
Climate Change and Crop Yields: The Interaction Between CO₂ and Temperature

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Abstract

Both temperature and carbon dioxide (CO₂) concentrations in the atmosphere are on the rise. Temperatures have historically lead to rising crop yields, yet if they continue past an uncertain approaching threshold, it is projected that it will become too hot for some crops to thrive. CO₂ generally increases crop yields through a fertilization effect and increased water efficiency. These two variables will have opposing effects in the future. In this paper I will explore the relationship between temperature, CO₂, and crop yields as well as the interaction between temperature and CO₂. I approach this using a Fixed Effects (FE) multiple linear regression framework. I use a panel dataset on crop yields for various crops (i.e. wheat, maize, rice, sorghum, soybean, and rapeseed), data for CO₂ levels, and surface temperatures for 63 countries from 2010 to 2016. I do not find unambiguous evidence that CO₂ has contributed to rising yields, in fact, I find some evidence that it has had negative impacts. These results may be clouded by misspecification which is discussed in detail. I conclude that further research is needed to disentangle the true climate impacts on crop yields.

1 Introduction/Literature Review

In this paper I seek to address the impact of rising temperatures and CO₂ levels, as well as their interaction on crop yields. I am interested in looking at regional impacts around the world. It is particularly an issue for developing countries who are not adequately equipped to respond to food-related crises.

Crop yields are an important issue because with growing populations and development of countries, the demand for crops will rise. To meet rising demands, agricultural lands can be expanded or crop yields can be increased. The latter is much more feasible and preferable from an ecological point of view as there are large costs associated with the conversion of land to agricultural use.

I focus on wheat, maize, rice, sorghum, soybean, and rapeseed (referred to as canola,¹ hereafter) for my analysis. Each of these crops are important because adverse changes in their yields and production indicate food insecurity. According to the Global Forum on Agricultural Research and Innovation (2012),

Wheat is the most widely grown crop in the world and provides 20% of the daily protein and of the food calories for 4.5 billion people. It is the second most important food crop in the developing world after rice. In recent years, wheat production levels have not satisfied demand, triggering price instability and hunger riots. With a predicted world population of 9 billion in 2050, the demand for wheat is expected to increase by 60%. To meet this demand, annual wheat yield increases must rise from the current level of below 1% to at least 1.6%.

This sheds light on the importance of wheat and outlines a goal for yield increases required to maintain food security. Likewise with rice, “the world’s most important food crop... is the main staple for about half of the world’s population—more than 3 billion people [and] provides about 20% of direct human calorie intake worldwide, making it the most important food crop” according to Zeigler and Barclay (2008, p.3). Rice is particularly important in developing countries as it thrives in semi-arid and arid climates. As for the importance of

¹Canola is a variation of rapeseed grown primarily in Canada that contains less erucic acid and lower levels of glucosinolates compared to traditional rapeseed.

maize, International Maize and Wheat Improvement Center (2016) states that “maize is often consumed indirectly in the form of eggs, corn syrup, milk and cheese products, beef and pork, but is commonly a staple food in developing countries, providing food for 900 million people earning less than US \$2 per day.” Therefore the yield impacts from climate change have large implications for developing countries as well as for a large basket of goods consumed in developed countries.

I include soybean and canola, as these oilseed crops are important inputs to the production of other food. Soybean has a high protein content and is used in animal feed (Chakravorty, 2017). Canola is mostly used for vegetable oil due to its high oil content (over 40% compared to soybean with 18%), cover soil in the winter to combat soil erosion, and to produce biomass (Agricultural Marketing Resource Center, 2018). It is also a large part of Canadian agricultural exports. Sorghum is also included in the analysis as it has various uses including livestock feed, grain, sorghum syrup, ethyl alcohol, and biofuel among others (Encyclopedia Britannica, 2019). Sorghum is of particular importance because it is drought-resistant and flourishes in arid and semi-arid regions (Taylor, 2003). Sorghum is an important component of agriculture in these countries and will be one of the crops that is first to bear the burden of climate change. This is because hot semi-arid regions are where temperatures are already among the highest in the world.

Agricultural production has adapted to certain weather events through learning and investments in technology such as irrigation (Wreford and Adger, 2010). However, will crops be able to maintain their current yields under a harsher climate? The two key climate variables in the current climate debate are CO₂ and temperature. It is well established that the level of CO₂ is at an all-time high (World Meteorological Organization, 2019).

What is still being fully understood is how crops interact with a constantly changing climate. This is important for issues of food security especially if there are incumbent damages that can be forecast. Therefore, I will be examining how CO₂ impacts the productivity of crops.

In his seminal paper de Saussure (1804), “...first demonstrated that peas exposed to high CO₂ concentrations grew better than control plants in ambient air” (Kimball and Idso, 1983, p.1). This marked the beginning of literature on the biological effect that CO₂ has on plants. The CO₂-fertilization effect works through amplifying yields and increasing water use efficiency.

The yield response from CO₂ varies based on the type of crop (Kimball, 2016; Deryng et al., 2016; Challinor et al., 2014). The main staple crops can be divided into two groups: C₃ and C₄ crops. The C₃ crops in my analysis include wheat, rice, canola, and soybean. The C₄ crops in my analysis include maize and sorghum. C₃ and C₄ crops differ in their CO₂ fixation. According to an article in Lovell (2018), “C₄ plants process CO₂ in a more complex way, and can process more CO₂ when it’s hot and dry than C₃ plants. . . These include wheat, canola, flax and soybeans. About 85 per cent of plant species are C₃ plants.” An increase in CO₂ to 550ppm from an ambient level of 353ppm was associated with an average increase in yields of 19% for C₃ crops and decreased evapotranspiration of both C₃ and C₄ crops by 10% (Kimball, 2016). The latter is especially important for developing countries in arid and semi-arid regions of the world, as these will be affected most negatively by climate change damages.

