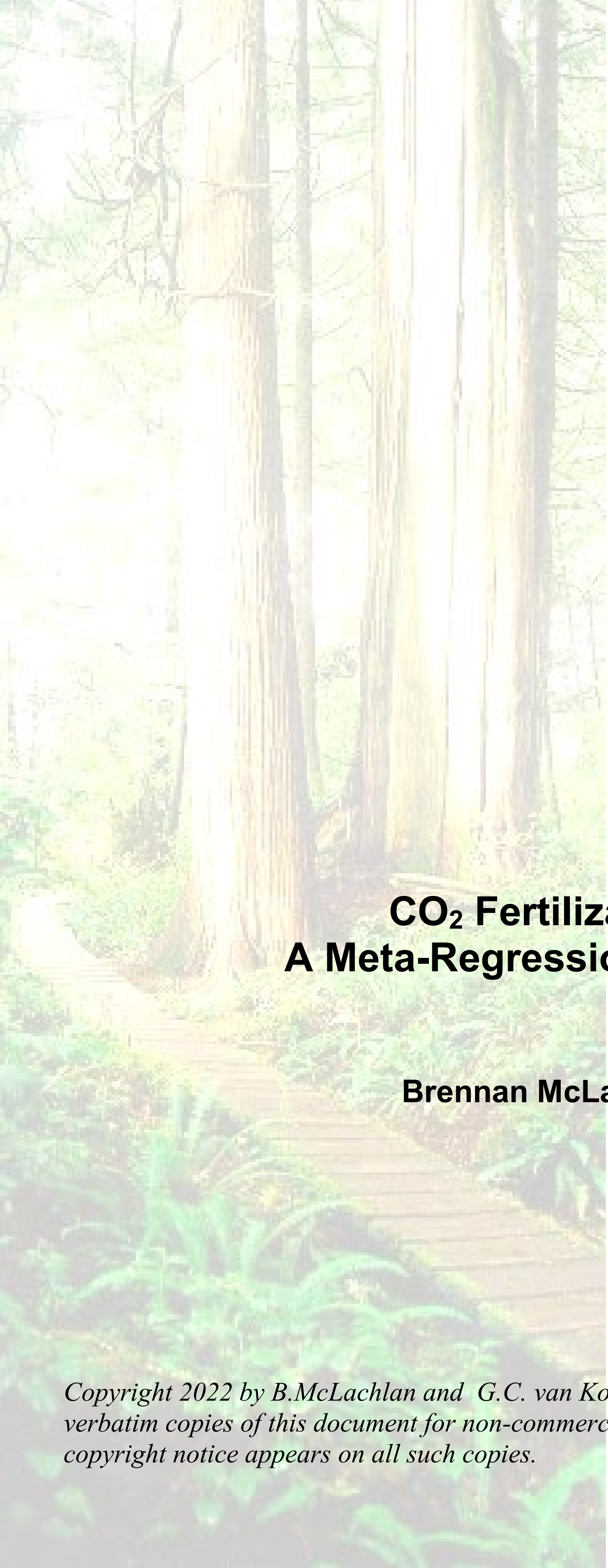

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CO_2 Fertilization versus Temperature: A Meta-Regression Analysis of Crop Yields

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Abstract

Food insecurity has been identified as a potentially dire consequence of climate change. For the most part, the impact on crop yields of increasing atmospheric CO_2 has received much less attention. Higher levels of CO_2 in the atmosphere are associated with increased water efficiency in plants and higher yields, with CO_2-fertilization a possible mitigating factor to global warming. In this study, we collect 493 observations from 47 studies that have examined crop yields at elevated levels of CO_2 relative to ambient levels. The current study employs regression analysis techniques to explore the effect that CO_2, temperature, and their interactive effects have on crop yields, using control variables to account for other confounding factors such as location, technology, et cetera. It was found that that a 100ppm increase in CO_2 is associated with a 16.08% (22.44%) increase in wheat yields at 12ºC (20ºC) and a 15.30% (6.95%) increase in rice yields at 16ºC (28ºC) suggesting more and less efficacy of the CO_2-fertilization effect at higher temperatures, respectively. Further, it was found that a 1ºC increase in temperature is associated with a 3.3% and 7.1% reduction in wheat and rice yields, respectively, at current atmospheric CO_2 levels. The paper also found that there is insufficient information about the impact that CO_2 has on yields in many regions and that more regional trials are required in arid regions and in developing countries.

Key words: Climate change and crop yields; CO_2-fertilization and heat effects; Food security; Meta-regression analysis

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1. INTRODUCTION

There has been extensive research on the effects of increased atmospheric carbon dioxide (CO_2) and rising temperatures on crop yields, although the impact of CO_2 on crop yields has been downplayed or even ignored. For example, Lobell and Field (2007) simulated crop yields using FAO crop yield data but ignored a potential CO_2-fertilization effect. These authors found large significant negative effects on regional yields from global warming, but their conclusions may well have been quite different if there had been adequate data on CO_2 levels. One needs to look at farm-level data to observe CO_2-fertilization effects because regional data on a global scale are not readily available. In the current study, therefore, we consider field-level and greenhouse studies to determine the potential effect that climate change could have on crop yields in various locations.

Food crops are impacted differently by climate change depending on whether they are C3 or C4 plants, with C3 crops expected to do better under an enhanced-CO_2 atmosphere than C4 crops. The most prevalent food crops are C3, which includes wheat, rice, barley, oats, many vegetables, and even important tree crops (e.g., apples), while the primary C4 crops are maize, sorghum, and sugar cane—crops that are also best suited to produce biofuels. There are proportionally more C4 plants among perennial weeds, which implies that they do less well under climate change than C3 plants; for example, C3 weeds would develop herbicide resistance more easily than C4 weeds as CO_2 increases.

Rising atmospheric CO_2 affects crop yields by increasing the rate of photosynthesis and water-use efficiency. Deryng et al. (2016) found that the ratio of crop yields to the rate of evapotranspiration will likely increase by 10 to 27 percent by 2080, with much less water required to achieve the same yields. This is crucial given the extent of population growth projected for the next fifty or more years, although projections of population growth remain contentious (Bricker & Ibbitson, 2019). The researchers employ a modelling approach and project crop yields in 2080 under climate change with and without a CO_2-fertilization effect. In the no CO_2-fertilization scenario, severe negative effects on crop yields occur; but, when CO_2 fertilization is taken into account, these negative effects are "fully compensated for in wheat and soybean, and mitigated by up to 90% for rice and 60% for maize" (Deryng et al., 2016, p.787). They conclude that rising atmospheric CO_2 can ultimately provide opportunities to increase food production to meet population growth without straining water resources, particularly in semi-arid and arid regions with rainfed crops.

Long et al. (2006) investigated the theoretical maxima of yields, finding that the remaining avenue for further yield improvements exists through photosynthesis. They found that the best means of increasing leaf photosynthesis was through elevated CO_2, although their research indicated that, as temperature rose, CO_2 uptake seemed to change. For example, they found that the existence of a tipping point in gross canopy CO_2 uptake with respect to temperature for C_3 crops occurs just above 20°C (Long et al., 2006, Figure 3). This tipping point does not seem to occur in C_4 crops, an advantage that such crops would have over C_3 crops.

