Investigating intercropping as an adaptive management strategy for climate change

by

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Abstract

Climate change has resulted in increasing global temperatures and increasing inter-annual temperature variability. Studies have shown that rising temperatures negatively affect crop yield, however these studies focused on intensive monoculture systems, and there has been little consideration of diverse farming systems as a way to adapt to climate change. Here we propose that intercropping can be employed to prevent reductions in crop yields due to temperature increases associated with climate change. To test this hypothesis, corn and soybean were planted in monocultures and polycultures in a greenhouse at two temperature treatments: a control ambient temperature and approximately +2 degrees C. Plant growth was measured weekly and above- and below-ground biomass was measured once plants had reached maturity. Our study demonstrated that growing corn and soybeans in polycultures yield more than monocultures when considering the same land area and we see this relationship in both control and higher temperature environments. We found that total corn biomass was significantly greater when planted in polyculture and at lower temperatures. Total corn biomass when planted in polyculture was not significantly different at different temperatures but was significantly lower at higher temperatures when planted in monocultures. We found that total soybean biomass was significantly greater when planted in monoculture and temperature did not appear to affect biomass. We see a greater facilitative effect of soybean on corn and a slightly increased competitive effect of corn on soybean plants at higher temperatures. Existing theoretical models for calculating yield sets can be modified to consider the variability of temperature as well as the increased facilitative effect of intercropping under high temperature scenarios. Future research should continue to explore intercropping as an adaptive management strategy for climate change.

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Introduction

Our climate is changing due to increased anthropogenic emissions of greenhouse gases (IPCC 2014). Major impacts of this climate change include, warming of the atmosphere and oceans, melting of snow and ice, and sea level rise (IPCC 2014). Of particular interest to agriculture are increasing global temperatures as well as increasing interannual temperature variability (IPCC 2014). These changes have the potential to significantly impact crop yields, food security, and farmer livelihoods. Several studies examining potential and current climate change impacts have found that increasing temperature drastically reduces cereal crop yields (Zhao et al. 2017, Challinor et al. 2014, Asseng et al. 2014, Lobell and Asner 2003). Crops have a specific temperature threshold, where yields tend to increase under slight temperature increases, but once the temperature reaches a threshold the yields significantly decline (Figure 1, Schlenker and Roberts 2009). These reductions in yield may be due to the connection between temperature and moisture, and their impacts on crop growth.

There has been a considerable amount of research examining how climate change and associated rising temperatures will affect crop yields (e.g. Zhao et al. 2017, Challinor et al. 2014, Asseng et al. 2014, Farooq et al. 2011, Lobell and Asner 2003). However, the majority of this research has focused on intensive monoculture systems, and there has been little consideration of diverse farming systems as a way to adapt to climate change. Traditional and indigenous farming practices are often more resilient than industrial agriculture practices, and we should leverage this knowledge to develop systems that are more resilient to climate change. In particular, intercropping has been used in traditional and indigenous farming practices and offers resilience. Intercropping provides many potential benefits including, buffering against microclimatic extremes, reducing soil temperature, increasing soil moisture, making resources more available, increasing productivity, reducing pest damage, and many others (Vandermeer 1989, Kremen et al. 2012, Brooker et al. 2016). These facilitative effects can be more important under climate change.

Facilitative effects of reducing soil temperature and increasing soil moisture may be the most important factors to consider when attempting to prevent reductions in crop yields as global temperatures rise. Higher temperatures increase atmospheric water demand, and these warmer temperatures increase plant transpiration and reduce soil moisture (Zhao et al. 2016, Zhao et al. 2017, Asseng et al. 2011, Clinch et al. 2009). In addition to the obvious reduction in water resource, reductions in soil moisture can impact nutrient availability. Nitrogen mineralization, the process of converting organic nitrogen to forms available to plants, is significantly reduced when water is limited (Kladivko and Keeney 1987). Intercrops can increase soil moisture through several different mechanisms. Polycultures of crops and trees can exhibit hydraulic lifting, when trees with deep roots transfer water from wetter, deeper soil layers to drier, shallower soil layers, providing a crop with shallower roots access to the water resource (Bayala et al. 2013). Intercropping can provide shade and create different microclimatic conditions which can reduce water evaporation and maintain soil moisture and temperatures (Clinch et al. 2009, Ghanbari et al. 2010, Zhang et al. 2008).

Climate change has resulted in increasing interannual temperature variability (IPCC 2014). This temperature variability creates different environments at different times throughout the growing season. Facilitative and competitive effects are different under different environmental conditions, and thus optimum planting densities of intercrops may be different under these different environmental conditions (Vandermeer 1989).

To evaluate ideal planting to determine optimal yields we must rely on ecological theory. The yield set allows us to conceptualize all possible yield combinations of all possible intercrops (Vandermeer 1989). The yield set can take many different forms, but there are three general trends. We can observe a concave yield set wherein there is underyielding and the monocultures outperform polycultures, a convex yield set wherein we observe intercrop overyielding, and an exaggerated convex yield set wherein there is the potential for transgressive overyielding (Figure 2). Transgressive overyielding is observed when the yield produced in polyculture is greater than the maximum yield possible if produced in monoculture (Wendling et al. 2017; Gravel et al. 2012). Furthermore, we consider the land equivalent ratio (LER), which measures how much land is needed to produce as much in monoculture as was produced in one hectare of polyculture, to determine whether intercropping is advantageous (Vandermeer 1989). The critical LER value is 1. When LER is greater than 1, intercrops produce optimal yields as more land is required to produce in monoculture than in polyculture. When LER is less than 1, monocultures produce optimal yields, and more land is required to produce in polyculture.