The crop-climate science literature has more recently moved towards the inclusion of CO₂ when looking at the impacts of global warming, and more generally climate change, on crop yields. Deryng et al. (2016) employ a modelling approach to predict crop water productivity, “the ratio of crop yield to evapotranspiration” (p.2) and the impacts from rising CO₂. They use crop models to simulate different scenarios of climate change with and without a CO₂ component. They find that the inclusion of a CO₂-fertilization effect is economically significant and, when included, negative effects from global warming are “fully compensated for in wheat and soybean, and mitigated by up to 90% for rice and 60% for maize” (p.3). Excluding this CO₂ effect leads to damages and reductions, which is evident in other studies that focus primarily on temperature such as Schlenker and Roberts (2009)

who find stark damages associated with global warming. My approach differs from Deryng et al. in that I am using a primarily empirical approach using available data. I am interested in contrasting my results with that of Deryng et al. to see if the results from their simulation modelling approach align with what is being observed. Cassman (2007) “highlight[s] ... that there are substantive differences between results obtained from geostatistical assessments based on recent climate trends and actual crop yields versus assessments based on results from controlled experiments... and crop modelling” (p.2). My approach falls in the former category where as Deryng et al. falls in the latter.

My methodology resembles that of Lobell and Field (2007). They use the same FAO data on crop yields and different temperature data to look at how yields will be affected by rising temperatures. They use temperature data from the Climate Research Units (Mitchel and Jones, 2005). They simulate crop yields and conclude that there will be large damages associated with crop yields with a 2°C increase in temperature relative to pre-industrial levels. In Lobell et al. (2011), they further explore this issue with an empirical model but still do not explicitly include CO₂ in their model. Rather, they look at historical temperature and precipitation in a panel analysis of maize, wheat, rice, and soybean yields (p.617). Their results of temperature and precipitation impacts are contrasted with yield impacts of CO₂ from another study; this ignores variation in CO₂ that is explanatory of crop yields and more importantly, the covariation between CO₂ and temperature. Maize is assumed to have no yield impact from CO₂ and all of rice, wheat, and soybean are assumed to have a 3% increase in yields, which is much lower than the results from Kimball (2016). Models of yield response without CO₂ will overestimate climate damages given the well-established positive effects of CO₂ and interactive effects between CO₂ and temperature.

In my paper, I include CO₂ as an explanatory variable of crop yields. The most important contribution I make is the empirical exploration of the interaction effect between CO₂ and temperature. This has been explored in many controlled experiments but, to the best of my knowledge, has not been explored empirically.

2 Methods

2.1 Data Collection

I use annual data on crop yields from 63 countries from 2010 to 2016. The crop yield data comes from the FAOSTAT database (Food and Agriculture Organization, 2018). There are between 40 and 63 countries growing each of these crops. To represent trends, annual yields for Brazil, Canada, and the US are shown in Figure 1.

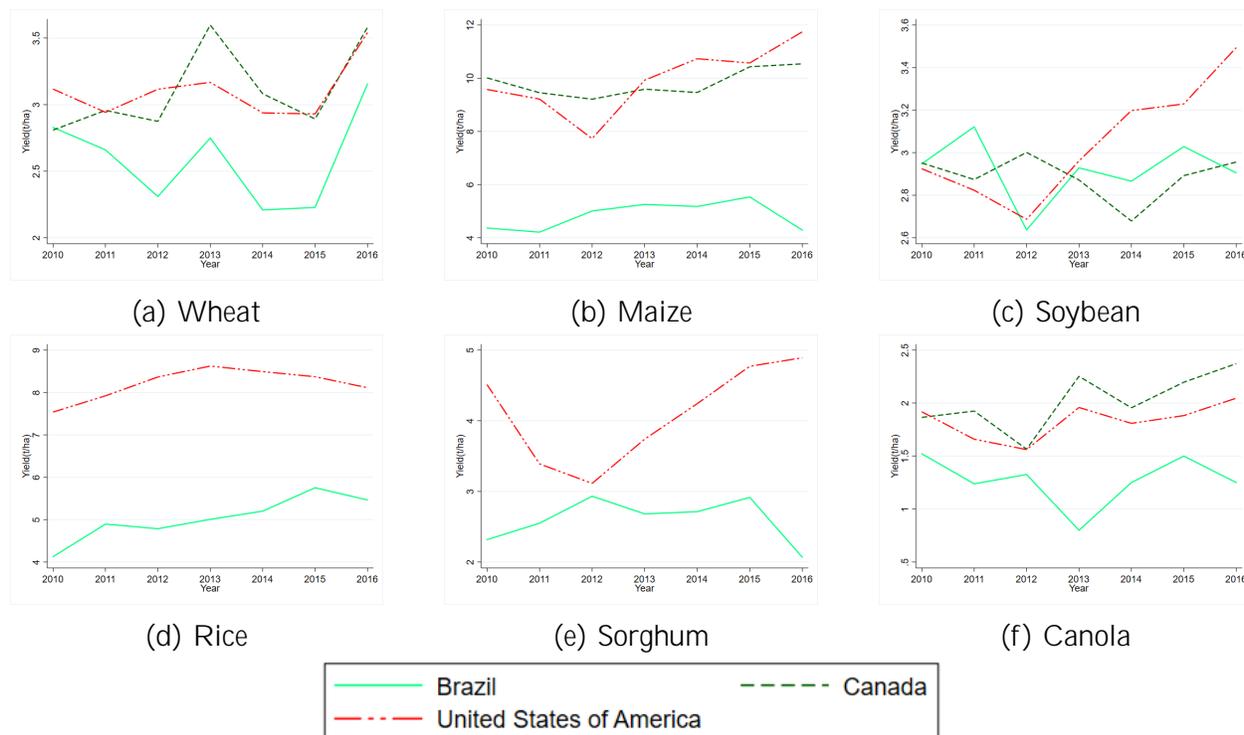


Figure 1: Annual Yields by Crop for Brazil, Canada, and the US

Source: (Food and Agriculture Organization, 2018)

I use newly available CO₂ data covering 2010 to 2016 from the NASA Atmospheric Infrared Sounder (AIRS) database (AIRS Science Team/Joao Teixeira, 2008). This will expand previous models that do not include CO₂. The data comes as a 2:5° 2:0° (lon. lat.) grid matrix of monthly CO₂ measurements which are averaged at the annual level in this analysis. To simplify, I take the centroids of countries as midpoints and use a single point as proxy for the CO₂ for a given country. This assumption leaves room for further exploration of

within-country variation in CO₂ and its impacts on crop yields—something I do not explore in this paper.

