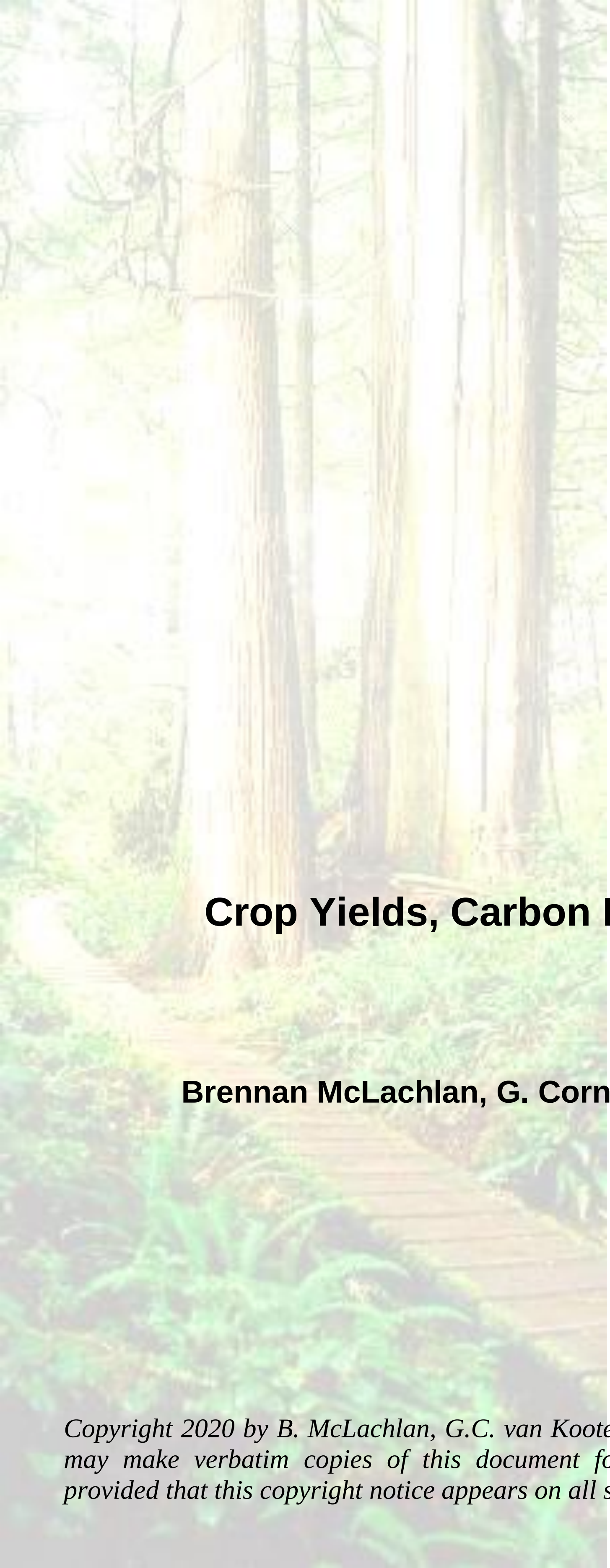

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Crop Yields, Carbon Dioxide, and Temperature: A Meta-Analysis

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Abstract

Food insecurity has been identified as one of the potential dire consequences of climate change. For the most part, the impact of increasing atmospheric CO_2 on crop yields has received much less attention. Higher levels of CO_2 in the atmosphere are associated with increased water efficiency in plants and higher yields. Thus, increased atmospheric CO_2 can serve as a mitigating factor, without which it would be easy to overestimate the negative impacts of rising temperatures. We collect observations from studies that have examined crop yields at elevated levels of CO_2 relative to ambient levels. We then employ meta-regression analysis to explore the effect that CO_2, temperature, and their interactive effects have on crop yields, using control variables to account for other factors such as location, technology, et cetera. We find that raised levels of CO_2 are a significant determinant of crop yields, with a failure to account for a CO_2-fertilization effect potentially leading to an exaggeration of the threat that climate change poses for food security. We also found that there is insufficient information about the impact that CO_2 has on yields in many regions. More regional trials are needed, particularly in arid regions in developing countries where the risk of food insecurity from climate change is greatest.