Free-air carbon enrichment (FACE) field experiments were developed as a result of suspected bias from experiments that do not reflect field conditions (Hendry et al., 1993), as is the case with controlled environment, closed-top and other laboratory studies (Kimball et al., 1995). Conclusions drawn from enclosed (‘glasshouse’) experiments are not always convincing, which led to the development of open-field FACE experiments that achieve artificial levels of elevated CO_2 by a state-of-the-art system. The system measures the concentration of CO_2 within an open-field plot, releasing CO_2 as required from an on-site tank; release of CO_2 is based on the direction and speed of the wind as measured by a weathervane at the center of the plot (Hendry et al., 1993). When the wind is blowing toward the north, for example, the computer releases CO_2 from the south end of the array so that it blows over the entire array. The computer automatically shuts off the CO_2 using an infra-red gas analyzer after the target level is achieved. Air temperatures are also continually recorded, allowing analysis of both temperature and CO_2 effects. Hendry et al. (1993) demonstrate how closely and non-invasively the FACE experiments replicate field conditions. An additional benefit of the FACE experiments is their ability to compare wet and dry conditions at ambient and elevated levels of CO_2, thereby providing insights into how water resources might be constraining under future climate scenarios.

The implications of an increasing concentration of atmospheric CO_2 are important for food security, where much of the conversation focuses on global warming. This is especially important for developing countries located in arid regions where crop yield efficiencies are lower, and water is scarcer than in developed countries. In the current study, therefore, meta-regression analysis of these experiments that have examined crop yields under elevated CO_2 at different temperatures is used to identify the effect that higher temperatures and enhanced CO_2, and their interaction, might have on crop yields.

2. METHODS: META-REGRESSION ANALYSIS AND CROP YIELDS

This study utilizes meta-regression analysis “to summarize a set of related studies” in the crop science literature (Card & Krueger, 1995). There are several reasons why a meta-regression analysis differs somewhat from a simple meta-analysis. One feature of meta-regression analysis is that the outcome variables, crop yields in our case, tend to be correlated within studies due to experimental conditioning and uncorrelated with the yields found in other studies. One way to overcome this specific form of dependence is to adopt a robust variance estimator for cluster-correlated data (Williams, 2000). Thus, the standard errors are clustered at the study level, which allows for correlation among observations within studies (an artefact of the experimental setting), while assuming independence between observations from different studies. This provides robust standard errors under the assumption that unobservable factors in inter-cluster observations are independent.

2.1 Data Sources and Description

We developed a dataset consisting of information from 47 studies completed between 1977 and 2016 and comprising 495 observations. This was done by systematically searching Google Scholar and Science Direct using keywords such as ‘elevated CO_2’, ‘crop yields’, and ‘FACE’, and selected published articles that sought to test plant yields at ambient and elevated levels of CO_2. We also examined references in published articles to discover additional sources of data.

One concern with the methodology used in this paper is the coverage of studies. Our intention was to have sufficient observations to establish the effect that CO_2 and heat (temperature) have on crop yields; however, we did not conduct a comprehensive analysis of the current scientific literature. The reason is that the current economic study concerns the aforementioned relationship between crop yields, CO_2 and heat, as opposed to a summary of the current literature on crop yields under elevated CO_2.

For each study in our analysis, crop yields are recorded in tonnes per hectare (t/ha) or grams per plant (g/plant), CO_2 in parts per million (ppm) by volume, the average growing-season temperature in degrees Celsius (°C), experiment by type, and the year of the study. When a study contained day and night temperatures, an average weighted by the reported day/night schedule is taken, or, when only maximum and minimum temperatures were reported, a simple average. The location in which each experiment was undertaken was found and recorded in terms of longitude and latitude. There were six types of experiments: (1) Free Air Carbon Enrichment (FACE) studies and studies that employed (2) controlled-environment chambers, (3) closed- and (4) open-top chambers, (5) glasshouse, and (6) field experiments. FACE studies were discussed earlier; controlled-environment chambers are large boxes using a combination of mylar walls and a thin, clear top made of cellulose acetate (Baker et al., 1989); closed-top chambers are typically clear, plastic, enclosed chambers that are exposed to natural sunlight; open-top chambers, the most frequent in our dataset, are essentially closed-top chambers without a top that are placed in fields to allow exposure to the true environment in which crops are grown; glasshouse studies are essentially crops grown in greenhouses; field experiments are when crops are grown and observed in natural field conditions. Crop data were collected from four regions: North America, Europe, Asia and Oceania. Spring wheat and winter wheat are assumed to be synonymous when collecting data as the two are often identical cultivars that are simply planted at different times of the year; further, the yields measured from studies reporting winter wheat and spring wheat are not statistically different (see Supplementary Material, Figure S2).

Summary statistics for studies that measured yields in t/ha and g/plant are reported in Tables 1 and 2, respectively. Naturally, yields vary between crops, with rice yields much higher than those of other crops. Variations in CO_2 and recorded temperatures were ideal for the identification strategy. The means that all dummy variables (which took on a value of 1 if the control was present and 0 otherwise) represent the proportion of studies belonging to the category in question. For example, a mean of 0.208 for Europe in Table 1 indicates that 20.8% of t/ha studies were conducted in Europe; a mean of 0.365 for rice indicates that 36.5% of t/ha studies involved rice. One study subjected crops to extreme temperatures and a concentration of CO_2 of 10,000 ppm. There were no FACE studies that reported yields in g/plant (Table 2). The magnitude of yields when measured in g/plant appear much higher than yields in t/ha, but the two measures are not directly comparable nor are the experiments conducted using these measures of yield.

Table 1: Summary Statistics for Studies that Measure Yields in tonnes per hectare, N=293

Variables	Mean	Sd	min	max
Yield (t/ha)	6.246	3.107	0.38	14
CO_2 (ppm)	495.631	146.640	140	1000
Temperature (°C)	20.953	6.280	9	34.1
Year of study	1997.669	9.714	1977	2016
Asia	0.464	0.500	0	1
Europe	0.208	0.407	0	1
North America	0.181	0.386	0	1
Oceania	0.147	0.354	0	1
Maize	0.0922	0.290	0	1
Rice	0.365	0.482	0	1
Soybean	0.0512	0.221	0	1
Wheat	0.491	0.501	0	1
Free Air Carbon Enrichment	0.137	0.344	0	0
Closed-top chamber	0.184	0.388	0	1
Controlled-environment chamber	0.119	0.325	0	1
Field study	0.024	0.153	0	1
Glasshouse	0.099	0.299	0	1
Open-top chamber	0.437	0.497	0	1

Major inputs such as nitrogen, phosphate and potassium were not measured nor reported in the vast majority of the studies examined, with the information on these omitted variables relegated to the error terms. The lack of data on these confounding factors introduces bias into our results, which should be considered. Moving forward the assumption that adequate levels of plant nutrients is made, although this assumption is questionable as there surely exists heterogeneity with respect to growing conditions that cannot be controlled for. The location reported in each study is used to control for variations in yield related to biogeographical differences other than temperature. When location was not specified, the midpoint latitude-longitude coordinates of the country in which the study was published is used. There was an attempt to collect precipitation/irrigation data, but surprisingly few studies reported this information, although it is redundant in the case of paddy rice grown in flooded fields. Further, studies that measured only biomass or the number of grains are ignored, relying exclusively on studies that examined how crop yields responded to changes in atmospheric CO_2 and temperature. This allows the potential damage to the agricultural sector attributable to climate change to be estimated.