Here we explore how intercropping can be employed to prevent reductions in crop yields due to temperature increases associated with climate change. Monocultures under high (climate change) temperatures produce lower yields than monocultures under lower temperatures (e.g. Zhao et al. 2017, Challinor et al. 2014, Asseng et al. 2014). However, we do not expect to observe the same trend in polycultures. We hypothesize that intercropping may maintain crop yields due to shading and microclimatic buffering, among other facilitative effects. The polyculture yield set under climate change may be above the land equivalent ratio (LER), resulting in overyielding in high (climate change) temperature scenarios, whereas under low (pre-climate change) temperatures underyielding may result (Figure 2).

Methods

Planting Design

This experiment was planted in the Matthaei Botanic Gardens greenhouse in Ann Arbor, MI to control and standardize growing conditions for all treatments. Crops were grown from July through September 2021. Crops were planted in 3-gallon nursery pots with Metro-Mix 830 Growing Mix soil. Six seeds were planted and then thinned after germination so that there were two total plants in each pot. We used Alfred Lea Organic Viking (095RM) O.84-95UP Seed Corn and Alfred Lea Organic Viking O.1518NUP Soybeans. Soybeans were inoculated with Exceed Peat for Soybean Inoculant prior to planting.

There were three planting treatments: monoculture soybean, monoculture corn, and polyculture soybean and corn. Each pot was assigned to a temperature treatment: control (ambient temperature) and higher temperature (approximately +2 degrees C). Plants in the higher temperature treatment were warmed with Vivosun seedling heat mats. We started with 20 replicates for each treatment, 120 pots in total. After the first 6 weeks, pots were rotated weekly. Soil temperature was checked weekly and adjusted as necessary to ensure higher temperature treatments were +2 degrees C above the control temperature treatments. All pots were watered, with reverse osmosis water, regularly and as needed to ensure plants did not dry out.

Fertilizer was applied evenly to all pots at each application. Ultrasol 20-10-20 Greenhouse Plus Water Soluble Fertilizer was applied to all pots 7 and 14 days after planting. Approximately 20 grams of Florikan Osmotic Fertilizer 90-day formula (16-5-11) was applied to each pot 43 days after planting. Botanicare HGC732110 Cal-Mag Plus (approximately 9.6 oz per pot) was applied 15 days and 31 days after planting. Lime (Pro Aglime Pulverized Doloitic Limestone manufactured by Austinville Limestone Co.) was applied to raise the pH of all pots 35 days after planting (1 teaspoon to each pot) and 52 days after planting (2 teaspoons to each pot).

Growth Rate and Plant Biomass

Plant height was measured weekly. At the end of the growing season, plants were harvested. Above- and below-ground biomass were collected for each plant. Biomass was dried and weighed for each plant. Weights of leaves and stems, pods/ears, and roots were recorded.

Data Analysis

Monoculture treatments had two plants of each crop and thus we calculated an average of the two plants for each of our growth and total biomass measurements. We looked at growth and biomass trends of corn and soybeans separately. To examine differences in growth based on planting and temperature treatments we ran linear regressions with an interaction term at three different time points throughout our experiment (20, 41, and 71 days after planting). We also ran linear regressions with an interaction term to determine significant differences in total

plant biomass based on planting and temperature treatments. Total plant biomass was used to calculate the Land Equivalent Ratio. Wilcoxon tests were run to determine if the LER for the different temperature treatments was significantly greater than 1 and significantly different from one another.

Results

Land equivalent ratio

The Land Equivalent Ratio (LER) calculated using total plant biomass is slightly greater in higher temperature treatments compared to control temperature treatments (Figure 3). The average LER in control temperature treatments is 2.10 and the average LER in higher temperature treatments is 2.13. The LER for control temperature treatments is not significantly different from the LER in higher temperature treatments ($p = 0.7905$). However, the LER in control temperature treatments ($p = 3.815e-06$) and the LER in higher temperature treatments ($p = 3.815e-06$) are both significantly greater than 1. The LER = 1 line is lower for the higher temperature treatments than the control temperature treatments (Figure 3). We observe transgressive overyielding for both higher temperature and control temperature treatments (Figure 3).

Corn productivity

Corn height throughout our experiment followed an S-shaped growth curve (Figure 4). At 20 days after planting, there was a slightly significant difference in corn height based on temperature treatment ($p = 0.0974$). Corn planted at higher temperatures was taller than corn planted at control temperatures. There were no significant differences in corn height based on planting treatment ($p = 0.3646$) and no interaction effect ($p = 0.2358$). At 41 days after planting, there were no significant differences in corn height across both temperature and planting treatments and no interaction effect. At 71 days after planting, we found significant differences in plant height based on temperature treatment ($p = 0.0163$) and planting treatment ($p = 8.16e-07$) as well as an interaction effect ($p = 0.0229$). Corn planted at control temperatures was significantly taller than corn planted at higher temperatures. Corn planted in polyculture was significantly taller than corn planted in monoculture.