Key words: Climate change and crop yields; Food security; Meta-regression analysis; CO_2-fertilization and heat effects in agriculture
JEL: Q18, Q54

1. INTRODUCTION

Climate change is one of the most contentious policy issues of the early 21st Century. In December 2015, nations signed the Paris Agreement, which aims “to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change”[1]. Likewise, the U.S. Fourth National Climate Assessment (NCA) fears that “climate change creates new risks and exacerbates existing vulnerabilities in communities across the United States, presenting growing challenges to human health and safety, quality of life, and the rate of economic growth” [2].

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 [3] 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 CO_2 had been considered. 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 parts of the world.

Rising atmospheric CO_2 affects crop yields by increasing the rate of photosynthesis and water-use efficiency. Deryng et al. [4] 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 [5]. 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” [4 p787]. 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.

Free-air carbon enrichment (FACE) field experiments were developed due to biased results from experiments that do not accurately reflect field conditions [6]. Controlled environment, closed-top, and laboratory studies do not reflect typical field settings [7]. Conclusions drawn from enclosed (‘glasshouse’) experiments are not always convincing, which led to the development of open-field exposures. FACE experiments get around the ‘realism’ problem by conducting experiments at artificial levels of elevated CO_2 where all else is truly equal. This is achieved by a state-of-the-art system that measures the concentration of CO_2 in the plot space and releases CO_2 from an on-site tank based on the direction and speed of wind – measured by a weathervane at the center of the plot [6]. 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. [6] demonstrate how closely and non-invasively the FACE experiments replicate field conditions. The inclusion of control plots (located 100m away from the treatment plots) makes these experiments ideal for measuring the direct impacts of CO_2 enrichment under local climate 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 CO_2 in the atmosphere 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. To concern ourselves with only the negative impacts of global warming would be short-sighted. In the current study, therefore, we conduct a meta-regression analysis of experiments that have examined crop yields under elevated CO_2 at different temperatures to identify the effect that higher temperatures and enhanced CO_2, and their interaction, might have on crop yields.

2. METHODS: META-ANALYSIS IN ECONOMICS

Meta-analysis is the process of collecting data from multiple sources, combining them into one dataset, and identifying patterns across studies. Meta-analyses are typically concerned with questions of consistency across studies. In the present analysis, we use meta-regression analysis to analyse a large dataset to evaluate the effect of climate change on crop yields at the farm level. We utilize meta-regression analysis "to summarize a set of related studies" in the crop science literature [8]. There are several reasons why a meta-regression analysis differs somewhat from a simple meta-analysis.

One feature of meta-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 [9]. Thus, we utilize standard errors 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 inter-cluster observations are independent.

Data Sources and Description

We construct a dataset consisting of information from 47 studies completed between 1977 and 2016, and comprising 514 observations. We systematically searched 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 looked up the references in published articles to discover additional sources of data.

One concern with our methodology is the coverage of studies. We intend for the analysis to have sufficient observations to enable us to establish the effect that CO_2 and heat (temperature) have on crop yields; however, we do not and cannot conduct a comprehensive analysis of the current scientific literature. The reason is that the current economic study concerns the aforementioned relationship between crop yields and 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, we recorded crop yields 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), the type of experiment, and the year of the study. When a study contained day and night temperatures, we took an average weighted by the day/night schedule reported, or, when only a maximum and minimum temperature were reported, a simple average. We determined the location in which each experiment was undertaken and recorded the location in terms of longitude and latitude. There were six types of experiments: Free Air Carbon

Enrichment (FACE) studies and studies that employed laboratory, controlled-environment chambers, closed- and open-top chambers, and glasshouse experiments. Crop data were collected from four regions: North America, Europe, Asia and Oceania. Quadratic terms for CO_2 and temperature, as well as their interaction, were constructed.

Summary statistics for studies that measured yields in t/ha and g/plant are reported in Tables 1 and 2, respectively. Yields vary between crops due to the nature of the harvesting process, with rice yields much higher than those of other crops. The variations in CO_2 and recorded temperatures were ideal for our identification strategy. The means for all dummy variables (indicated by a minimum and maximum of 0 and 1, respectively) represent the proportion of studies belonging to the category in question. For example, a mean of 0.204 for Europe in Table 1 indicates 20.4% 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. We discovered one study that subjected crops to extreme temperatures and a concentration of CO_2 of upwards to 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.