Table 2: Summary Statistics for Studies that Measure Yield in grams per plant, N=202

Variables	Mean	Sd	min	max
Yield (grams/plant)	46.037	58.993	0	336.760
CO_2 (ppm)	535.673	157.590	160	1000
Temperature (°C)	23.366	5.928	14	33
Year of study	1996	6.399	1981	2013
Asia	0.317	0.466	0	1
Europe	0.218	0.414	0	1
North America	0.421	0.495	0	1
Oceania	0.0446	0.207	0	1
Maize	0.0297	0.170	0	1
Rice	0.342	0.475	0	1
Soybean	0.243	0.430	0	1
Wheat	0.386	0.488	0	1
Closed-top chamber	0.0149	0.121	0	1
Controlled-environment chamber	0.396	0.490	0	1
Field study	0.0446	0.207	0	1
Glasshouse	0.228	0.420	0	1
Open-top Chamber	0.317	0.466	0	1

White's (1980) test for homoskedasticity indicated evidence of hetero-skedasticity in the data. To correct for heteroskedasticity, we adopted robust standard errors clustered by study for all models. Data sources are reported in Table 3. We omit four of the six observations from Reuveni and Bugbee (1997) as they conducted experiments at extreme levels of CO_2 (up to 10,000 ppm), and are thus treated as outliers; indeed, observations where CO_2 exceeded 1,000 ppm are omitted from further consideration as they do not provide a meaningful contribution to the present analysis.

Table 3: Data Sources for Elevated CO_2 Experiments[a]

Study	# of Obs	Location	Crop	Mean yield	Units	CO_2	
						Min	Max
Abebe *et al.* (2016)	12	India	Maize	4.99	t/ha	397	550
Allen Jr. *et al.* (1995)	23	U.S.	Rice	5.62	t/ha	330	660
Baker (2004)	38	U.S.	Rice	12.46	g/pl	358	705
Baker *et al.* (1990)	6	U.S.	Rice	2.28	g/pl	160	900
Baker *et al.* (1992)	4	U.S.	Rice	6.33	t/ha	330	660
Baker *et al.* (1989)	6	U.S.	Soybean	11.07	g/pl	330	660
Batts *et al.* (1998)	22	U.K.	Wheat	8.53	t/ha	365	698
Bugbee *et al.* (1994)	10	U.S.	Wheat & rice	5.82	t/ha	340	680
Conroy *et al.* (1994)	9	Australia	Wheat	23.86	g/pl	350	900
Fiscus *et al.* (1997)	12	U.S.	Soybean	156.3	g/pl	360	700
Gifford (1979)	16	Australia	Wheat	4.61	t/ha	340	590
Gifford (1997)	3	Australia	Wheat	9.7	t/ha	140	490
Heagle *et al.* (2000)	18	U.S.	Wheat	12.74	g/pl	379	707
Kimball *et al.* (1995)	4	U.S.	Wheat	7.63	t/ha	370	550
Manderscheid & Weigel (1995)	6	Germany	Wheat	25.83	g/pl	372	539
Manderscheid & Weigel (1997)	12	Germany	Spring wheat	16.46	g/pl	379	689
Mayeux *et al.* (1997)	8	U.S.	Wheat	1.69	t/ha	200	350
McKee & Woodward (1994)	16	U.K.	Wheat	2.66	g/pl	400	700
Meng *et al.* (2014)	6	China	Maize	291.72	g/pl	390	550
Moya *et al.* (1998)	36	Philippines	Rice	4.80	t/ha	370	665
Mulholland *et al.* (1997)	6	U.K.	Spring wheat	7.05	t/ha	379	700
Mulholland *et al.* (1998)	6	U.K.	Spring wheat	9.60	t/ha	384	682
Otera *et al.* (2011)	24	Japan	Soybean	39.98	g/pl	389	589
Pleijel *et al.* (2000)	11	Sweden	Spring wheat	5.88	t/ha	347	675
Prasad *et al.* (2005)	3	U.K.	Soybean	18.25	g/pl	160	660
Qiao *et al.* (2019)	30	China	Soybean & maize	5.92	t/ha	394	705
Rawson (1995)	24	Australia	Wheat	7.52	t/ha	360	700
Reuveni & Bugbee (1997)	6	Israel	Wheat	7.63	t/ha	350	10,000
Rudorff *et al.* (1996)	6	U.S.	Wheat & maize	5.20	t/ha	350	500
Sionit *et al.* (1981)	3	U.S.	Wheat	33.03	g/pl	350	1000
Teramura *et al.* (1990)	12	U.S.	Wheat-rice-soybn	45.79	g/pl	350	650
van Oijen *et al.* (1999)	8	Nederland	Spring wheat	7.19	t/ha	373	754
Wang *et al.* (2018)	8	China	Rice	10.23	t/ha	390	590
Weigel *et al.* (1994)	10	Germany	Wheat	27.41	g/pl	384	718
Wheeler *et al.* (1996)	8	U.K.	Wheat	7.87	t/ha	380	713
Xiao *et al.* (2005)	13	China	Spring wheat	1.25	t/ha	360	450
Xiao *et al.* (2009)	7	China	Spring wheat	2.17	t/ha	364	404
Yang *et al.* (2006)	16	China	Rice	10.12	t/ha	383	583
Zhang *et al.* (2015)	12	Japan	Rice	7.08	t/ha	379	585
Ziska *et al.* (1996)	34	Philippines	Rice	68.94	g/pl	373	664

[a] Units indicate tonnes per hectare (t/ha) or grams per plant (g/pl).

All studies in the sample reported yields in elevated CO_2 on the treatment plot and on the control plot. The treatment and control results are recorded as two separate observations; thus, for a study that reports on four experiments, there would be eight observations. Many studies have just one control variable upon which they report and many more observations of yields for various levels of CO_2. In the analysis, maize is not considered for lack of data points (9% of ton/ha and <3% of g/plant studies). Further, only wheat and rice studies that measure yields in ton/ha and soybean studies that measure yields in g/plant are used as these constitute a reasonable number of observations for the present analysis. The rest of the data collected here serves the purpose of expanding current data collection and making more crop experiments readily available to readers.

2.2 Regression Model

Serial autocorrelation is not an issue because these are not studies that provide measures of yield over time, but, rather, measures of yields from different studies conducted at different times. The variability in yield from one year to the next is negligible under controlled conditions, as it would only be affected by technological advancements such as new and improved cultivars; but, year dummies are used to account for time-related fixed effects. This implies that the yield of a study in a particular year is likely uncorrelated with other studies in previous years. Further, the model is estimated using the natural logarithm of yields as the dependent variable. This is done to allow a better interpretation of the results and because yields are log-normally distributed (Lobell & Field, 2011). Quadratic terms are not explored as the data do not cover a sufficient range of effects between CO_2 and temperature (see Supplementary Material). The shortcoming of this approach is that linear marginal effects are imposed which may misrepresent the true underlying relationship—this is left to future research.

The regression model takes the following form:

$$\log(Y_i) = \beta_0 + \beta_1 \, CO2_i + \beta_2 \, T_i + \beta_3 \, T_i \times CO2_i + \boldsymbol{\alpha}_1 \, \mathbf{Ty}_i + \alpha_2 \, \mathrm{Yr}_i + u_i, \tag{1}$$

where Y_i measures the crop yield from observation i in t/ha or g/plant; $CO2_i$ and T_i measure, respectively, the carbon dioxide level and temperature (ºC) employed in observation i; $\mathbf{Ty}_i$ is a vector of dummy variables containing the types of experiments; Yr_i is the year in which a particular experiment is undertaken; and β_i and $\boldsymbol{\alpha}_i$ are, respectively, coefficients and vectors of coefficients to be estimated. Finally, the error structure is represented by u_i.