Total corn biomass was impacted by planting and temperature treatments (Figure 5). Average biomass of each corn plant when planted in monoculture was 218.47g and 185.82g for control temperatures and higher temperatures, respectively (Figure 5). The average biomass of each corn plant when planted in polyculture was 333.89g and 299.8g for control temperatures and higher temperatures, respectively (Figure 5). We found that total corn biomass was significantly greater in polyculture than when planted in monoculture ($p = 3.57e-10$). We also found that total corn biomass was significantly greater when planted at control temperatures than when planted at higher temperatures ($p = 0.0379$). We did not find an interaction effect of these two different treatments ($p = 0.9483$). Total corn biomass planted in monoculture was significantly less when planted at higher temperatures compared to control temperatures ($p= 0.01774$), however there were no significant differences in total corn biomass when planted in polyculture across the temperature treatments ($p = 0.05915$).

Soybean productivity

Soybean growth also followed an S-shaped growth curve throughout our experiment (Figure 6). At 20 days after planting, we found a significant difference in soybean height based on planting treatment ($p = 0.0121$). Soybeans planted in polyculture were significantly taller than soybeans planted in monoculture. We found no significant differences based on temperature treatments ($p = 0.2679$). We found a slight interaction effect between planting and temperature treatments on soybean height ($p = 0.0605$). At 41 days after planting, we continued to observe that soybeans planted in polyculture were significantly taller than soybeans planted in monoculture ($p = 0.0309$). We continued to see no significant differences in soybean height based on temperature treatments ($p = 0.8932$). We found no interaction effect at 41 days ($p = 0.2732$). At 71 days after planting, we found no significant differences in soybean height across all treatments and no interaction effect.

Soybeans did not seem to be as impacted by temperature as they were by planting treatment (Figure 7). The average biomass for each soybean plant planted in monoculture was 2.01g and 1.74g for control temperatures and higher temperatures, respectively (Figure 7). The average biomass for each soybean plant planted in polyculture was 1.16g and 0.90g for control temperatures and higher temperatures, respectively (Figure 7). We found that total soybean biomass was significantly greater in monocultures than when planted in polyculture ($p = 0.010131$). We found no significant differences in soybean yield based on temperature treatment ($p = 0.405891$) and no interaction effect ($p = 0.988692$).

Discussion

Intercropping may be an adaptive management strategy for climate change. In this study, we demonstrate that polycultures produce more biomass than monocultures when considering the same land area and we observe this trend in both higher temperature environments and control temperature environments. This finding aligns with many other studies that have also found land equivalent ratios greater than one when planting corn and soybean together in polyculture (Burton and Kemanian 2022; Putnam et al. 1985; Zaeem et al. 2019; Martin et al. 1990; Raza et al. 2021). We observe transgressive overyielding whereby corn and soybeans produce more in polyculture than they could ever produce when grown in monoculture (Wendling et al. 2017; Gravel et al. 2012), and this trend is observed in both control and higher temperature treatments. Furthermore, we observed an increased facilitative effect of soybeans on corn and a slightly increased competitive effect of corn on soybeans in polycultures at higher temperatures. We propose a conceptual model to explain the mechanism and allow researchers to predict how these effects will impact production as this experiment is scaled up.

While existing literature suggests that intercropping may be a way to adapt to climate change (e.g. Lin 2011), there was no existing empirical research examining intercrop yield and temperature changes nor is there theoretical research examining climate change and intercropping. We seek to fill the gap and propose a model to describe a mechanism for how intercrops can be an adaptive management strategy as our planet continues to warm. Here we use total biomass as a proxy for yield.

We propose the following model based on the findings of our empirical study:

$$y = M_y - (a + j)x$$
$$x = M_x - (b - e)y$$

Where a is the effect of crop x on crop y, b is the effect of crop y on crop x, and M_x and M_y are the monoculture yields of crop x and y, respectively, and e is the increased facilitative effect of crop y on crop x and j is the increased competitive effect of crop x on crop y. The increased facilitation is unidirectional and even results in a slight increase in competition on the crop that is not receiving the additional facilitation.

We can apply this model to estimate yields of corn and soybeans planted in polycultures at higher temperatures. Based on the data from control temperatures, we can determine the effect of corn on soybean, a, is 0.0025 and the effect of soybean on corn, b, is -99.87. We can set j to 0.00027 as the increased competitive effect on soybeans is very small and we can set e to 27.14 as the increased facilitative effect on corn is rather large. We can then use the model to estimate intercrop yields under a 2°C increase in temperature. Our model predicts that in polycultures at higher temperatures, average soybean yield (total plant biomass) is 0.90g and average corn yield is 299.80g. These estimates closely match the actual yields we found when growing soybean and corn in polycultures at higher temperatures (Table 1).

