance Soil Carbon

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ABSTRACT

The Texas cotton production is currently facing challenges arising from frequent extreme climate events, including increased temperatures and droughts. These environmental factors have had a severe impact on soil health, particularly in dry soils. To counteract the negative effects of climate change on the soil, one potential solution could be enhancing the soil health by reducing soil organic matter (SOM) loss and promoting microbial biomass. This study investigated the effectiveness of incorporating residues to improve SOM content and stimulate microbial biomass under soil warming in irrigated and rain-fed conditions. The experiment utilized open top chambers (OTCs) to passively heat the soil in cotton fields located in Lubbock, Texas. The results indicated that the OTCs did not impact soil temperature but raised air temperature by 2 °C. However, the application of residue and irrigation led to reduced soil temperature, and there was a noticeable decrease in the diurnal temperature variation with residue application. While OTCs did not directly affect soil organic matter, they did increase CO2 flux. Moreover, the combination of OTCs and residue application resulted in an increase in microbial biomass, whereas without residue, OTCs led to a decline in microbial biomass. Irrigation increased SOM, microbial biomass, aboveground and belowground biomass, and seed cotton yield. Overall, the findings suggest that both residue addition and irrigation can mitigate the adverse effects of warming by enhancing SOM and microbial biomass levels. This, in turn, can help attenuate the potential impacts of future climate change on soil health and crop production in semiarid environments.

## 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 (SOM) is the major source of organic carbon in the soil – contains 58-60 % carbon (Pribyl, 2010) with the remainder comprised of other elements such as nitrogen, phosphorus, and sulfur. SOM promotes plant growth by supplying nutrients, improves soil aggregate formation (Hoyle, 2013), improves water retention (Rawls et al., 2003), and supports soil biological activity (Benbi et al., 2016) in the soil. However, soil organic matter (SOM) in cultivated soils undergoes constant changes influenced by climatic factors like temperature and precipitation, as well as cultivation methods. Therefore, it becomes crucial to investigate the various factors that have the potential to influence SOM stocks and carbon loss in the warmer world. By understanding these key driving forces, we can effectively address the challenges posed by climate change, ensuring agricultural sustainability, and maintaining a balanced ecosystem.

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), although whether it 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; van Groenigen et al., 2014) 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 (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; moisture, microbial abundance, availability and accessibility of soil microbes to the substrate, 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), However, in a natural environment, temperature interacts with various other factors within the soil system (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). Therefore, it is imperative to study how interaction of 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.

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 pattern, which may govern soil moisture regime and substrate availability, influences the response of soil microbial activity and biomass to warming. In drier environments, microbial growth and biomass production is negatively corelated 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. 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.

In a cultivated agricultural soil, 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 adopting certain agricultural management practices such as no-tillage, irrigation, residue management, cover cropping, and crop rotation (Mandal et al. 2007; Page et al., 2020). 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). Conversely, it is important to note that the increased presence of active soil organic matter resulting from residue incorporation may accelerate the decomposition rate and lead to carbon loss in the form of CO2 flux (Zhao et al., 2013). Nevertheless, this process keeps the soil system active and dynamic. The residue also reduces evaporation and enhances water retention rate of the soil, minimizing moisture loss due to excessive evaporation at higher temperatures (Russel 1940). Therefore, residue may be a viable strategy for reducing temperature and moisture fluctuations in the soil profile and minimizing soil health degradation during climate extremes.

The High Plains of Texas 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 dryland soils. Recent statistics showed that while total cotton acreage planted in the Texas High Plains has increased over the years, yet cotton productivity has decreased (USDA-NASS, 2020) due to wet and mild weather during the planting season in May and hot and dry conditions during the critical growth phase in August (PCG 2020). Furthermore, groundwater, which is the region's main source of irrigation, is depleting at a quicker rate than before (Ouapo et al., 2013), thus the growers are forced to switch to dryland cultivation which could reduce yields by up to half (Dorminey, 2012). Many researchers have proposed conservation agricultural practices such as no tillage, residue retention, and cover cropping as potential mitigation approaches 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 how effective these practices would be in moisture-limited arid and semi-arid environments under climate change scenario. In this study, we investigated the effects of climate warming under residue application on soil carbon dynamics and cotton yield in irrigated and dryland soils of semi-arid High Plains.