The interaction effect is included to test how the CO_2-fertlization effect varies with temperature, which allows interpretation of the marginal effects as follows:

$$\frac{\partial Y}{\partial CO_2} = \beta_1 + \beta_3 T_i \tag{2}$$

$$\frac{\partial Y}{\partial T} = \beta_2 + \beta_3 CO2_i \tag{3}$$

Upon estimating regression equation (1), the estimated parameter β_3 enables analysis of the interaction effect on marginal crop yields using equations (2) and (3).

The regression models are estimated separately for each crop. Wheat and rice yields are measured in t/ha whereas soybean is measured in g/plant. This analysis does not convert the g/plant observations to t/ha for consistency as doing so requires knowledge of sowing density, plant survival rates, et cetera.

The model is estimated using ordinary least squares (OLS) regression with cluster-robust standard errors for all specifications. Standard errors are clustered at the study level to allow for correlation between observations within the same study with the assumption of independence across studies. This makes sense in the context of the present analysis as observations from the same study are held at the same conditions with respect to irrigation, solar irradiance, the chemical composition of the air and soil, location, and other factors.

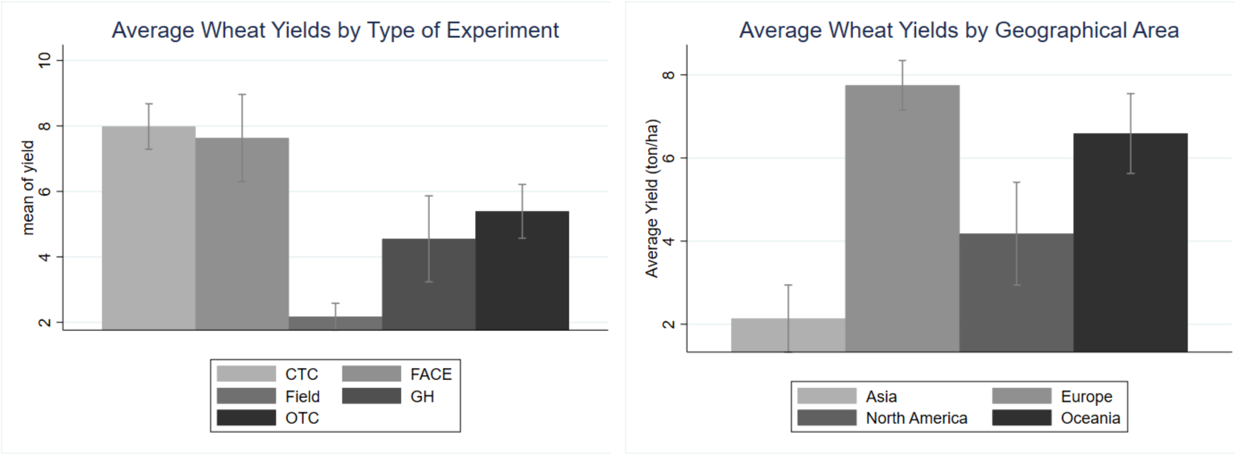
3. RESULTS

3.1 Data Analysis

In this section, differences in crop yields between types of experiments are explored to determine whether there exist systematic differences in outcomes between certain experimental settings. Differences attributable to geographical areas are also explored. Average yields in experiments using Closed-Top Chambers (CTC), fields, FACE, glass house (GH), Open-Top Chambers (OTC), and Closed-Environment Chambers (CEC) are examined.

Wheat yields by type of experiment are summarized in Figure 1(a). FACE studies are systematically higher than GH and OTC studies. Wheat yields in FACE studies are not statistically different than those from CTC studies. Both FACE and CTC yields are higher than in other non-

FACE field studies by a factor of nearly four. Since field studies do a poor job of facilitating an elevated CO_2 scenario, the result that FACE studies result in higher yields is expected.



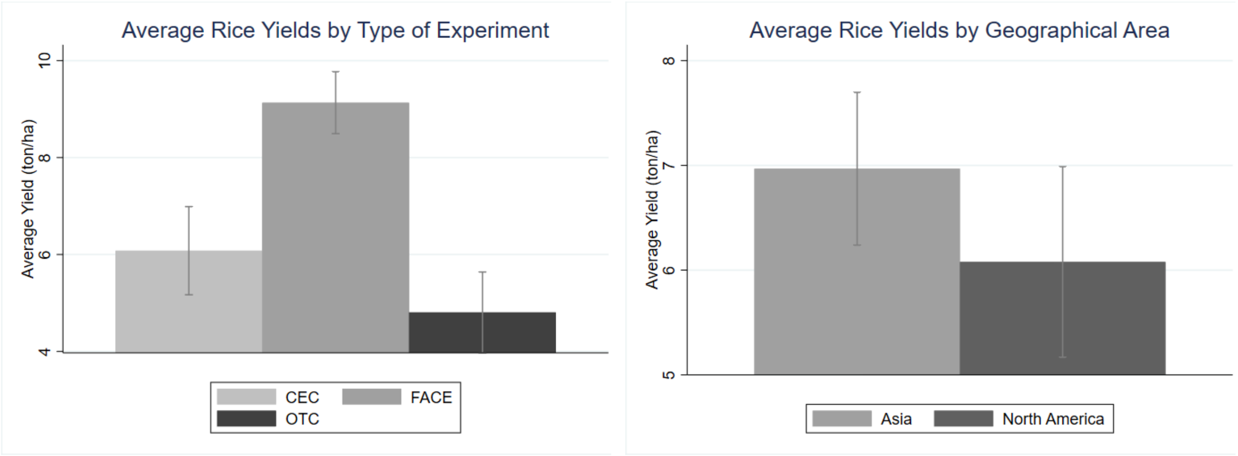
(a) (b)

Figure 1: Wheat Yields by (a) Type of Experiment and (b) Geographical Area, ton/ha, 95% confidence interval

Wheat yields by geographical region are summarized in Figure 1(b). European experiments report systematically higher results for wheat yields than Asian and North American experiments at the 1% level of significance. European and Oceanian experiments are not statistically different at the 5% level of significance.

Rice yields by type of experiment are summarized in Figure 2(a). FACE studies are systematically higher (at the 5% level of significance) than those from CEC and OTC studies. CEC studies report higher yields on average compared to OTC studies; this is consistent with the narrative that CEC studies overestimate the impact of CO_2-fertilization due to unrealistic conditions that OTC studies address. However, contrasting OTC and CEC studies with FACE studies, which are state-of-the-art in replicating field conditions under elevated CO_2, we get a different story.

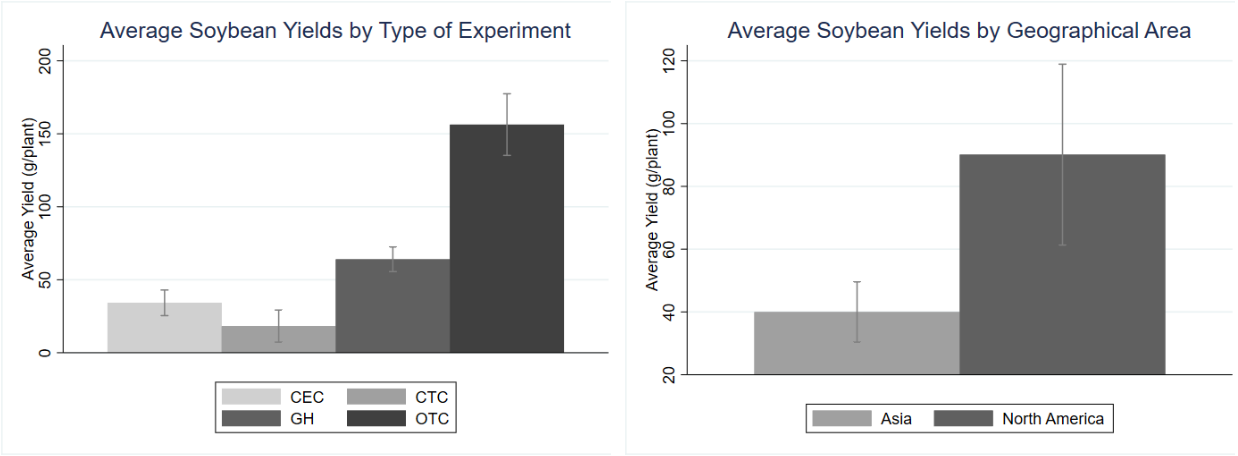
Rice yields by geographical area are summarized in Figure 2(b). Experiments for rice were only conducted in Asia and North America, which constitute the largest producing regions of rice. Asian rice yield experiments report, on average, higher yields than North American studies. This difference is not statistically significant, however.