Soybeans are nitrogen fixing legumes and likely make nitrogen more available to corn, thereby creating a facilitative effect. As corn grown with soybeans makes use of that nitrogen, it grows larger using up more resources and creating more shade over the soybean plants. We observe that this may cause soybean plants grown with corn to grow taller than those without, but the plants grown with corn focus most their energy on growing taller and dedicate less energy to growing stronger (producing more biomass).

This conceptual model can be helpful to researchers when scaling up the results of this study. As temperature increases become more extreme and this experiment is moved into a field and out of a controlled greenhouse environment, the effects of facilitation and competition may become even stronger.

Corn growth and productivity

In the beginning of our experiment, corn was taller when grown at higher temperatures compared to a control. This was likely due to the higher temperatures providing an ideal environment and increasing germination rates and early growth. By the midpoint of our experiment, there were no significant differences in height based on temperature or planting treatment. As our experiment continued, corn grown in polycultures grew significantly taller than corn grown in monocultures. At the end of our experiment, we see an interaction effect of planting treatment and temperature on corn height. Corn grown in monoculture was taller at control temperatures than higher temperatures, and we see the opposite effect for corn grown in polyculture. Corn is taller at higher temperatures when grown in polyculture. This interaction effect is what we hypothesized we would observe, demonstrating that growing corn in polyculture can protect against crop declines associated with rising temperatures.

Corn total biomass does not display the same interaction effect we see at the end of our experiment with height. Corn grown in monoculture is significantly impacted by temperature, however, corn grown in polyculture produces similar amounts of biomass in both temperature treatments. This finding indicates that polycultures are more resilient. Producers can more reliably produce the same amount of corn despite increasing temperatures when growing corn in polyculture.

Soybean growth and productivity

We observe almost the opposite effect in soybean growth and total biomass compared to our observations for corn. At the beginning of our experiment, soybeans grown in polyculture are significantly taller than soybeans grown in monoculture. This trend is likely due to soybeans competing with corn which grows quite quickly and tall. We find no significant effect of temperature on height throughout the experiment. However, we find an interactive effect of planting treatment and temperature treatment on soybean height at the beginning of our experiment. This effect can be explained as the height of soybeans at control temperatures is very similar for both polycultures and monocultures, however at higher temperatures soybeans grown in polyculture are much taller than soybeans grown in monoculture. As our experiment

continued, soybeans grown in polyculture continued to be significantly taller than those grown in monoculture, and the interaction effect was no longer significant. By the end of our experiment, we found no significant differences in soybean height across all treatments.

Soybean total biomass also demonstrated significant differences based on planting treatment, however here we observe the opposite trend we observed in soybean height. Soybeans grown in monoculture produced greater yields than soybeans grown in polyculture. This is likely due to the tradeoffs the plants faced – those competing with corn likely dedicated more resources to growing taller whereas those competing with soybeans of similar height could dedicate more resources to producing stronger stems and more leaves and pods. Soybeans did not appear to be impacted by temperature. Planting soybeans prior to corn may allow soybeans to grow strong and produce greater yields in the long term.

Additional benefits of intercropping

In addition to increasing productivity, intercropping reduces risks, particularly those associated with climate variability and change (Borron 2006; Altieri and Koohafkan 2008). Intercropping increases yield stability and reduces productivity declines during periods of water stress and extreme climatic events such as hurricanes (Altieri and Koohafkan 2008; Holt-Gimenez 2001; Natarajan and Willey 1986). Our study found increased facilitative effects of intercropping for corn at higher temperatures while controlling all other conditions. In natural environments, climate change is associated with higher temperatures and increased temperature variability (IPCC 2014), as well as increased precipitation variability and water stress and more frequent extreme weather events (IPCC 2014). These changes to our climate will also affect insect pests, pathogens, and weed populations and thus intercropping and increased functional biodiversity in agricultural systems could increase resilience and allow these systems to adapt to climatic changes (Altieri et al. 2015).

Limitations

As with all studies examining just one aspect of climate change, there are several tradeoffs that present limitations to our work. A key limitation of our conceptual model is that this model is very simplified. Here we examine the effect of temperature on growing crops in monoculture and polyculture. In reality, climate change is associated with many more detrimental impacts to agriculture such as increased temperature and precipitation variability and increased frequency of extreme weather events. Furthermore, our model is built on linear equations and thus is only a linear approximation. Additionally, our model does not incorporate the differing competitive and facilitative effects of different planting densities. This requires empirical data with the same planting densities planned for the polycultures. To isolate the effect of temperature and control all other conditions, we grew crops in pots in a greenhouse. The conditions present in a greenhouse and growing crops in pots with regular watering are likely different than the conditions experienced by farmers growing crops in fields. Thus, there may be some differences when replicating this in the field. Our study is likely conservative, as we water plants as needed

and therefore plants did not experience water stress. Under field conditions without irrigation, as is present in most small and medium sized farms throughout the world, the facilitative effect of intercropping could be even stronger.

Future work

Our results underscore the importance of investigating diverse farming methods as ways to adapt to climate change and create more resilient food systems. Further research, should examine the effects of intercropping and climate change in the field, allowing studies to explore more than just the temperature factor examined in our study. Additionally, further studies should explore how different planting densities of intercrops and how more extreme temperatures can alter production. Furthermore, more complex models should be developed to allow farmers more information in making decisions about how to plant crops and prevent yield losses in our changing climate.