Major inputs such as nitrogen, phosphate and potassium were not measured nor reported in the vast majority of the studies we examined, with the information on these omitted variables relegated to the error terms. We use the location reported in each study to control for variations in yield related to biogeographical differences other than temperature. When location was not specified, we took the country in which the study was published and used its midpoint latitude-longitude coordinates. We attempted 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, we ignored studies that measured biomass or the number of grains, relying exclusively on studies that examined how crop yields responded to changes in atmospheric CO_2 and temperature. This allows us to examine the potential damage to the agricultural sector as a result of climate change.

Table 1: Summary Statistics for Studies that Measure Yields in tonnes per hectare

Variables	N	Mean	Sd	min	max
Yield (t/ha)	299	6.221	3.122	0	14
CO_2 (ppm)	299	553.9	640.0	140	10,000
Temperature (°C)	299	21.07	6.340	9	36.20
Year of study	299	1998	9.648	1977	2016
Asia	299	0.468	0.500	0	1
Europe	299	0.204	0.404	0	1
North America	299	0.184	0.388	0	1
Oceania	299	0.144	0.351	0	1
Maize	299	0.0903	0.287	0	1
Rice	299	0.365	0.482	0	1
Soybean	299	0.0502	0.219	0	1
Spring wheat	299	0.184	0.388	0	1
Wheat	299	0.311	0.464	0	1
Free Air Carbon Enrichment	299	0.134	0.341	0	0
Closed-top chamber	299	0.181	0.385	0	1
Controlled-environment chamber	299	0.124	0.330	0	1
Field study	299	0.0234	0.151	0	1
Glasshouse	299	0.0368	0.189	0	1
Laboratory	299	0.0736	0.262	0	1
Open-top chamber	299	0.428	0.496	0	1

Table 2: Summary Statistics for Studies that Measure Yield in grams per plant

Variables	N	Mean	Sd	min	max
Yield (grams/plant)	215	43.25	58.22	0	336.8
CO_2 (ppm)	215	545.9	158.0	160	1000
Temperature (°C)	215	24.24	6.731	14	40
Year of study	215	1996	6.281	1981	2013
Asia	215	0.298	0.458	0	1
Europe	215	0.205	0.404	0	1
North America	215	0.456	0.499	0	1
Oceania	215	0.0419	0.201	0	1
Maize	215	0.0279	0.165	0	1
Rice	215	0.381	0.487	0	1
Soybean	215	0.228	0.420	0	1
Spring wheat	215	0.0698	0.255	0	1
Wheat	215	0.293	0.456	0	1
Closed-top chamber	215	0.0140	0.118	0	1
Controlled-environment chamber	215	0.358	0.481	0	1
Field study	215	0.0419	0.201	0	1
Glasshouse	215	0.214	0.411	0	1
Laboratory	215	0.0744	0.263	0	1
Open-top Chamber	215	0.298	0.458	0	1

Employing White's [10] test for homoskedasticity, we found evidence of heteroskedasticity and thus adopted heteroskedasticity-robust standard errors for all regression models. The data sources are reported in Table 3. We omit four of the six observations from [11] as they conduct 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]