(a) (b)

Figure 2: Rice Yields by (a) Type of Experiment and (b) Geographical Area, ton/ha 95% confidence interval

Finally, soybean yields by type of experiment are summarized in Figure 3(a). OTC studies yield substantially higher crop yields than the other three types of experiments. Exposing soybean crops to the elements, a better representation of field conditions, appears to have positive effects on crop growth. This implies that constraints imposed on soybean experiments have biased results downwards. Soybean yields by geographical area are provided in Figure 3(b). Studies conducted in North America report soybean yields that are, on average, more than twice as large, even when they use the same cultivar. This difference is statistically significant at the 5% level of significance.



(a) (b)

Figure 3: Soybean Yields by (a) Type of Experiment and (b) Geographical Area, g/plant, 95% confidence interval

3.2 Regression Results

Regression results for wheat, rice, and soybean are provided in Tables 4 through 6. Crop yields are regressed on CO_2, temperature, the interaction between CO_2 and temperature, type of experiment, and the study year using OLS with heteroskedasticity-robust standard errors clustered at the study level. Full model specifications are used in each calculation of the marginal effects.

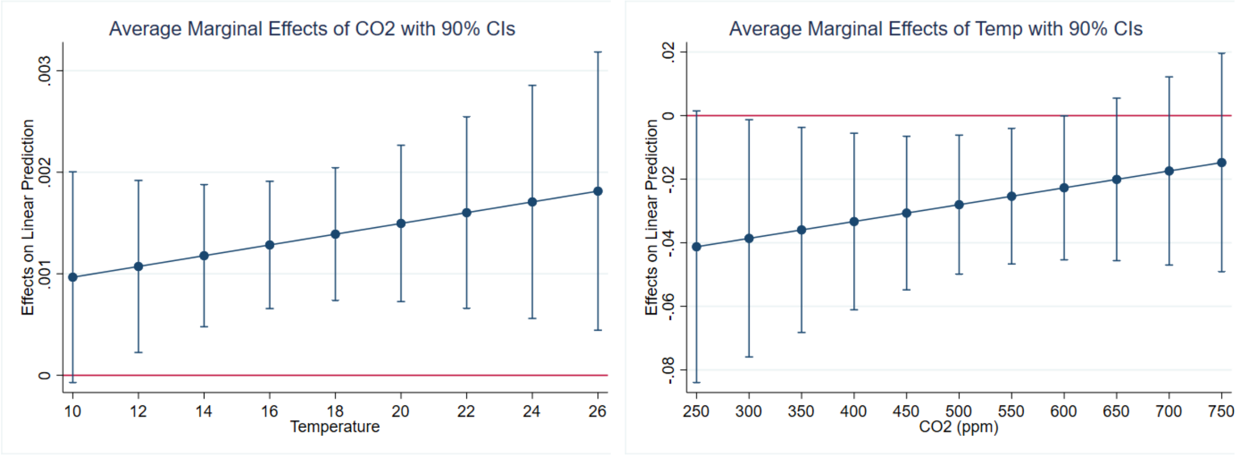
Table 4: Regression Results for Wheat[a]

Dependent Variable: Log(Yield)	No Controls (1)	No Controls (2)	Controls (1)	Controls (2)	Controls+Year (1)	Controls+Year (2)
CO_2	0.00184**	-0.00018	0.00146**	-0.000340	0.00135**	0.000436
	(-3.54)	(-0.10)	(3.09)	(-0.27)	(3.47)	(0.35)
Temp	-0.0407	-0.0982	-0.0275	-0.0809	-0.0274*	-0.0545
	(-1.51)	(-1.46)	(-1.89)	(-1.67)	(-2.27)	(-1.33)
CO_2 × Temp		0.000116		0.000104		0.0000530
		(-1.22)		(-1.37)		(0.73)
Field			-1.257***	-1.264***	-0.4.01	-0.423
			(-21.70)	(-21.41)	(-0.78)	(-0.79)
CTC			-0.301*	-0.324*	-0.289**	-0.301**
			(-2.33)	(-2.45)	(-3.86)	(-3.65)
GH			-0.875***	-0.861***	-1.575**	-1.552**
			(-4.61)	(-5.33)	(-3.28)	(-3.11)
OTC			-0.800*	-0.829*	-0.562**	-0.582**
			(-2.33)	(-2.42)	(-2.98)	(-3.05)
Year					-0.0720	-0.0704
					(-1.67)	(-1.58)
Constant	1.370*	2.383*	1.966***	2.912**	145.5	142.8
	(2.10)	(1.84)	(5.44)	(3.27)	(1.70)	(1.61)
N	144	144	144	144	144	144
adj. R^2	0.213	0.220	0.339	0.344	0.450	0.448

[a] FACE is the excluded dummy variable; t-statistics are provided in parentheses with * $p<0.05$ ** $p<0.01$ and ***$p<0.001$. CTC=Closed-top Chamber; GH=Glasshouse; OTC=Open-top Chamber.

In the regressions, there is no separate dummy variable for FACE studies, which implies that the experimental dummy variables are to be interpreted relative to the FACE group. Standard field studies report wheat yields that are 1.257 t/ha lower than FACE studies on average; the difference is statistically significant at the 0.1% level. Further, all of CTC, GH, and OTC studies report lower wheat yields, but to a lesser extent than field studies. These differences are all statistically significant at the 5% level, except for GH which is significantly lower than FACE studies at the 0.1% level of significance. Further, in specifications Controls+Year (1), the inclusion of a variable controlling for the year in which a study is done renders temperature negative and statistically significant at the 5% level. In Controls+Year (1), CO_2 is positive and statistically significant at the 1% level of significance with a coefficient similar of that of No Controls (1) and Controls (1). In this specification, field studies are not statistically different than FACE studies, although all of CTC, GH, and OTC studies are statistically lower at the 5% level of significance. Adding the interaction term in the Controls+Year (2) specification renders the CO_2 term statistically insignificant and close to zero.

The inclusion of the interaction term makes it impossible to compare outcomes to specifications that do not include an interaction term, so one must look at marginal effects to assess these results properly. The marginal effects for wheat are estimated in Figure 4 below. The marginal effects shown are based on the Controls+Year (2) specification to see how the CO_2 (temperature) marginal effect varies with temperature (CO_2).