CO₂ levels in six major agricultural producers including Canada, the US, the UK, China, India and Brazil, are shown in Figure 2. Note there are some data points missing (e.g. India and Canada). To account for this, these measurements are simply ignored in the calculation of annual CO₂ levels such that, for example, 11 rather than 12 months are used in the average.

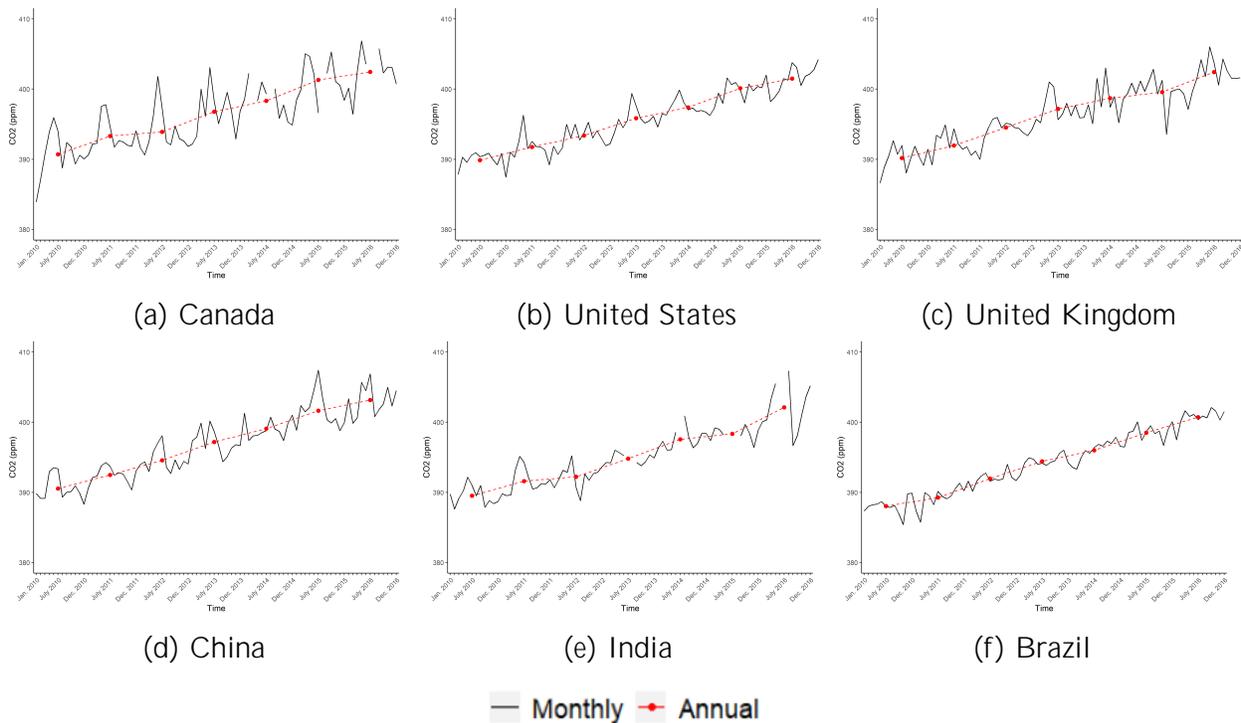


Figure 2: CO₂ levels, 2010 - 2016

Source: (AIRS Science Team/Joao Teixeira, 2008)

I use the Berkeley Earth Surface Temperature (BEST) Series (Berkeley Earth, 2019) data which measures surface temperatures all around the globe on a monthly basis. I average the monthly data to obtain annual temperature data. I use mean temperatures based on areas in which crops are grown for large countries, such as Canada, United States, China, and India, and country-level averages for regular and small sized countries. Year-long temperatures are used in the average as opposed to the typical growing season due to the complicated

nature of differing growing seasons across different crops, as well as within different cultivars of crops. The BEST series measures deviations from the average temperature across 1951 to 1980 as a baseline. This temperature is reported, and I combine the two to obtain an estimate of surface temperatures for each country.

Working within the bounds of each dataset, the final dataset comprises annual crop yields, CO₂, and temperatures for 7 years between 2010 and 2016 for 20 countries. Overlapping subsets of the 20 countries are used to create balanced panels for each crop. Summary statistics by crop are reported in Table 1.

Table 1: Summary Statistics by Crop

Variables	Wheat					Maize					Soybean				
	obs	mean	sd	min	max	obs	mean	sd	min	max	obs	mean	sd	min	max
Yield (ton/ha)	427	3.837	2.226	0.492	10.668	441	6.213	5.463	0.441	36.762	308	2.074	0.804	0.368	4.400
Temperature (°C)	427	16.065	7.470	-0.850	29.140	441	18.940	7.217	-0.681	30.086	308	18.415	6.908	0.681	28.617
CO ₂ (ppm)	427	396.010	4.240	387.183	404.238	441	395.887	4.253	387.183	404.238	308	395.864	4.231	387.183	403.615
# of Countries	61					63					44				
Variables	Rice					Sorghum					Canola				
	obs	mean	sd	min	max	obs	mean	sd	min	max	obs	mean	sd	min	max
Yield (ton/ha)	336	4.798	2.285	0.592	10.683	322	3.177	3.348	0.191	25.247	280	2.346	0.970	0.600	4.795
Temperature (°C)	336	20.663	6.171	8.508	29.269	322	20.449	6.157	6.846	29.269	280	12.844	6.608	0.850	26.104
CO ₂ (ppm)	336	395.7447	4.264	387.183	403.967	322	395.8706	4.264	387.183	404.238	280	396.302	4.187	388.056	403.608
# of Countries	48					46					40				

2.2 The Statistical Model

I use a FE multiple linear regression framework to explore region-specific impacts of CO₂ and temperature on crop yields. This is done to control for country-specific characteristics that do not vary over time such as soil quality, acidity, and crop management. The base model is as follows:

$$\log(Y_{cit}) = \alpha_0 + \alpha_1 C_{it} + \alpha_2 T_{it} + \alpha_3 C_{it} T_{it} + \mu_i + \mu_t + u_{cit} \quad (1)$$

where $\log(Y)$ is the natural logarithm of yield of crop c in country i at time t , C is CO₂ in country i at time t , T is temperature within country c at time t , μ_i are the country fixed effects, μ_t are the time fixed effects, and u_{cit} is the error structure.