	# of			Mean		CO_2	
Study	Obs	Location	Crop	yield	Units	Min	Max
Abebe et al. [12]	12	India	Maize	4.99	t/ha	397	550
Allen Jr. et al. [13]	23	U.S.	Rice	5.62	t/ha	330	660
Baker [14]	38	U.S.	Rice	12.46	g/pl	358	705
Baker et al. [15]	6	U.S.	Rice	2.28	g/pl	160	900
Baker et al. [16]	4	U.S.	Rice	6.33	t/ha	330	660
Baker et al. [17]	6	U.S.	Soybean	11.07	g/pl	330	660
Batts et al. [18]	22	U.K.	Wheat	8.53	t/ha	365	698
Bugbee et al. [19]	10	U.S.	Wheat & rice	5.82	t/ha	340	680
Conroy et al. [20]	9	Australia	Wheat	23.86	g/pl	350	900
Fiscus et al. [21]	12	U.S.	Soybean	156.3	g/pl	360	700
Gifford [22]	16	Australia	Wheat	4.61	t/ha	340	590
Gifford [23]	3	Australia	Wheat	9.7	t/ha	140	490
Heagle et al. [24]	18	U.S.	Wheat	12.74	g/pl	379	707
Kimball et al. [8]	4	U.S.	Wheat	7.63	t/ha	370	550
Manderscheid & Weigel [25]	6	Germany	Wheat	25.83	g/pl	372	539
Manderscheid & Weigel [26]	12	Germany	Spring wheat	16.46	g/pl	379	689
Mayeux et al. [27]	8	U.S.	Wheat	1.69	t/ha	200	350
Mckee & Woodward [28]	16	U.K.	Wheat	2.66	g/pl	400	700
Meng et al. [29]		China	Maize				
Moya et al. [30]	36	Philippines	Rice	4.80	t/ha	370	665
Mulholland et al. [31]	6	U.K.	Spring wheat	7.05	t/ha	379	700
Mulholland et al. [32]	6	U.K.	Spring wheat	9.60	t/ha	384	682
Otera et al. [33]	24	Japan	Soybean	39.98	g/pl	389	589
Pleijel et al. [34]	11	Sweden	Spring wheat	5.88	t/ha	347	675
Prasad et al. [35]	3	U.K.	Soybean	18.25	g/pl	160	660
Qiao et al. [36]	30	China	Soybean & maize	5.92	t/ha	394	705
Rawson [37]	24	Australia	Wheat	7.52	t/ha	360	700
Reuveni & Bugbee [11]	6	Israel	Wheat	7.63	t/ha	350	10,000
Rudorff et al. [38]	6	U.S.	Wheat & maize	5.20	t/ha	350	500
Sionit et al. [39]	3	U.S.	Wheat	33.03	g/pl	350	1000
Teramura et al. [40]	12	U.S.	Wheat-rice-soybn	45.79	g/pl	350	650
van Oijen et al. [41]	8	Nederland	Spring wheat	7.19	t/ha	373	754
Wang et al. [42]	8	China	Rice	10.23	t/ha	390	590
Weigel et al. [43]	10	Germany	Wheat	27.41	g/pl	384	718
Wheeler et al. [44]	8	U.K.	Wheat	7.87	t/ha	380	713
Xiao et al. [45]	13	China	Spring wheat	1.25	t/ha	360	450
Xiao et al. [46]	7	China	Spring wheat	2.17	t/ha	364	404
Yang et al. [47]	16	China	Rice	10.12	t/ha	383	583
Zhang et al. [48]	12	Japan	Rice	7.08	t/ha	379	585
Ziska et al. [49]	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 our sample reported yields in elevated CO_2 on the treatment plot and on the control plot. We report the treatment and control results as two separate observations; thus, for a study that reports on four experiments, we would then have 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.

Meta-Analysis Regression Model

Serial autocorrelation is not an issue because we do not have 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 we do use year dummies to account for time-related fixed effects. This leads us to believe that the yield of a study in a particular year is likely uncorrelated with other studies in previous years.

Our regression model takes the following form:

$$Y_i = \beta_0 + \beta_1\, CO2_i + \beta_2\, CO2_i^2 + \beta_3\, T_i + \beta_4\, T_i^2 + \beta_5\, T_i \times CO2_i + \boldsymbol{\alpha}_1\, \mathbf{Crop}_i + \boldsymbol{\alpha}_2\, \mathbf{Type}_i + u_i, \qquad (1)$$

where Y_i measures the crop yield from study i in t/ha or g/plant; $CO2_i$ and T_i measure, respectively, the carbon dioxide level and temperature (°C) employed in observation i; $\mathbf{Crop}_i$ is a vector of dummy variables for the crops included in this study (see Tables 1 and 2); $\mathbf{Type}_i$ is a vector of dummy variables containing all types of experiments; and β_i and $\boldsymbol{\alpha}_i$ are coefficients or vectors of coefficients to be estimated. Finally, the error structure is represented by u_i. We include the interaction effect to test how the CO_2-fertlization effect varies with temperature.