Conclusion

Climate change models have predicted that increasing temperatures will significantly reduce crop yields, however these models have not considered how intercropping can be implemented to prevent decreases in yield (Zhao et al. 2017, Asseng et al. 2014). The facilitative effects of intercropping may be greater under higher temperature (climate change) environments. The conceptual framework above can be used to calculate polyculture crop yields under higher temperature environments. While intercropping can help farmers to adapt to climate change, this single change is unlikely to be sufficient to address climate change. Effective adaptation to climate change requires policies, investments, cooperation, infrastructure, and behavioral and lifestyle changes (IPCC 2014).

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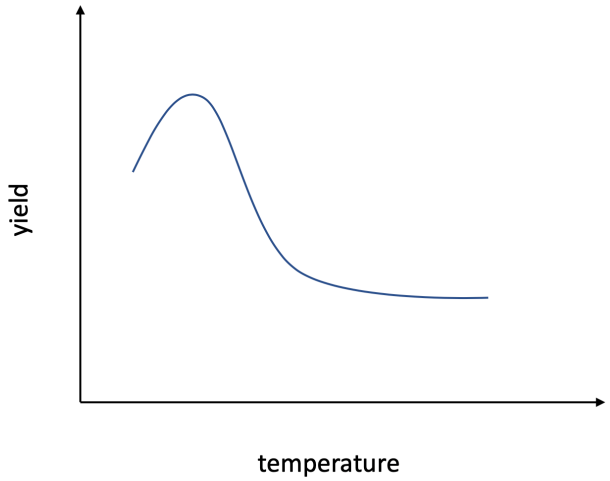


Figure 1. Model demonstrating a crop's temperature threshold, where slight temperature increases result in yield increases until the threshold is reach and yield drastically declines.

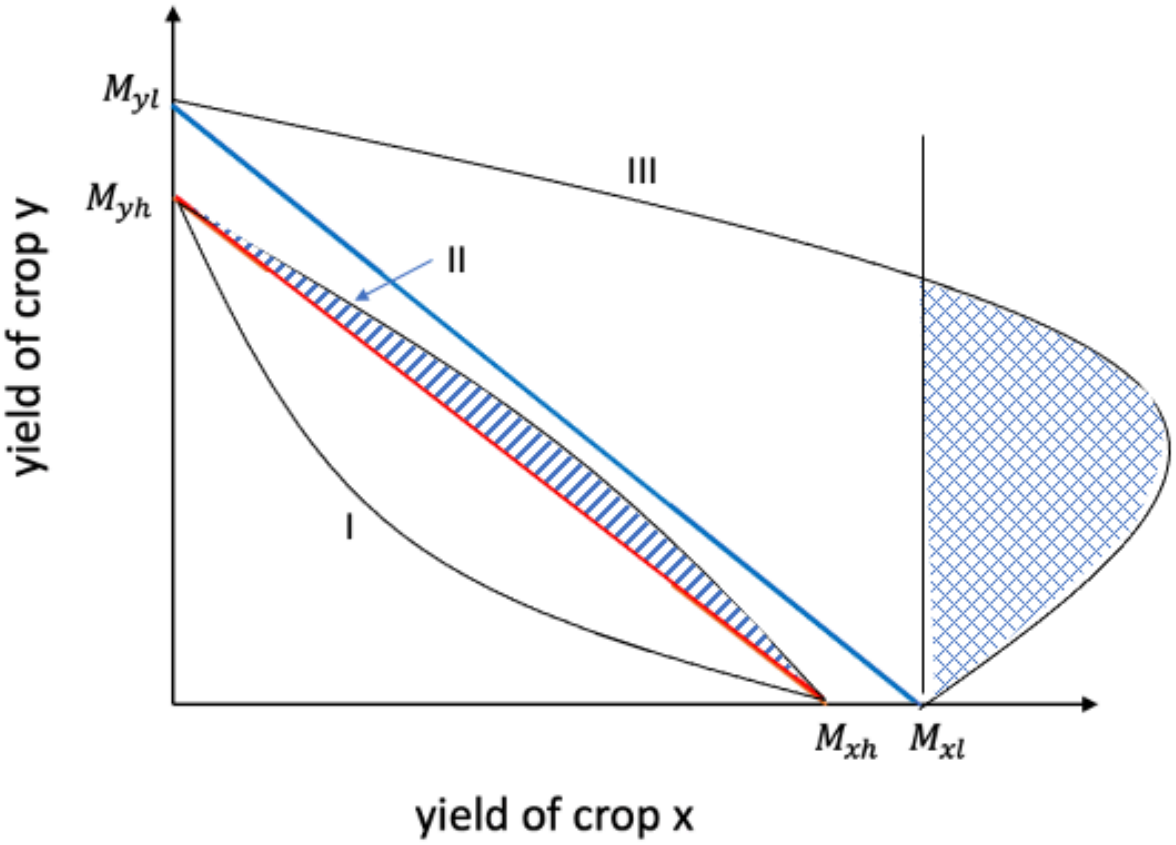


Figure 2. Yields of two crops, x and y, planted in monoculture and polyculture. The black curves represents the yield set (all possible intercrop yields) – I = concave yield set, contains no possibilities for intercrop overyielding under the two assumptions of monocultural yields, II= convex yield set with hatched area representing intercrop overyielding, III = exaggerated convex yield set with the potential for transgressive overyielding (hatched area). The orange line represents the land equivalent ratio (LER) = 1 under high (climate change) temperatures, and the blue line represents the land equivalent ratio (LER) = 1 under lower (pre-climate change) temperatures. M_{xh} and M_{yh} represent the monocultural yield of crop x and y, respectively, under high (climate change) temperatures. M_{xl} and M_{yl} represent the monocultural yield of crop a and y, respectively, under lower (pre-climate change) temperatures.