I build my model around Lobell et al. (2011), who use an empirical model based on Nicholls (1997). Lobell et al. use first differences in yields, whereas I use the natural logarithm. They use first differences to effectively detrend the series—I use time fixed effects to address this. Further, they include temperature as well as precipitation where I use temperature and CO₂. They also use first differences as independent variables where I use levels—this allows me to interpret my results differently. I also use mean annual temperatures where they use both mean minimum and maximum annual temperatures. Their model also spans from 1961 to 2002 and mine is 2010 to 2016. They use average global yields of crops, whereas I look at average regional yields to see if there is heterogeneity with which yields are affected by certain climate variables.

From a theoretical perspective, I expect *a priori* that the marginal effects of CO₂ and temperature will vary across their distributions; however, the span of data is not granular enough to justify the inclusion of quadratic terms. This approach will give us two marginal effects of interest:

The CO₂-Fertilization Effect (2) and the Temperature Effect (3)

$$\frac{\partial Y_{cit}}{\partial C_{it}} = \alpha_1 + \alpha_3 T_{it} \quad (2)$$

$$\frac{\partial Y_{cit}}{\partial T_{it}} = \alpha_2 + \alpha_3 C_{it} \quad (3)$$

The interaction effect is captured with β_3 and varies with temperature and CO₂. I also expect *a priori* that $\beta_1 > 0$ and $\beta_3 < 0$ given the crop science literature. Most studies mentioned previously looking at the CO₂-fertilization effect have found positive impacts from rising CO₂. There is no structural interpretation given around this and the effect that CO₂ has on temperature is not modelled.

To control for any potential across-country heteroskedasticity, the standard errors in all regressions will be clustered at the country level. This allows unexplained variation in any given period to be correlated with unexplained variation in other periods within the same cluster without violating the assumptions required to properly estimate the effects of the independent variables.

3 Results

I run the log-level model for each crop through four distinct specifications. I start with a simple fixed effects model with just the linear CO₂ and temperature terms with only country fixed effects. Next, I add the time fixed effects to see what difference this makes. Then I include the interaction between CO₂ and temperature with only country fixed effects. Likewise, I add the time fixed effects to this model to construct the final specification. These specifications are labelled (1) through (4).

I decided to use the log-level model because it allows for an interesting interpretation of the results and “yields follow a log-normal distribution” (Lobell et al., 2011, p. 3).

3.1 C_3 Crops: Wheat, Rice, Soybean, and Canola

Table 2: Fixed Effects Regression Analysis of Wheat and Rice

Dependent Variable: log(Yield)	Wheat				Rice			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
CO ₂	0.00904*** (3.66)	-0.0194 (-1.20)	0.0188*** (3.12)	-0.00875 (-0.45)	0.00456*** (2.98)	0.000365 (0.07)	0.00315 (0.49)	-0.00225 (-0.25)
Temp	-0.0212 (-1.10)	-0.0201 (-1.04)	0.190 (1.46)	0.175 (1.32)	-0.00545 (-0.34)	0.00861 (0.44)	-0.0302 (-0.27)	-0.0318 (-0.28)
CO ₂ Temp			-0.000567* (-1.70)	-0.000526 (-1.56)			0.0000657 (0.23)	0.000108 (0.38)
Constant	-2.067** (-2.30)	8.999 (1.41)	-5.732** (-2.47)	4.994 (0.65)	-0.264 (-0.43)	1.058 (0.52)	0.268 (0.11)	2.042 (0.57)
Time Fixed Effects	No	Yes	No	Yes	No	Yes	No	Yes
N	427	427	427	427	336	336	336	336
F	6.784	2.608	6.181	4.396	4.510	3.016	3.141	3.101
p	0.0116	0.0203	0.00362	0.000318	0.0390	0.0106	0.0524	0.00681
R ²	0.188	0.165	0.187	0.175	0.210	0.180	0.193	0.196

t statistics in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The regression results for wheat are reported in Table 2. Model (1) is the basic model with only C and T included; T is not statistically significant. CO₂ is statistically significant at the 1% level of significance and the parameters are in the range of likely estimates so it is also economically relevant. The addition of the time fixed effects in specification (2) renders CO₂ statistically insignificant and temperature relatively unchanged and still statistically insignificant. Specification (3) adds the interaction term, which is statistically significant at the 10% level of significance; likewise, CO₂ is statistically significant at the 1% level and temperature is not statistically significant. Much like (2), adding the time fixed effects in specification (4) renders CO₂ and its interaction with temperature statistically insignificant. Further, the F statistic associated with the test of joint significance is statistically significant at the 1% level—the regressors are jointly significant.

To fully assess the implications of the interaction effect, I compute the marginal effects

and plot them over the ranges of the other variable (e.g. the marginal CO_2 effect depends upon temperature). This is shown in Figure 3.