For our final regression model, we de-mean the CO_2 and temperature data so that the model takes the following final form:

$$\begin{aligned} Y_i = \beta_0 &+ \beta_1 (CO2_i - \overline{CO2_i}) + \beta_2 (CO2_i^2 - \overline{CO2_i^2}) + \beta_3 (T_i - \overline{T_i}) + \beta_4 (T_i^2 - \overline{T_i^2}) \\ &+ \beta_5 (T_i - \overline{T_i}) \times (CO2_i - \overline{CO2_i}) + \boldsymbol{\alpha}_1\, \mathbf{Crop}_i + \boldsymbol{\alpha}_2\, \mathbf{Type}_i + u_i, \qquad (2) \end{aligned}$$

This allows us to interpret the marginal effects as:

$$\frac{\partial Y}{\partial CO_2} = \beta_1 + 2\beta_2 CO2_i + \beta_5(T_i - \overline{T_i}) \tag{3}$$

$$\frac{\partial Y}{\partial T} = \beta_3 + 2\beta_4 T_i + \beta_5(CO2_i - \overline{CO2_i}) \tag{4}$$

Upon estimating regression equation (2), the estimated parameter β_5 enables us to analyse the interaction effect on marginal crop yields using equations (3) and (4). We can also evaluate the marginal effect at the average values of T and CO_2, respectively, but doing so isolates the marginal effects, because the interaction effect is nullified at the averages. This is especially valuable in evaluating the turning points beyond which these effects lead to a reduction in crop yields.

The regression models are estimated using 295 observations that measured yield in t/ha and 215 observations that measured it in g/plant. We cannot convert the g/plant observations to t/ha as doing so requires us to make assumptions regarding how many plants are in a hectare, which would require knowledge of sowing density, plant survival rates, et cetera. We employ heteroskedastic-robust, ordinary least squares (OLS) regression for all specifications. We cluster the standard errors at the study level to allow for correlation between observations within the same study, but assume independence across studies. This accounts for heteroskedasticity across studies by allowing a limited form of dependence between observations within the same study. This makes sense in the context of the present analysis as observations from the same study are held at the exact same conditions with respect to irrigation, solar irradiance, the chemical composition of the air and soil, location and other factors.

3. RESULTS

In this section, we provide regression results stratified by units. We regress crop yields on CO_2, temperature, the quadratic CO_2 and temperature terms, the interaction term, and the control variables using OLS. We display graphs of the relationship between crop yields, temperature, and

CO_2 in Figures 2 and 3, including simple quadratic lines fit to the data. We use the full model specifications in each of our calculations of marginal effects.

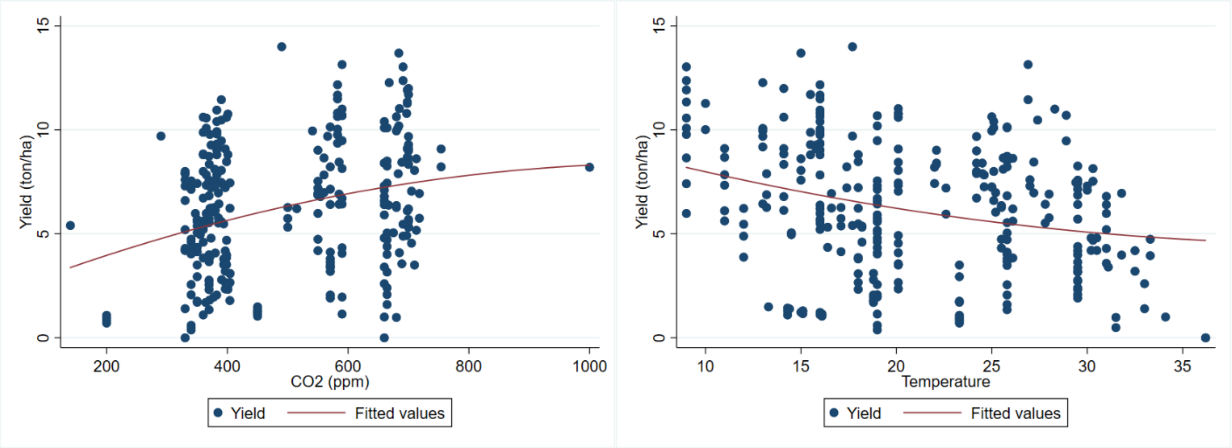

Figure 1: Scatter Plot Values and Fitted Quadratic Functions, Crop Yields in tonnes/ha