(a) CO_2-fertilization *(b) Temperature*

Figure 4: Marginal Effects for Wheat, 90% confidence interval

There is a clear positive CO_2-fertilization effect for wheat as shown in Figure 4(a). The positive interaction effect between CO_2 and temperature implies that CO_2 is more effective at amplifying yields at higher temperatures. At 12°C (20°C), a 100ppm increase in CO_2 is approximately associated with a 10% (15%) increase in wheat yields. The CO_2-fertilization effect appears to be more effective at higher temperatures. There are negative impacts from temperature shown in Figure 4(b) as expected. These impacts appear to dissipate with rising CO_2, suggesting a potential compensating effect from rising CO_2. At 400ppm (600ppm) atmospheric CO_2 concentration, a 1°C increase in temperature is approximately associated with a 3.5% (2.5%) reduction in wheat yields. Wheat damages from temperature are lower at higher CO_2 concentrations, and not different from zero beyond 600ppm CO_2.

In the No Controls (1) specification in Table 5, there is a positive, statistically insignificant CO_2 term and a negative temperature term that is statistically significant at the 1% level. Upon adding the interaction effect in the No Controls (2) specification, the positive CO_2 term becomes statistically significant at the 5% level, while temperature remains negative but statistically insignificant; their interaction remains negative and statistically insignificant. Upon adding dummy variables for type of experiment in the Controls (1) specification, CO_2 is positive and statistically significant at the 5% level of significance and temperature is negative and statistically significant at the 10% level. Further adding a variable controlling for the year of study in Controls +Year (1) leads to a larger negative coefficient on temperature as well as rendering it statistically significant at the 1% level of significance over the specification without year. The coefficient on CO_2 is relatively unchanged and remains statistically significant at the 5% level of significance.

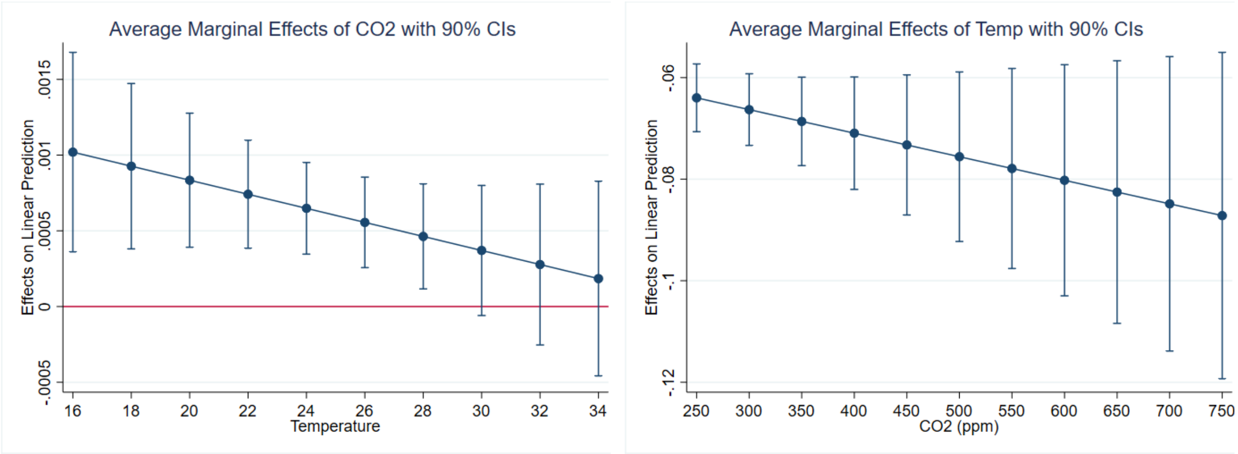
Looking at the final specification, Controls + Year (2), CO_2 is positive and yet not quite statistically significant, temperature is negative and statistically significant at the 1% level, and the interaction term is negative and not statistically significant. The coefficient on the CO_2 term is 25% lower than the estimate obtained from the Controls (2) regression with no year variable. This suggests that without controlling for year, the model overestimates the CO_2-fertilization effect.

Table 5: Regression Results for Rice[a]

Dependent Variable: Log(Yield)	No Controls (1)	No Controls (2)	Controls (1)	Controls (2)	Controls+Year (1)	Controls+Year (2)
CO_2	0.000325	0.00187*	0.000511*	0.00237	0.000524*	0.00176
	(1.54)	(2.77)	(2.90)	(2.12)	(3.02)	(2.08)
Temp	-0.0713**	-0.0425	-0.0498	-0.0150	-0.0763***	-0.0524**
	(-4.35)	(-2.18)	(-1.97)	(-0.63)	(-8.23)	(-5.60)
CO_2 × Temp		-0.0000579		-0.0000694		-0.0000464
		(-2.24)		(-1.64)		(-1.40)
CEC			-0.292	-0.296	-0.623	0.596
			(-1.28)	(-1.32)	(-1.63)	(1.60)
OTC			-0.515*	-0.519*	-0.435*	0.1667
			(-2.21)	(-2.58)	(-2.01)	(0.92)
Year					0.0444**	0.0432
					(2.49)	(2.42)
Constant	3.432***	2.667***	2.756***	2.126**	-84.87*	-83.79
	(9.32)	(7.42)	(3.78)	(4.72)	(-2.39)	(-2.34)
N	107	107	107	107	107	107
adj. R^2	0.281	0.277	0.358	0.356	0.387	0.383

[a] See note for Table 4. CEC=Controlled-environment Chamber; OTC=Open-top Chamber.

Now the magnitude and interpretation of marginal effects given the inclusion of the interaction effect are examined. The marginal effects for rice are plotted in Figure 5 computed using the Controls+Year (2) specification. Looking at Figure 5(a), a 100ppm increase in CO_2 at 16°C (28°C) is associated with a 10% (5%) increase in rice yields. Further, a 200ppm increase in CO_2 at 16°C (28°C) is associated with a 20% (10%) increase in rice yields. The marginal CO_2-fertilization effect for rice is clearly less effective at higher temperatures, and not statistically different from zero at the 10% level of significance beyond 28°C, which is problematic for developing countries located in semi-arid climates. A 1°C increase in temperature at 400ppm (600ppm) atmospheric CO_2 is associated with a 7% (8%) reduction in rice yields. A 2°C increase in temperature at 400ppm (600ppm) atmospheric CO_2 is associated with a 14% (16%) reduction in rice yields. This effect is statistically significant at the 1% level for all values of CO_2.