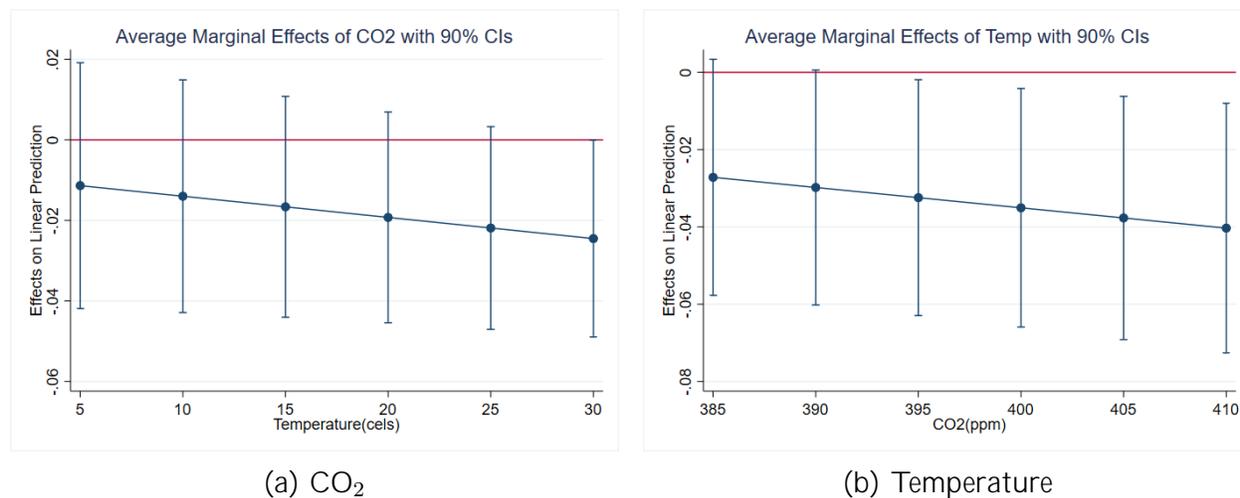


Figure 3: Marginal Effects for Wheat

Looking at Figure 3a, the marginal CO_2 effect is statistically significant across the range of temperatures. Further, the sign is negative, implying CO_2 has a negative impact on wheat yields. The negative sign on the interaction term implies that CO_2 is more damaging at higher temperatures. Figure 3b shows that the marginal temperature effect is negative and statistically significant at the 10% level for $\text{CO}_2 > 395$ ppm. This implies that rising temperatures have an adverse impact on wheat yields, consistent with the crop science literature.

The regression results for rice are reported in Table 2. The initial specification (1) has CO_2 as statistically significant at the 1% level of significance. The temperature term is statistically insignificant. Upon adding the time fixed effects in specification (2), CO_2 is rendered very statistically insignificant ($t = 0.07$). Looking at specification (3) with the interaction term, neither CO_2 nor temperature are statistically significant even without time fixed effects. Adding time fixed effects does not change the results that much as all remain statistically insignificant. The F test indicates that the regressors are jointly statistically significant at the 1% level of significance. To further explore the implications of the interaction effect, I

plot the marginal effects in Figure 4.

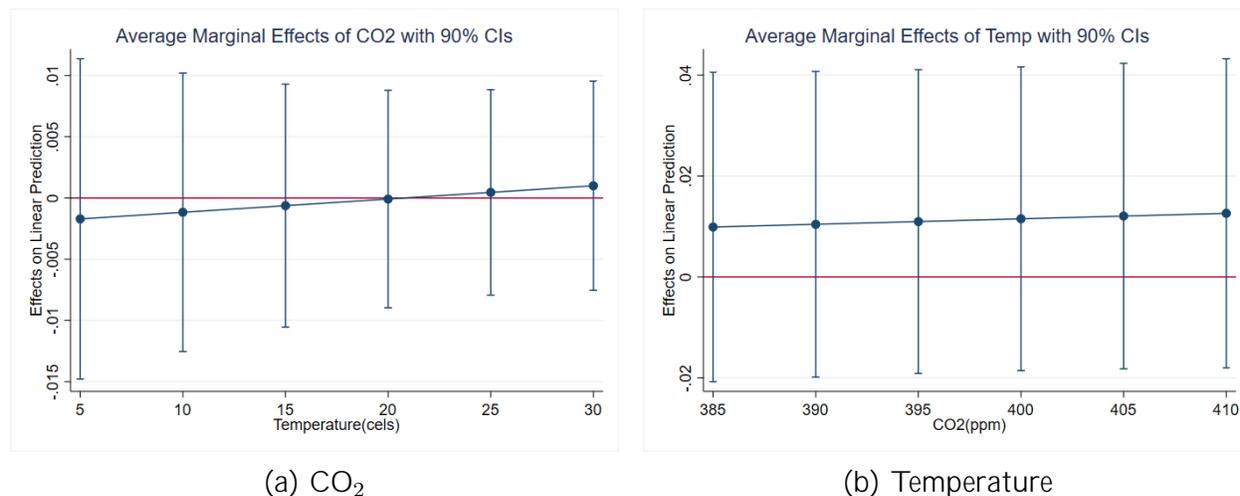


Figure 4: Marginal Effects for Rice

The marginal effects are quite close to zero; rice yields are largely unaffected by CO₂ (Figure 4a). The temperature effect shown in Figure 4b also shows statistical insignificance although the magnitude appears to be positive.

Table 3: Fixed Effects Regression Analysis of Soybean and Canola

Dependent Variable: log(Yield)	Soybean				Canola			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
CO ₂	0.00610** (2.37)	-0.00963 (-0.81)	0.0150** (2.39)	-0.000232 (-0.02)	0.00893*** (2.99)	-0.00507 (-0.23)	0.0275*** (3.45)	0.0182 (0.73)
Temp	-0.00436 (-0.22)	-0.0179 (-0.78)	0.181 (1.34)	0.165 (1.19)	0.0633*** (3.09)	0.0660*** (3.18)	0.562*** (2.78)	0.553*** (2.73)
CO ₂ Temp			-0.000475 (-1.36)	-0.000469 (-1.29)			-0.00132** (-2.57)	-0.00129** (-2.53)
Constant	-1.693* (-1.89)	4.715 (1.01)	-5.167** (-2.19)	1.052 (0.18)	-3.595*** (-3.08)	1.813 (0.21)	-10.63*** (-3.40)	-7.031 (-0.72)
Time Fixed Effects	No	Yes	No	Yes	No	Yes	No	Yes
<i>N</i>	308	308	308	308	280	280	280	280
<i>F</i>	3.438	2.553	4.861	3.408	11.14	6.072	10.15	7.086
<i>p</i>	0.0706	0.0273	0.0125	0.00407	0.00187	0.0000787	0.000282	0.00000953
<i>R</i> ²	0.168	0.242	0.202	0.244	0.238	0.243	0.205	0.209

t statistics in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The regression results for soybean are reported in Table 3. CO_2 is statistically significant and positive at the 1% level of significance in specification (1); however, upon adding time fixed effects in specification (2), CO_2 is rendered statistically insignificant and negative. Looking at specification (3), the interaction term is negative although not statistically significant, and CO_2 is positive and statistically significant at the 5% level of significance. Adding time fixed effects in specification (4) renders CO_2 very statistically insignificant ($t = 0.02$). The F test indicates that the regressors are jointly statistically significant at the 1% level of significance. The marginal effects are plotted in Figure 5.