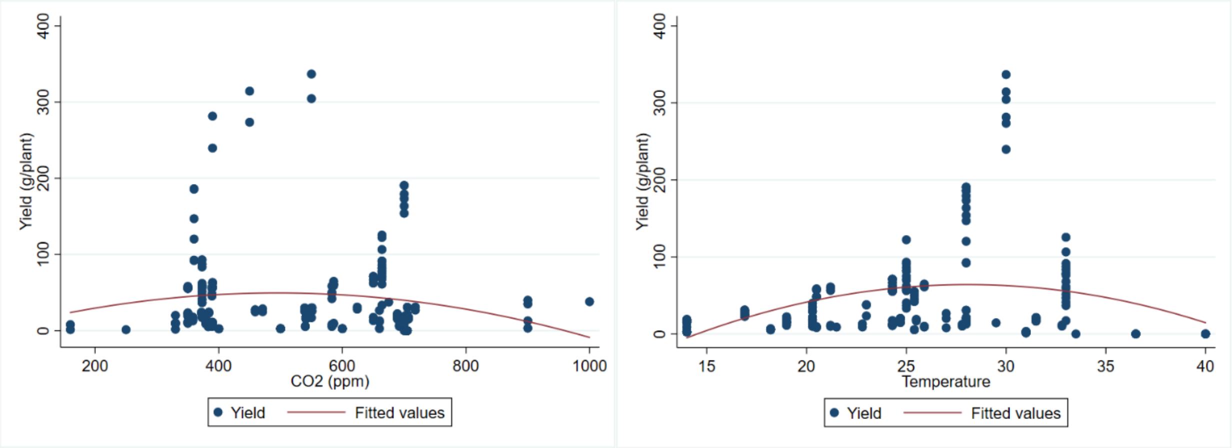

Figure 2: Scatter Plot Values and Fitted Quadratic Functions, Crop Yields in g/plant

As shown in Figure 1, we observe that an increased concentration of CO_2 in the atmosphere has a positive but diminishing fertilization effect on yield, while rising temperatures tend to reduce yields. The CO_2-fertilization effect is as anticipated, but one would also expect a positive effect for temperature followed by a tipping point beyond which further increases in heat reduce crop yields. We believe this to be due to the nature of our data – we employ data from studies that conducted experiments at various temperatures and we measured temperature as differences in those studies. The negative trend of temperature in the t/ha data is likely the result of studies that used very high temperatures, which tended to reduce yields relative to ambient yields.

When we examine the effect of higher atmospheric concentrations of CO_2 and surface temperatures on yield measured in g/plant, we find that both fitted relations are quadratic, indicating that there are turning points. This is shown in Figure 2. Notice the clusters of points at different temperatures. This is a result of the nature of our data: If we found a study that recorded yields at 300 and 600 ppm of CO_2, and the experiment was undertaken at 30°C, both yield observations would appear as vertically connected (e.g., as seen in the right-hand panel of Figure 2); likewise, in the figure on the left, vertical points represent a particular change in temperature, but different concentrations of CO_2, say.

The simple OLS regression results for crop yield measured in t/ha are provided in Table 4, with the full model provided in column (3) of the table. When CO_2 and temperature are taken together, the underlying partial effects are properly estimated. In the regression, different crops have different intercepts, which constitutes a restriction that we address in a later section; however, these restrictions imply that the partial effects are the same for each crop. It is also worth noting that our data consist of controlled experiments where temperatures do not fluctuate throughout the growing season, which likely explains the statistical insignificance of the temperature effects, although it could also be the result of insufficient data. We control for the type of experiment to isolate variation in the variables of interest, but one cannot determine the marginal effect attributable to the type of experiment as the experiment variable is binary.

Table 4: Estimated Impact of CO_2 and Temperature on Crop Yields (t/ha)[a]

Variables	(1)	(2)	(3)[b]
CO_2	0.016**		0.026***
	(2.195)		(3.523)
CO_2-squared	-0.00001		-0.00002***
	(-1.600)		(-2.887)
Temperature		-0.012	0.128
		(0.061)	(0.629)
Temperature-squared		-0.009**	-0.009**
		(-2.189)	(-2.457)
CO_2 × temperature			-0.0002
			(-1.412)
Maize	3.580*	5.496***	5.171***
	(1.939)	(3.522)	(3.739)
Rice	-2.440***	4.730***	4.304***
	(-2.882)	(3.417)	(3.271)
Spring wheat	-1.099	1.964**	1.619*
	(-1.342)	(2.006)	(1.789)
Soybean	-0.201	-0.040	-0.327
	(-0.109)	(-0.026)	(-0.240)
Constant	3.830***	-1.408	-0.541
	(4.348)	(-1.364)	(-0.551)
Observations	295	295	295
Adjusted R-squared	0.559	0.629	0.680

[a] Robust t-statistics in parentheses. Standard errors clustered at the study level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

[b] This specification uses de-meaned variables for CO_2 and temperature, as indicated in equation (2).