(a) CO_2-fertilization *(b) Temperature*

Figure 5: Marginal Effects for Rice, 90% confidence interval

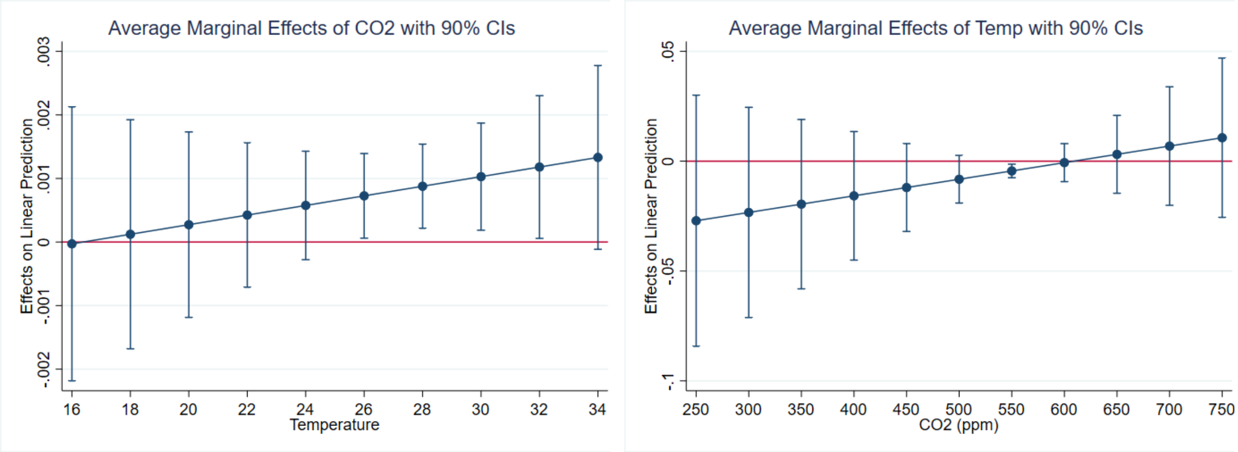
In the No Controls (1) specification in Table 6, there are positive CO_2 and temperature terms that are not statistically different from zero. In the No Controls (2) specification with the interaction term, none of the terms are statistically significant, CO_2 and temperature are negative, and the interaction term is positive. Upon adding dummy variables for type of experiment in Controls (1), CO_2 is remains statistically insignificant and the coefficient is halved; temperature becomes statistically significant at the 5% level. Adding the interaction term to this model in Controls (2) makes the temperature term statistically significant at the 1% level. Adding the study year to the regression in the Controls+Year (1) specification leaves the coefficient on CO_2 unchanged over the specification without the year variable and does not change the lack of statistical significance. Adding the interaction term in the Controls+Year (2) specification renders all variables statistically insignificant.

Without controlling for the year of the study, the CTC, GH and OTC studies lead to yields that are systematically higher than those for FACE studies. Controlling for year, the CTC, GH and OTC studies report average soybean yields that are 0.57 t/ha higher, 1.51 t/ha higher and 2.20 t/ha higher, respectively, than yields from FACE studies. These coefficients suggest that over-estimation of yield responses from these studies are a result of the experimental setting. To fully analyze the meaning behind these results, the marginal effects are computed using the final specification, Controls+Year (2). These marginal effects are plotted in Figure 6.

Table 6: Regression Results for Soybean[a]

Dependent Variable: Log(Yield)	No Controls (1)	No Controls (2)	Controls (1)	Controls (2)	Controls+Year (1)	Controls+Year (2)
CO_2	0.00158	-0.00337	0.000727	-0.00129	0.000753	-0.00124
	(2.52)	(-0.84)	(2.05)	(-0.62)	(2.13)	(-0.52)
Temp	0.0599	-0.0325	-0.0704*	-0.108**	-0.00896	-0.0460
	(0.55)	(-0.30)	(-3.02)	(-6.64)	(-1.47)	(-0.95)
CO_2 × Temp		0.000187		0.0000767		0.0000756
		(1.22)		(0.99)		(0.86)
CTC			-0.121	-0.115	0.568***	0.574***
			(-0.45)	(-0.45)	(15.84)	(17.21)
GH			0.970**	0.972**	1.508***	1.510***
			(5.36)	(5.36)	(717.51)	(665.82)
OTC			2.078**	2.074**	2.209***	2.204***
			(7.92)	(7.60)	(69.65)	(88.15)
Year					0.0448***	0.0448***
					(72.95)	(81.34)
Constant	1.395	3.832	4.531***	5.520***	-86.74***	-85.75***
	(0.56)	(1.56)	(13.53)	(8.62)	(-58.05)	(-36.04)
N	49	49	49	49	49	49
adj. R^2	0.035	0.019	0.541	0.531	0.592	0.583

[a] See note on Table 4. CTC=Closed-top Chamber; GH=Glasshouse; OTC=Open-top Chamber.



(a) CO_2-fertilization *(b) Temperature*

Figure 6: Marginal Effects for Soybean, 90% confidence interval

Looking at Figure 6(a), the CO_2-fertilization effect appears to be non-existent for soybean, although this may be a result of the statistical approach. Although between 24ºC and 32ºC, the effect is positive and statistically significant at the 10% level of significance. An increase of 100ppm in atmospheric CO_2 at 30ºC is associated with a 10% increase in soybean yields, although this effect is not different from zero for temperatures below 26ºC and above 34ºC. Further, this effect seems to be relatively insensitive to changing temperatures compared to the situation for wheat and rice. From Figure 6(b), soybean yields appear to be temperature invariant; the only marginal temperature effect that is significant at the 10% level is at 550ppm atmospheric CO_2, but the effect is very small, with a 1ºC increase in temperature associated with a <1% decrease in yields.

4. DISCUSSION

Current research on climate change focuses on the negative impact that climate change will have on crop yields. What seems to be downplayed are the windfall gains from rising atmospheric CO_2—the CO_2-fertilization benefits. CO_2-fertilization has clear, positive impacts on wheat and rice yields as indicated by the studies explored in this analysis. The benefits to wheat increase with temperature, while, for rice, they decrease with temperature and become statistically insignificant beyond a threshold of 28ºC. Rising temperatures are damaging to wheat yields, although this negative effect is mitigated beyond atmospheric CO_2 levels of 600ppm, hinting at a potential compensatory effect. For rice, temperature unambiguously reduces crop yields, and, in this study, the damage is found to be greater at higher levels of CO_2. This may be an artefact of the statistical approach as it does not impose structural interpretations on the model and this is likely due to the nature of the relationship between CO_2 and temperature. For example, the model does not account for how CO_2 may impact how a plant responds to temperatures and vice versa. Soybean yields were found to be largely unaffected by CO_2 and temperature.

Overall, yields of some major crops are likely to increase within the range of CO_2 concentrations and temperatures projected by the IPCC (2018). What is ignored, however, are potential technological changes due to new crop varieties, use of enhanced farm management techniques (e.g., drones that identify infestations of weeds within a field and target herbicide applications), and, importantly, yield increases and other potential benefits from genetic engineering. There will be genetic modifications that tailor new species of crops to the changing climate and allow for further improvement in yields.

Recent research finds that the CO_2-fertilization effect may be 50 percent larger than previously thought (Haverd et al., 2020). Further, Allen et al. (2020) indicate that the CO_2-fertilization effect found in FACE studies may increase yields by 1.5 times more than originally indicated due to the irregular fluctuation experienced in these experimental settings relative to what is actually experienced. They state that this adjustment factor is necessary to correct for yield reductions attributable to fluctuating CO_2—for example, in FACE experiments it is challenging to keep the CO_2 concentration constant. In Table 7, this correction factor is applied to the earlier results and contrasted with the temperature results found in this study.

Table 7: CO_2-fertilization and Temperature with Correction Factor

ΔCO_2 = 100ppm	T=12°C	T=20°C
Wheat	10.720%	14.959%
Wheat (with ×1.5 correction)	16.080%	22.439%
	T=16°C	T=28°C
Rice	10.197%	4.630%
Rice (with ×1.5 correction)	15.296%	6.945%
ΔT=1°C	CO_2 = 400ppm	CO_2 = 600ppm
Wheat	-3.331%	-2.272%
	CO_2 = 400ppm	CO_2 = 600ppm
Rice	-7.094%	-8.022%

The benefits from CO_2-fertilization are clear even without the adjustment factor. Applying this factor generates much more optimistic results. Kimball (2016) finds average yield increases of 19% in C3 crops from a 200ppm increase in atmospheric CO_2 concentration, so the results of this analysis suggest a similar CO_2-fertilization effect with only a 100ppm increase when applying the adjustment factor. Asseng et al. (2015) employ a modelling approach exploring temperature responses and find that wheat yields fall by 6% on average for a 1°C increase in temperature, which is lower than the estimate found here at current CO_2 levels (~400ppm) of a 3.3% reduction in yields. The results found in this analysis, compared with others, suggest a more beneficial CO_2-fertilization effect and a less damaging temperature effect.