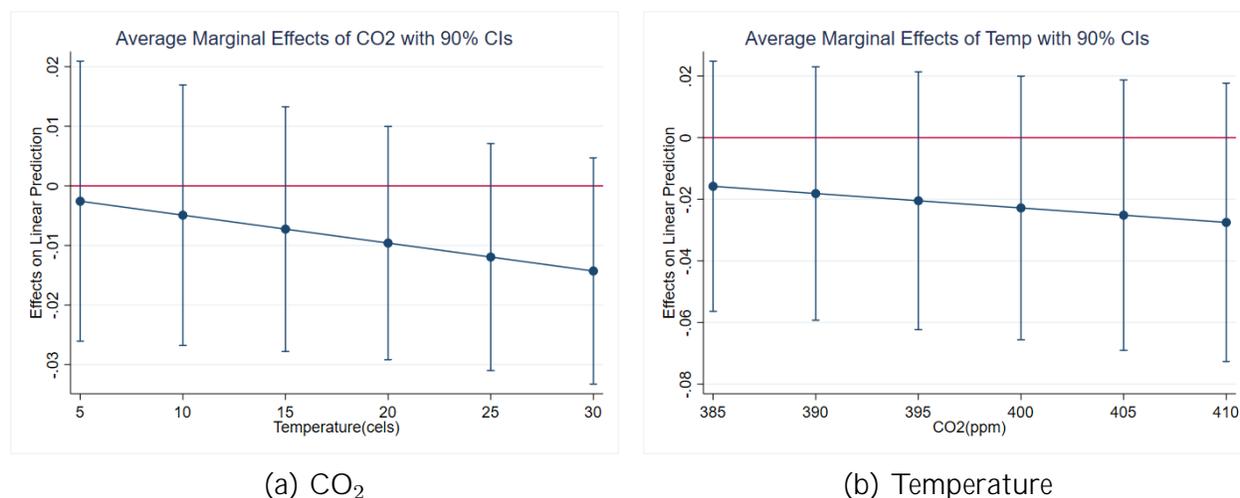


Figure 5: Marginal Effects for Soybean

Figure 5a shows that the CO_2 -fertilization effect is statistically insignificant across the range of temperatures; CO_2 appears to have a negative impact on soybean yields for all temperatures. The interaction term being negative implies that CO_2 is more damaging at higher temperatures. Figure 5b shows negative, statistically insignificant impacts from temperature that are relatively insensitive to changing CO_2 .

The regression results for canola are also reported in Table 3. CO_2 and temperature are both statistically significant at the 1% level and positive in specification (1). Adding time fixed effects renders CO_2 statistically insignificant, although temperature remains positive and statistically significant at the 1% level of significance. The magnitude of this estimate

does not change either. Looking at specification (3), the linear CO_2 and temperature terms are positive and statistically significant at the 1% level of significance, and the interaction term is negative and statistically significant at the 5% level of significance. Upon adding time fixed effects in specification (4), the linear CO_2 term becomes statistically insignificant and all other terms are largely unaffected. The F test indicates that the regressors are jointly statistically significant at the 1% level of significance. The marginal effects are plotted in Figure 6.

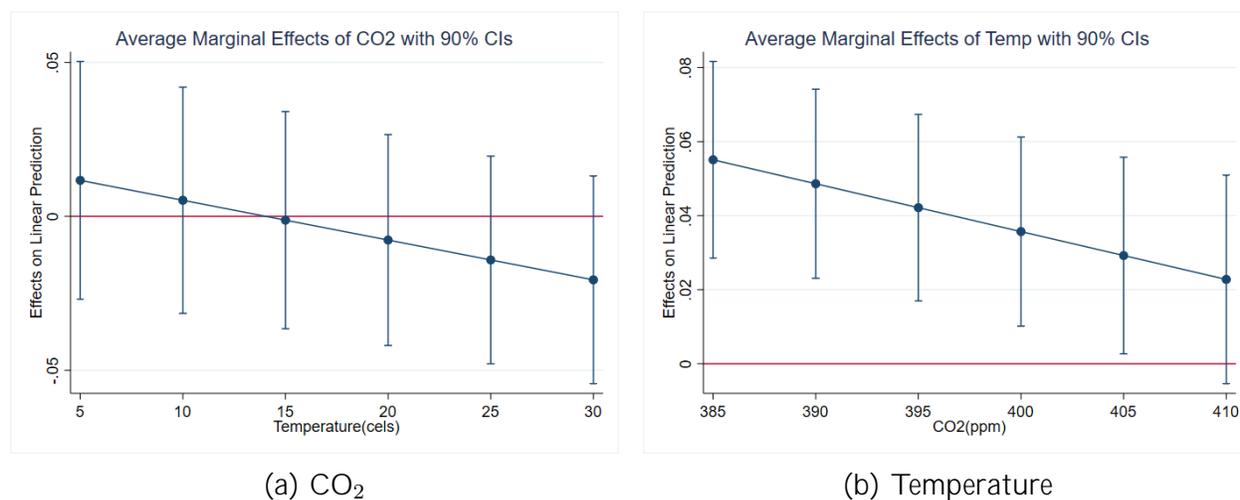


Figure 6: Marginal Effects for Canola

There is no evidence for a CO_2 -fertilization effect in my model (Figure 6a). The interaction term implies a decreasing marginal CO_2 effect; however, the effect is very close to zero. There is evidence of a positive temperature effect (Figure 6b). Canola yields are positively affected by rising temperatures, but less so as CO_2 rises. For example, at 395 ppm atmospheric CO_2 , a 1°C increase in temperature is associated with a 4% increase in canola yields.

The crop science literature suggests positive CO_2 -fertilization effects for C_3 . It is surprising to find negative CO_2 impacts on wheat, although this may be due to identification issues discussed in section 4.