## 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 in a semi-arid climate with a mean annual precipitation of 472 mm and a mean annual temperature of 15.9 ⁰C. The hottest month is July, with an average monthly temperature of 33.8 ⁰C, and the coolest month is January, with an average monthly temperature of 3.3 ⁰C. 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 ⁰C (the hottest month was June, with an average monthly temperature of 27.3 ⁰C, and the coolest month was October with an average monthly temperature of 18.21 ⁰C). 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. The experiment had split-plot randomized plot design. Irrigation was applied in a whole plot level and warming and residue treatment to a sub plot level. Irrigated field received drip irrigation in addition to rainfall, and the dryland had rainfall as the sole water source. 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. 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 sub plot plots in each whole plot. Therefore, each whole plot contained two replicates of four treatment combinations (control, OTC, residue, and OTC plus residue) administered randomly. Each treatment was replicated six times, resulting in a total of 48 plots. Cotton (variety: Phytogen 394) 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 (⁰C) and volumetric moisture content (m3/m3) every 30 minutes at 10 cm soil depth in each plot. In addition, we used ibuttons (Maxim Integrated, California, USA) to record air temperature (⁰C) and relative humidity (%) at 50cm above the ground surface every four hours. The ibuttons were covered by the radiation shields to prevent heating od 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 ⁰C 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 K2SO4 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 (μmol CO2 m-2s-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.

### *Harvesting and Biomass 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 1m x 1m. 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 environmental variables such as soil temperature, air temperature, volumetric soil moisture content, 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. The distribution for generalized linear mixed model was selected based on AIC values. The selected model had a distribution that improved behavior of residuals and had lower AIC value. Cotton yield traits viz. seed cotton yield, the number of bolls per plant, aboveground biomass, and belowground biomass was also analyzed using linear mixed effect model. We used ‘lmer’ and ‘glmer’ function in ‘lme4’ package (Bates et al., 2015) for linear mixed effects, and generalized linear mixed effects models, respectively. Since we took two soil samples from each plot, the data from the two samples was averaged to get plot level data before fitting into the model. Whole plots were 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. We also fit a separate model to evaluate the effects of climate data and soil variable for each response variable. First, we shortlisted a few predictors for each of our response variable based on previous literatures, then, we fit the liner mixed models in R. 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.

## Results

We observed a strong temporal variation in soil and air temperature throughout the growing season (Supplemental figure S1). The random effects (block and months) accounted for majority of the variation in the soil temperatures (R2 marginal = 0.019; R2 conditional *=* 0.95) and air temperatures (R2 marginal = 0.054; R2 conditional *=* 0.987). Soil temperatures were not affected by the OTCs but were affected by residue (*χ*2 = 8.34, *P* = 0.0039) and irrigation (χ2 = 7.77, *P* = 0.0053). Residue decreased soil temperature by 0.6 ⁰C, while irrigation decreased soil temperature by 0.8⁰C (Figure 1a). Residue application also decreased (χ2 = 25.03, *P* < 0.001) average daily temperature range in the soil system by 1.5 °C (Figure 2). OTCs (χ2 = 112.69, *P* < 0.0001) increased average air temperature by 2.2 ⁰C (Figure 1b).

Volumetric water content also showed a temporal fluctuation throughout the growing season (Fig 3a). Random effects (block and months) accounted for majority of the variation in the volumetric water content (R2 marginal = 0.063; R2 conditional *=* 0.628). Irrigation did not have significant main effect on volumetric water content, but OTCs (χ2 = 18.86, *P* < 0.00001) and residue (χ2 = 10.47, *P* = 0.0012) significantly changed volumetric water content. We observed a significant interaction between OTC and irrigation (χ2 = 10.69, *P* = 0.0011), and OTC and residue (χ2 = 10.26, *P* = 0.0013). Our results also showed a significant three-way interaction between OTC, residue, and irrigation (χ2 = 5.06, *P* = 0.024). Similarly, in dryland, in the presence of OTCs, residue increased volumetric water content by 7.5 %, but with no OTCs treatment residue decreased water content by 19.3 % (Figure 3b).

OTCs and residue did not affect soil organic matter content. However, there was a significant effect of irrigation on soil organic matter (χ2 = 8.05, *P* = 0.0046), with dryland soils having 36.8 % lower soil organic matter compared to irrigated soils (Figure 4a). Soil organic matter was also negatively correlated with soil temperature (χ2 = 4.02, *P* = 0.044; Figure 5a). We observed a significant interaction effect of OTC and residue (χ2 = 7.37, *P* = 0.0066) on microbial biomass. OTCs increased microbial biomass by 34.9 % under residue application, but with no residue OTCs did not have a significant effect on microbial biomass (Figure 4b). Irrigation (χ2 = 4.73, *P* = 0.029) increased the microbial biomass by 27.5 %. Additionally, a significant positive relation was observed between microbial biomass and organic matter (χ2 = 8.39, *P* = 0.003; Figure 5b), as well as microbial biomass and available nitrates (χ2 = 7.42, *P* = 0.0064; Figure 5c). The residue application (χ2 = 72.84, *P* < 0.001) significantly increased soil respiration; the residue applied plots had 78.2 % higher soil CO2 flux rate than non-residue plots (Figure 4c). We also observed a significant interaction effect of irrigation and OTCs (χ2 = 5.64, *P* = 0.017) on soil respiration. The OTC increased soil respiration in dryland by 35.1 % but did not significantly change soil respiration in irrigation plots.