There is a clear need for more extensive FACE research in different regions of the world. There are a lot of experiments in similar, temperate climates that simply confirm the same facts. If more experiments were conducted in arid and tropical regions, the implications for developing countries could be better recognized and growth opportunities seized. Without high quality research in these regions, the true effect of climate change in developing countries is hard to extrapolate from results based on temperate countries. This is apparent from the heat maps reported in the Supplementary Material (see Figure S1); they show a sheer lack of overlap between deciles of both our CO_2 and temperature data.

Without having more data from varied experiments, the interaction effects of CO_2 and temperature on crop yields are hard to quantify accurately as there is not a complete analysis of these two explanatory variables across different levels. This reinforces the point that more research needs to be devoted to this area so that models can do a better job of quantitatively and qualitatively evaluating the risk that climate change poses for food security.

This research contributes to an expanding literature on the relation between climate change and food security; it also aids future research by providing direct reference to available data. The analysis corroborates other studies' results that have demonstrated the importance of the CO_2-fertilization effect in raising crop yields. It is important for future research to incorporate the biophysical effects from CO_2 within future analyses of food security if damages from climate change are to be adequately assessed. In particular, more research is needed to assess the impact of global warming on crop yields in developing countries, which are likely most at risk from climate change. One possible avenue is to adopt FACE experiments more broadly as they simulate elevated CO_2 under ordinary field conditions. Such experiments are ideal for evaluating the future impacts of rising CO_2 and the potential for mitigating the projected negative effects of higher temperatures.

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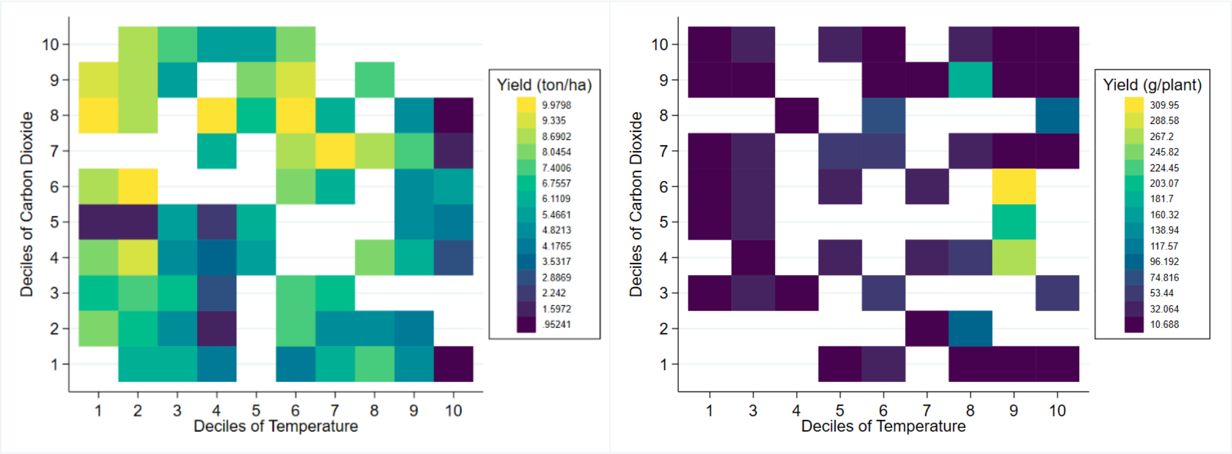
SUPPLEMENTARY MATERIAL

Heat Maps

When we separate levels of CO_2 and temperature into deciles and generate a heat map (Figure S1), we see a severe lack of coverage. This leads us to believe that we cannot accurately interpret the interaction effect between CO_2 and temperature on crop yields as we miss a large portion of the *combinations* between them. This is apparent in the ton/ha data and even more so in the g/plant data.



(a) (b)

Figure S1: Heat Map of (a) ton/ha and (b) g/plant Data Collected

Spring versus Winter Wheat

In the analysis, spring and winter wheat yield data have been combined in the crop-level regressions. From Figure S2, there is no statistical difference between spring and wheat yields when yield is measured in t/ha, but it is questionable if this should be done when yield is measured in terms of g/plant. Winter and spring wheat are (typically) the same cultivar; they are just planted at different times of the year.

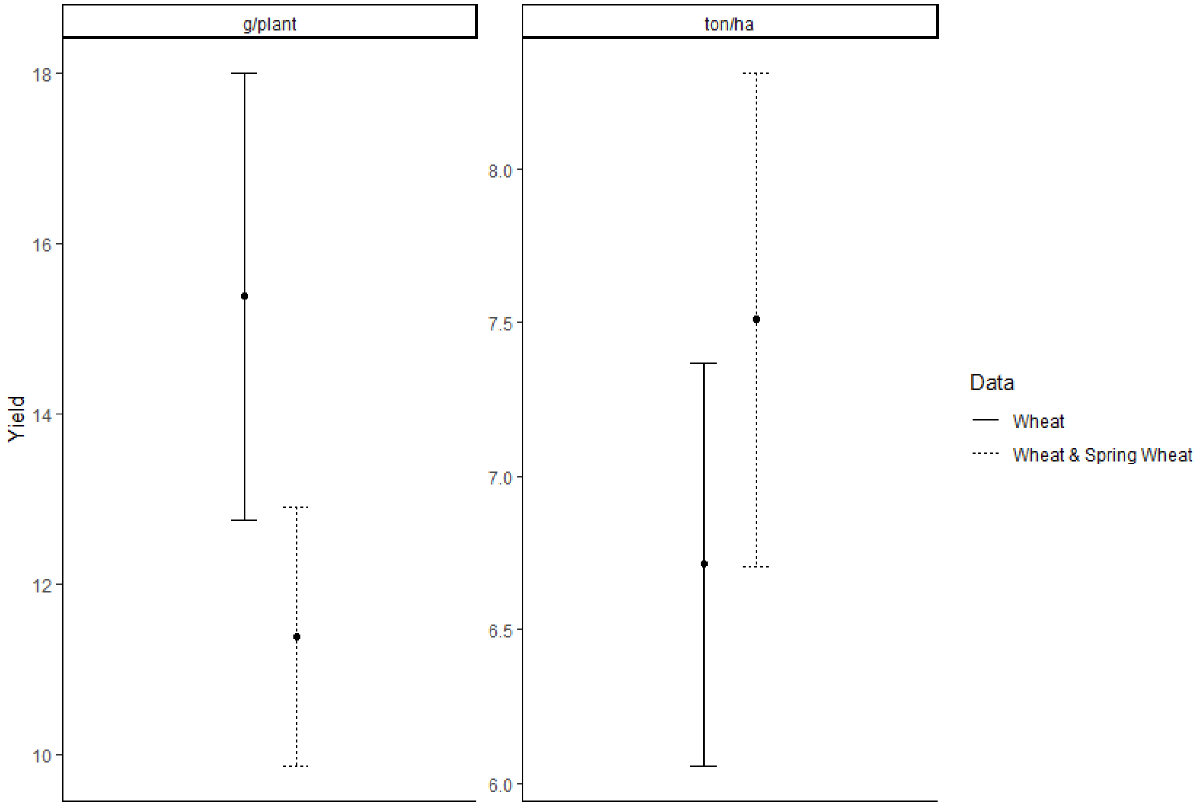


Figure S2: 95% Confidence Intervals for Yields for Wheat (Spring and Winter Wheat Combined)