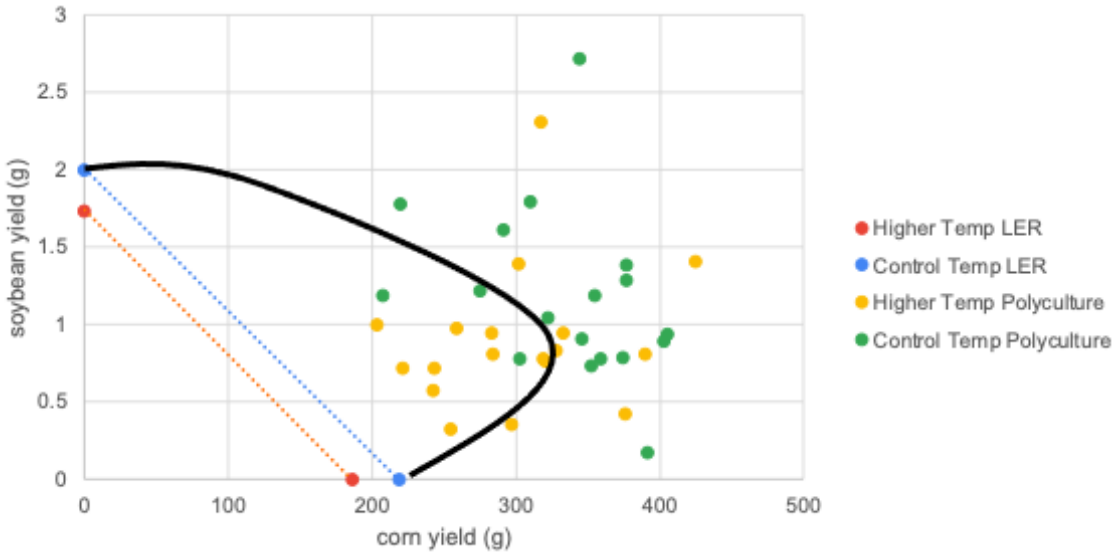


Figure 3. Land Equivalent Ratio plot. Blue points represent average monoculture yields at control temperatures and red points represent average monoculture yields at higher temperatures. Blue line is the LER=1 line for control temperatures. Red line is the LER=1 line for higher temperatures. Yellow points represent polyculture yields for higher temperature treatment pots and green points represent polyculture yields for control temperature treatment pots.