Canola having positive yield impacts from rising temperatures is consistent with the

narrative that countries with colder climates such as Canada will experience net gains global warming. This is a good sign for Canadian agribusiness given Canada is the world leader and produces 28.11% of all canola, globally (United States Department of Agriculture, 2020, p.29).

None of the parameters in the rice regression are statistically significant at any conventional levels of significance. This may be due to surface temperature being a poor proxy for the conditions in which rice is grown—it is grown in a submerged field called a rice paddy. Surface warming is likely systematically different from how rice paddies warm in growing seasons. This unfortunately implies an inability to gauge CO_2 -fertilization and temperature effects for rice outside of an experimental setting like FACE studies.

My analysis shows that C_3 crops are insensitive or damaged by CO_2 which is inconsistent with the crop science literature looking at CO_2 -fertilization mentioned previously, although this may be a product of my statistical approach.

3.2 C_4 Crops: Maize and Sorghum

Table 4: Fixed Effects Regression Analysis of Maize and Sorghum

Dependent Variable: log(Yield)	Maize				Sorghum			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
CO ₂	0.0103*** (4.27)	0.0210 (1.45)	0.00673 (1.14)	0.0170 (1.22)	0.00463 (1.14)	-0.0250 (-1.22)	0.0300* (1.69)	0.00616 (0.29)
Temp	-0.0271 (-1.09)	-0.0274 (-1.00)	-0.0955 (-0.90)	-0.0873 (-0.83)	-0.0121 (-0.28)	-0.0230 (-0.44)	0.433 (1.53)	0.397 (1.44)
CO ₂ Temp			0.000180 (0.62)	0.000159 (0.54)			-0.00119 (-1.64)	-0.00113 (-1.59)
Constant	-2.053** (-2.25)	-6.215 (-1.06)	-0.697 (-0.33)	-4.687 (-0.85)	-0.786 (-0.45)	10.98 (1.42)	-10.30 (-1.50)	-0.725 (-0.09)
Time Fixed Effects	No	Yes	No	Yes	No	Yes	No	Yes
N	441	441	441	441	322	322	322	322
F	9.186	3.832	6.130	3.322	0.661	2.128	1.033	2.45
p	0.00355	0.00160	0.00372	0.00319	0.421	0.0597	0.364	0.0271
R ²	0.216	0.224	0.216	0.224	0.167	0.147	0.169	0.165

t statistics in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The regression results for maize are reported in Table 4. In specification (1), CO₂ is positive and statistically significant at the 1% level of significance. Temperature is negative and statistically insignificant. Upon adding time fixed effects in specification (2), temperature is unchanged and CO₂ is rendered statistically insignificant yet still positive. The magnitude of CO₂ also doubles in size. Looking at specification (3), none of the terms are statistically significant. The interaction term is positive yet statistically insignificant. Adding the time fixed effects does not change the significance of the results. The F test indicates that the regressors are jointly statistically significant at the 1% level of significance. The marginal effects are plotted in Figure 7.

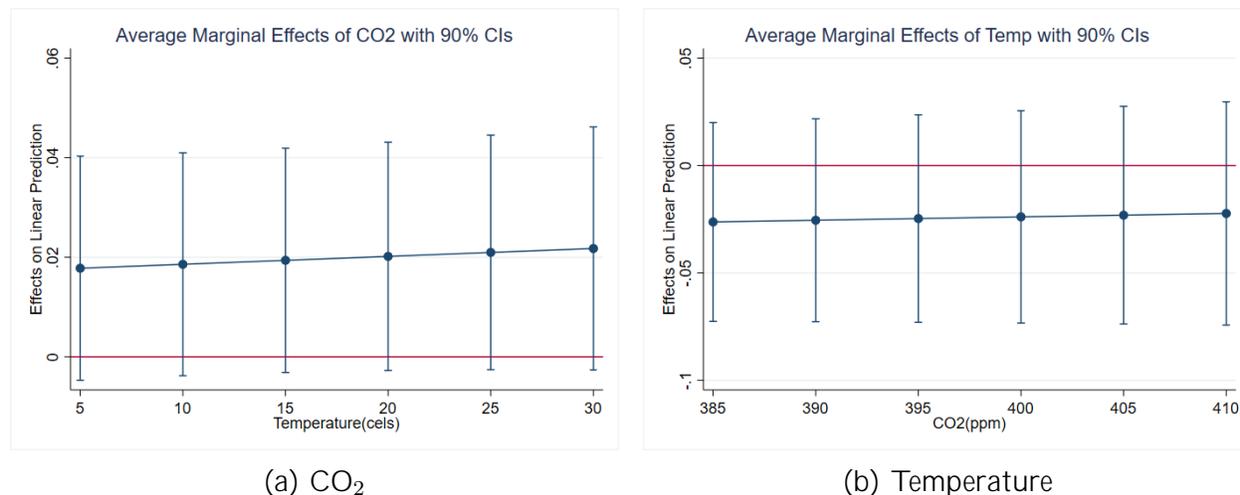


Figure 7: Marginal Effects for Maize

Figure 7a shows a positive CO_2 -fertilization effect that is nearly statistically significant at the 10% level of significance. Although seemingly insensitive, this effect appears to be more beneficial at higher temperatures due to the positive interaction term. The temperature effect is negative, as expected, although statistically insignificant. Likewise, due to the positive interaction term, temperature is becoming less damaging as CO_2 rises.

The regression results for sorghum are reported in Table 4. In specification (1), CO_2 and temperature are both statistically insignificant. CO_2 is positive and temperature is negative. The F test of joint significance also indicates that these regressors are not jointly significant. Adding time fixed effects in specification (2) renders CO_2 negative and both are still statistically insignificant. Further, adding the time fixed effects makes the regression jointly significant at the 10% level of significance. In specification (3), the interaction term is negative and nearly statistically significant at the 10% level and the CO_2 is positive and statistically significant at the 10% level. Temperature is positive yet statistically insignificant. However, the lack of time fixed effects in this specification makes the regression jointly insignificant as indicated by the low F statistic. Adding the time fixed effects in specification (4) makes the regression jointly statistically significant at the 5% level of significance. It also renders CO_2 statistically insignificant, leaving all else relatively unchanged. The marginal

effects are plotted in Figure 8.