Now consider yield measured in g/plant, with results provided in Table 5. As expected based on Figure 2, the CO_2-fertilization effect has a positive impact on crop yields, but its effect diminishes with rising atmospheric CO_2 – the CO_2-fertilization effect only works to amplify yields up to a certain critical threshold. Unlike the regressions in Table 4, the CO_2 effect appears to be statistically insignificant, perhaps due to too few observations. The negative sign on the linear term for CO_2 is likely incorrect as the estimated parameter is statistically insignificant, but it also results in a marginal effect from the g/plant data that is likely incorrect. We report the marginal effects of CO_2 and temperature from the final specifications for both yield measures in Table 6.

Table 5: Estimated Impact of CO_2 and Temperature on Crop Yields (g/plant)[a]

Variables	(1)	(2)	(3)
CO_2	0.079**		-0.022
	(2.037)		(-0.379)
CO_2-squared	-0.00004		-0.00002
	(-1.270)		(-0.506)
Temperature		11.896***	12.491***
		(3.754)	(4.168)
Temperature-squared		-0.207***	-0.252***
		(-4.169)	(-5.160)
CO_2 × temperature			0.003**
			(2.454)
Maize	277.949***	230.669***	229.171***
	(21.835)	(10.883)	(11.655)
Rice	65.874***	56.884***	55.977***
	(7.090)	(8.649)	(9.646)
Spring wheat	-66.959***	-64.928***	-65.291***
	(-3.702)	(-3.401)	(-4.027)
Soybean	88.748***	70.768***	68.954***
	(7.771)	(7.367)	(8.100)
Constant	-45.527**	-18.920	-17.667
	(-2.505)	(-0.828)	(-0.898)
Observations	215	215	215
Adjusted R-squared	0.922	0.918	0.927

[a] See footnotes on Table 4.

Table 6: Marginal Effects of CO_2 and Temperature[a]

Units	CO_2	Temperature
t/ha	$0.026 - 0.00004\,\mathrm{CO2} - 0.0002(\mathrm{T} - \overline{\mathrm{T}})$	$0.128 - 0.018\,\mathrm{T} - 0.0002(\mathrm{CO2} - \overline{\mathrm{CO2}})$
g/plant	$-0.022 - 0.00004\,\mathrm{CO2} - 0.003(\mathrm{T} - \overline{\mathrm{T}})$	$12.491 - 0.504\,\mathrm{T} - 0.003(\mathrm{CO2} - \overline{\mathrm{CO2}})$

[a] Computed as the partial derivative of yield with respect to CO_2 and temperature. The marginal effects of CO_2 can be evaluated at the mean of temperature such that we can evaluate the marginal effect without the interaction effect. The same can be done for temperature.

The marginal effect of CO_2 on crop yield from the t/ha data is positive until CO_2 reaches 650 ppm, well outside the range of any currently envisioned scenario. The estimated parameter on the interaction term is not statistically different from zero, so increases in temperature have no discernable effect on crop yields at the margin. Thus, at no point within the current analysis can an increase in CO_2 reduce crop yields at the average temperature, or at any other temperature in our dataset. Nonetheless, the marginal effect of CO_2 on crop yields is lower at higher temperatures.

In contrast, it appears that the marginal effect from the g/plant regression is negative throughout. Even though the intercept term (-0.022) is statistically insignificant, the estimated parameter on the interaction term is statistically significant at the 5% level, indicating that yields decline with higher temperatures. Absence of a positive effect is likely an artefact of the data. Individual plant studies employed levels of CO_2 that led to little if any effect of marginal changes in CO_2 on crop yields; in these studies, changes in temperature are the primary factor affecting crop yields. Further, the results in Table 6 do not isolate the effects of CO_2 and temperature on particular crops, something we examine more closely in the following section. Finally, the dependent variables are not directly comparable because they are measured in different units. The positive CO_2-fertilization effect from the t/ha data is consistent with the crop science literature.