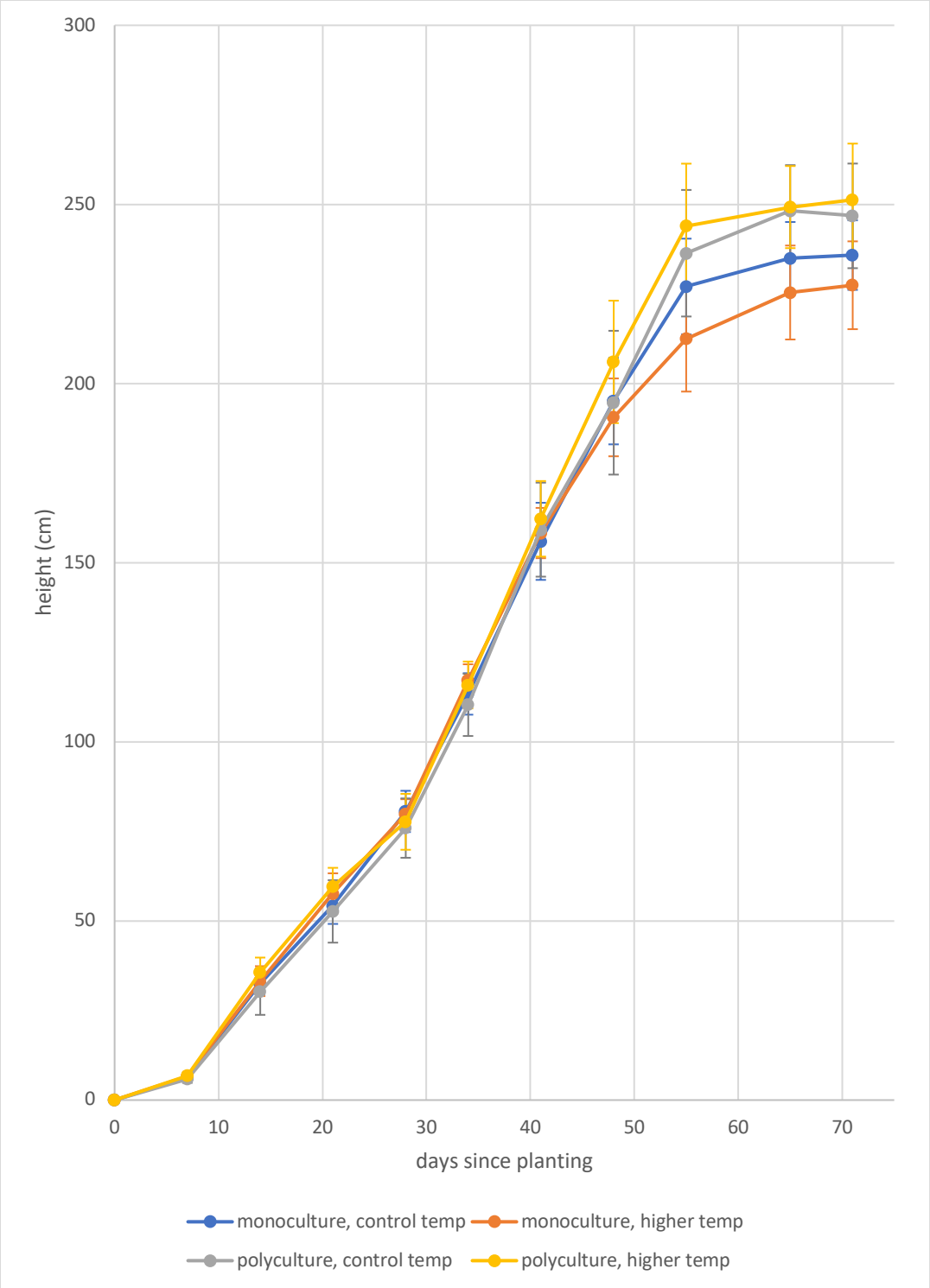


Figure 4. Average corn growth for each unique treatment over time. Corn grown in monocultures at control temperatures and higher temperatures is demonstrated with blue and orange lines, respectively. Corn grown in polycultures at control temperatures and higher temperatures is demonstrated with gray and yellow lines, respectively. Height is measured in centimeters. Error bars represent standard deviation.

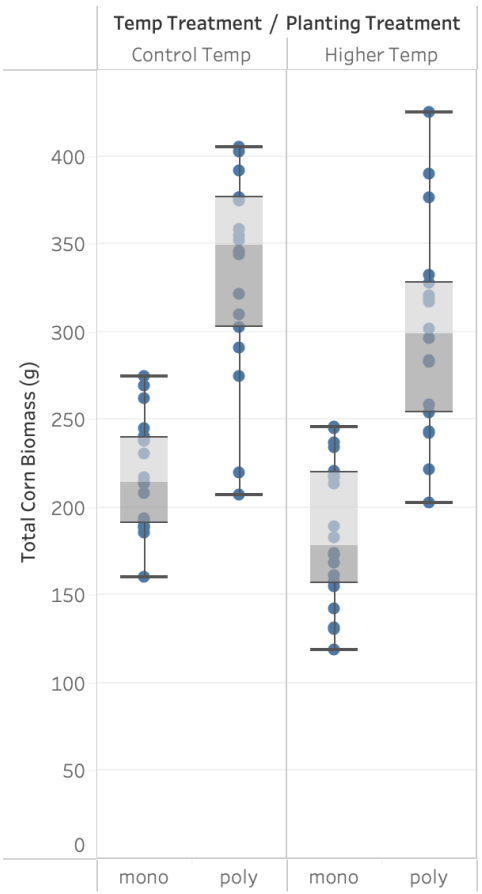


Figure 5. Total above- and below-ground corn biomass based on temperature and planting treatments. Each circle represents a replicate. Total biomass is measured in grams.