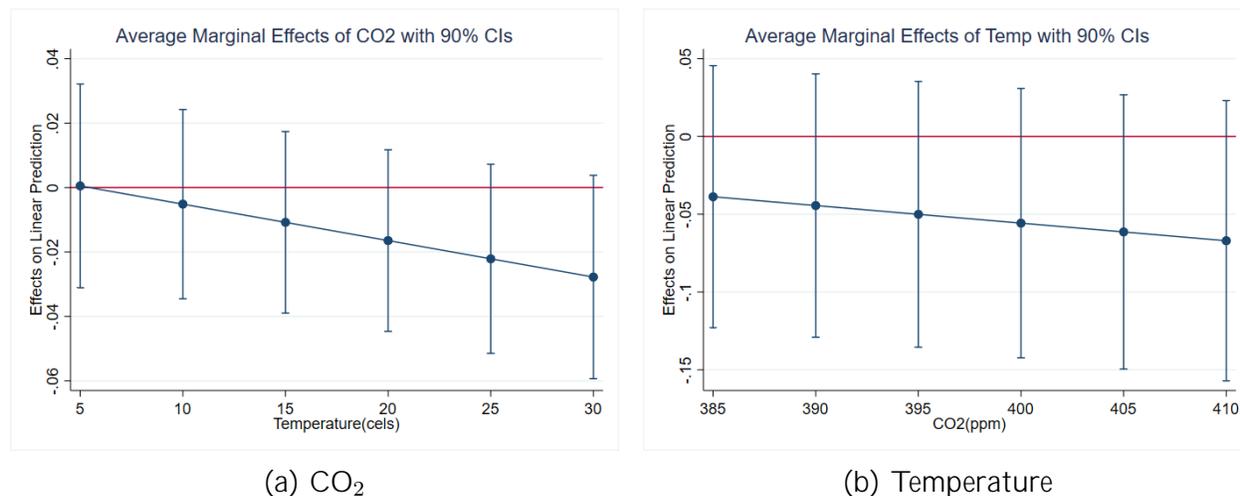


Figure 8: Marginal Effects for Sorghum

Figure 8a shows no effect from rising CO₂ and increasingly negative impacts as temperatures rise due to a negative interaction term. Given sorghum's prevalence as a staple crop in many African countries, this is a troubling result. Temperature has negative impacts on sorghum yields that appears to be relatively insensitive to rising CO₂. None of these results are statistically significant at any point in the ranges of CO₂ and temperature examined.

According to Taub (2010), there is little effect from increased CO₂ concentrations on photosynthetic rates of C_4 species (e.g. maize and sorghum). Although, C_4 species do respond by decreasing stomatal conductance, leading to some enhancement of photosynthesis by reducing water use. In fact, only one third of photosynthesis stimulation experienced in C_3 plants are seen in C_4 plants. This may explain the lack of significant results found. This analysis does, however, cast doubt as to the existence of a CO₂-fertilization effect on C_4 crops. Again, this may be due to my identification strategy rather than there not being an effect, as many studies have found CO₂-fertilization effects in C_4 crops.

None of the parameters in the final maize regression are statistically significant at any conventional levels of significance. The lack of CO₂-fertilization effect is explained by the physiology of the plant, as C_4 plants have substantially less benefits from increased concen-

trations of CO₂.

A big concern is the potential negative impact in semi-arid regions, where most developing countries are situated. Technological advancement will likely be required to combat climate damages, although this is not something explored in this analysis.

4 Limitations of the Research

It is difficult to disentangle the *true* underlying CO₂-fertilization effects. This paper should serve as a guide for further research. In light of newly available data on CO₂, there are opportunities for conducting further econometric analysis. Exploring the variability of crop yields *within* countries using this CO₂ data would be an interesting topic and provide an avenue for future research.

Another caveat in my modelling approach is the omitted precipitation variable seen in other studies. I was unable to include reliable, regional precipitation data. This leads to a major endogeneity issue as this unexplained variation is very likely correlated with temperature and CO₂. This is a potential source of bias in my estimates.

I intended to replicate an experimental setting to isolate the regional impacts of CO₂ and temperature on crop yields. There exists large variation in temperatures among countries, although CO₂, as expected, is largely uniform across the globe. While variation in regional CO₂ exists, there is little. Without controlling for all other determinants of crop yields in an experimental setting, it is therefore difficult to exploit this variation as the differences among countries are not substantial enough to account for large differences in crop yields.

5 Discussion

It is unclear whether CO₂-fertilization has impacted crop yields. My results are ambiguous: I find positive effects, negative effects, and no effects depending on the crop, and very little statistical significance. The effect of CO₂ and temperature on crop yields likely occur over the long-run, so analyzing data between 2010 and 2016 was likely insufficient to detect the effects of these variables. Upon examining interactions between CO₂ and temperature, it seems likely that the impacts from rising atmospheric CO₂ are greater in colder climates, whether they are positive or negative. Benefits from CO₂ are greater and damages less severe at colder temperatures. This implies that Canada, a country with an average temperature fluctuating around zero, could see benefits from rising CO₂.

While most countries diversify and grow most of the crops in the sample, some countries rely on monoculture. For example, Canada has the largest canola industry in the world but still cultivates all of the crops examined in this analysis. For countries geographically able to diversify, climate change will adversely affect some crops and benefit others. For countries that only focus on one or two at risk crops, implications from climate change may be worse.

Despite government efforts and regulations, temperatures will inevitably rise. It is widely accepted that increases in temperature are exacerbated by increasing levels of CO₂. For this reason, high levels of CO₂ are often considered problematic. While this CO₂ effect is well-documented, “economists use temperature (not CO₂ levels) to determine economic damages” (van Kooten, 2020, p. 336). Although I have not found unambiguously positive benefits of CO₂ on crop yields, current climate literature is exploring the potential benefits of CO₂. If increased CO₂ improves crop yields, economists may be generally overstating the impacts of climate change on agriculture. Research in this area has mostly consisted of experimental studies; however, taking a similar empirical approach as I have done enables the quantification of historical impacts of CO₂ on crop yields to better predict future outcomes. Future studies should improve upon my methodology to come closer to answering the complex question of how CO₂ has impacted crop yields.

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