Seed cotton yield was not affected by OTCs but irrigation (χ2 = 6.87, *P* = 0.0087) and residue (χ2 = 4.83, *P* < 0.027) had a significant impact on seed cotton yield. The residue and irrigation increased seed cotton yield by 15.2 % and 37.3 %, respectively (Figure 6c). Moreover, both OTCs and residue treatment did not change aboveground biomass and belowground biomass. Irrigation however increased aboveground biomass by 150.5 % (χ2 = 22.61, *P <* 0.0001; Figure 6a), and belowground biomass by 129.7% (χ2 = 9.01, *P <* 0.0026 Figure 6b).

## 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 plant productivity 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 in some studies (Escolar et al., 2012; [León-Sánchez](https://www.ncbi.nlm.nih.gov/pubmed/?term=Le%26%23x000f3%3Bn-S%26%23x000e1%3Bnchez L%5BAuthor%5D&cauthor=true&cauthor_uid=30078910) 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. Residue lowered soil temperature in our study which is consistent with Turmel et al. (2015). Covering soils with residue insulated 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. Higher soil moisture produces high evaporative cooling, especially during a warmer time of the day. Soil moisture also 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.

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 did not increase volumetric water content. A significant increase in cotton biomass was seen under irrigation, which may have led to a rise in plant water consumption. Therefore, there was no discernible difference in soil moisture content between dryland and irrigated plots with supplemental irrigation water. 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. However, with OTCs 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 ⁰C, 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 anticipated 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. 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.

### *Effects of OTC, Residue, and Irrigation on Cotton Biomass and yield*

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 ⁰C, but decreases boll growth rate above 25 ⁰C (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 ⁰C) temperature during early growth period in June to August, later in the season during critical reproductive growth period in September to October temperature started deceasing gradually. Even with the OTC treatments, the daily mean air temperature was within the optimum range (~ 26 ⁰C) 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 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).

### *Conclusion*

In a semi-arid agroecosystem, OTCs and residue resulted in variation in soil temperate 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 loss from the soil via CO2 flux, but irrigation improved plant and microbial biomass production, thereby maintaining total soil organic matter stocks in the soil. 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.

## References

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A graph of different types of weather

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##### **Figure 1**:Diurnal trend of (a) soil temperatures at 10 cm soil depth, (b) air temperature measured near leaf canopy, across the treatments. The vertical bars show the weekly total rainfall; C: No Open Top Chamber, No Residue; OTC: Open Top Chamber, No Residue; R: No Open Top Chamber, Residue; and OTC + R: Open Top Chamber, Residue.

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**Figure 2**:Average daily temperature range measured at 10 cm soil depth across OTC, irrigation, and residue treatments. The larger square dots indicate the model-predicted average temperature, while error bars represent 95% confidence intervals. Each smaller dots represents the average temperatures range of an individual plot.

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##### **Figure 3**:(a)Weekly average volumetric water contents (VWC) measured at 10 cm soil depth. The vertical bars show the weekly total rainfall. (b) average VWC, across OTC, irrigation, and residue treatments. The larger square dots indicate the model-predicted average temperature, while error bars represent 95% confidence intervals. Each smaller dots represents the average temperatures of an individual plot; C: No Open Top Chamber, No Residue; OTC: Open Top Chamber, No Residue; R: No Open Top Chamber, Residue; and OTC + R: Open Top Chamber, Residue.

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**Figure 4:** Average (a) soil organic matter (SOM), (b) microbial biomass carbon (MBC) and (c) soil respiration, across OTC, irrigation, and residue treatments. The larger square dots indicate the model-predicted average temperature, while error bars represent 95% confidence intervals. Each smaller dots represents the average temperatures of an individual plot.

A diagram of different types of soil

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**Figure 5**: Regression plots showing a relationship between (a) soil organic matter and soil temperature, (b) microbial biomass carbon and soil organic matter, and (c) microbial biomass carbon and available nitrate nitrogen in soil. The solid line represents a least square regression line predicted from linear mixed effect model. The shaded region represents 95% confidence intervals.

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##### **Figure 6:** Average (a) above ground biomass, (b) belowground biomass and (c) seed cotton yield across OTC, irrigation, and residue treatments. The larger square dots indicate the model-predicted average temperature, while error bars represent 95% confidence intervals. Each smaller dots represents the average temperatures of an individual plot.

**Supplemental Figures:**

A graph of different types of weather

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##### **Figure S1:** Weekly average of (a) soil temperature, (b) air temperature, and (c) daily temperature range measured at 10 cm soil depth. C: Ambient temperature, No Residue; OTC: Open Top Chamber, No Residue; R: Ambient temperature, Residue; and OTC + R: Open Top Chamber, Residue.

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**Figure S2:** Growing season’s average (a) soil temperature and (b) air temperature across OTC, irrigation, and residue treatments. The larger square dots indicate the model-predicted average temperature, while error bars represent 95% confidence intervals. Each smaller dots represents the average temperatures of an individual plot.