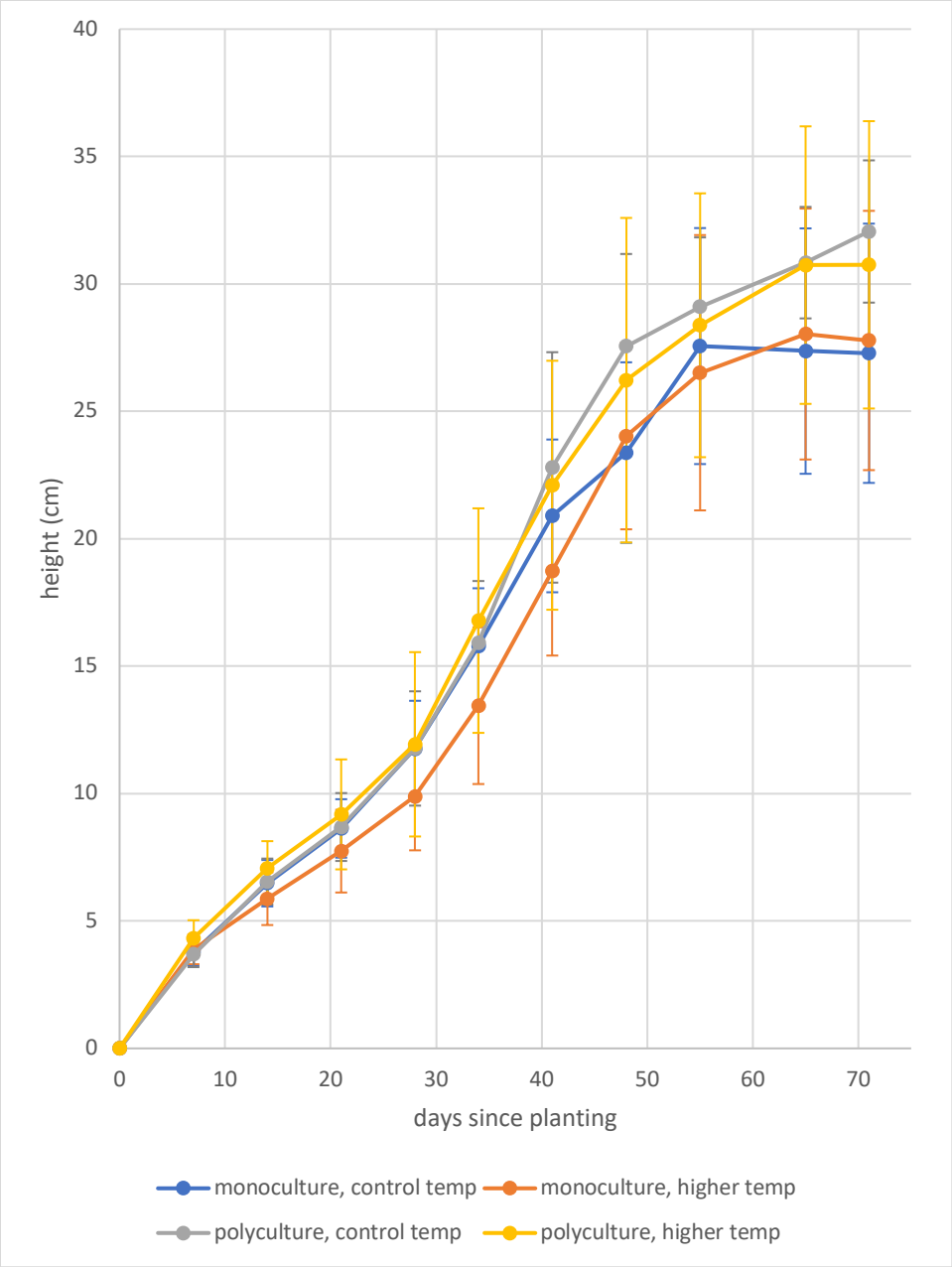


Figure 6. Average soybean growth for each unique treatment over time. Soybeans grown in monocultures at control temperatures and higher temperatures is demonstrated with blue and orange lines, respectively. Soybeans grown in polycultures at control temperatures and higher temperatures is demonstrated with gray and yellow lines, respectively. Height is measured in centimeters. Error bars represent standard deviation.

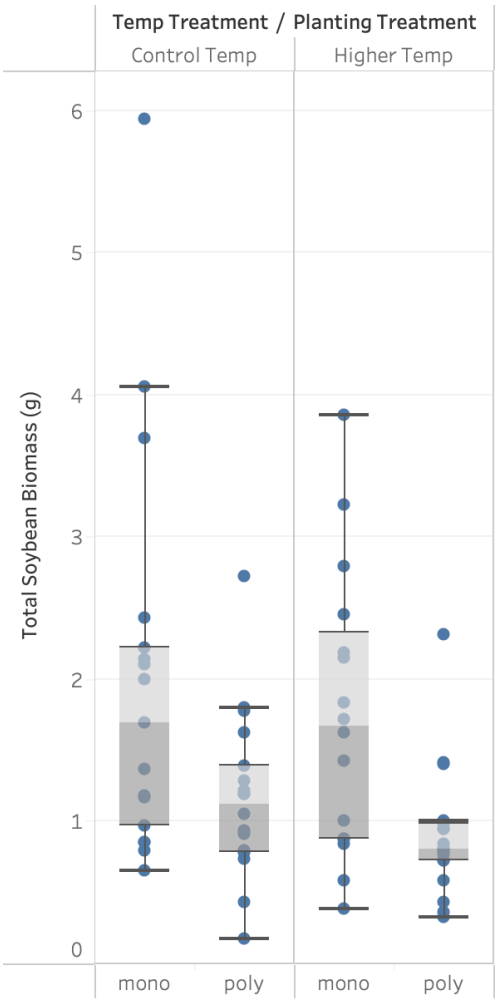


Figure 7. Total soybean plant biomass based on temperature and planting treatments. Each circle represents a replicate. Soybean biomass is measured as total above and below ground biomass. Total biomass is measured in grams.

Monoculture Corn	Monoculture Corn +2C	Monoculture Soybean	Monoculture Soybean +2C	Polyculture Corn	Polyculture Corn +2C	Polyculture Soybean	Polyculture Soybean +2C
218.47	185.82	2.01	1.74	333.89	299.80	1.16	0.90

Table 1. Average biomass of corn and soybeans grown in monocultures and polycultures at control temperatures and higher temperatures. Average biomass is calculated as the average total (above- and below-ground) biomass for each individual plant. Biomass is reported in grams.