If we were to evaluate the t/ha marginal effect of CO_2 at the average temperature, a projected increase in atmospheric CO_2 from 400 to 500 ppm, say, is associated with an increased yield of one tonne per hectare ($[0.026 - 0.00004\times CO_2]\times \Delta CO_2 = [0.026 - 0.00004 \times 400]\times 100$). This is a considerable increase that would likely net out some of the negative future effects of temperature.

Based on the g/plant data, the increase in atmospheric CO_2 would be associated with a slight increase in yields as long as temperature also increased. The coefficients on the linear and quadratic CO_2 terms are statistically insignificant and it is only the coefficient on the CO_2-temperature interaction term that is slightly positive and statistically significant, thereby indicative of a CO_2-fertilization effect.

If we consider the marginal effect of temperature, we find that, at the mean of CO_2, a 1ºC increase in mean surface temperature would decrease crop yield by about ¼ tonne per hectare. If we consider the marginal effect of temperature in the g/plant data, we derive a tipping point at 24.78°C on average (= 12.491/0.504), although this will differ from one crop to another.

4. ALLOWING EFFECTS TO VARY BY CROP

We now estimate the full model separately for each crop using the two yield measures, t/ha and g/plant, thereby allowing the marginal effects to vary from one crop to another. This is likely more representative of the true nature of the underlying relationships. A summary of the data associated with the individual crop regression analyses is found in Table 7. The regression results are provided in Tables 8 and 9, while the marginal impacts are provided in Table 10.

Yield Measure: Metric Tons per Hectare

The regression results for the case where yield is measured in t/ha are found in Table 8. Standard errors cannot be computed for soybean because the number of regressors exceeds the number of observations, so soybean were excluded from these results. We combine the winter and spring wheat data as there is no fundamental difference in the cultivar used; only the timing at which each is planted differs. That is, there is no statistical difference in the yields of winter and spring wheat (see supplementary material). In the table, we provide the parameter estimates for various types of experiments, but we do not show the estimated parameters on the geographic controls and other dummy variables.

Table 7: Summary Statistics for Yields, CO_2 and Temperature, by Crop[a]

Crop	Observations	Yield	Temperature (°C)	CO_2 (ppm)
		Measure of Yield: tonnes per hectare (t/ha)		
Wheat[b]	148	6.1375	16.8764	604.0115
Maize	27	6.9115	24.7333	487.3959
Rice	109	6.5542	26.0835	509.9284
Soybean	15	3.3840	19.4000	498.2787
		Measure of Yield: grams per plant (g/plant)		
Wheat[c]	78	16.2217	17.2885	546.2436
Maize	6	291.7233	30.0000	463.3333
Rice	82	37.4598	29.8159	583.0610
Soybean	49	65.5559	25.28571	493.2245

[a] Arithmetic means are used to compute marginal effects of temperature and CO_2 on yields.
[b] Combined winter and spring wheat
[c] Since individual plants are examined, there is no distinction between winter and spring wheat.

The lack of significance on the estimated parameters for CO_2 and temperature for maize is likely due to data limitations (too few observations). In the case of rice, enhanced CO_2 seems to have little impact on yields, perhaps because the relationship is misidentified given the dominance of paddy rice cultivation and/or the CO_2-fertilization effect is dominated by the positive effect of additional heat units.

Table 8: Regression Analysis of Yields for Combined Winter & Spring Wheat, Maize, and Rice, metric tons per hectare[a]

Variables	Wheat	Maize	Rice
CO_2	0.024^{***}	-0.027	0.007
	(3.303)	(-0.266)	(0.173)
CO_2-squared	-0.00002^{***}	0.00001	0.00000
	(-2.846)	(0.113)	(0.113)
Temperature	-2.304^{***}	1.956^{***}	1.889^{*}
	(-5.146)	(3.425)	(1.916)
Temperature-squared	0.054^{***}	-0.054^{***}	-0.041^{**}
	(4.558)	(-3.217)	(-2.507)
CO_2 × Temperature	0.00001	0.001	-0.0003
	(0.053)	(0.928)	(-1.636)
FACE	11.364^{***}		
	(5.899)		
Laboratory	6.325^{***}		
	(8.808)		
Closed-top container	6.262^{***}		
	(3.731)		
Glasshouse	8.429^{***}		
	(7.485)		
Open-top container	9.620^{***}		-4.596^{***}
	(7.068)		(-4.784)
Controlled environment chamber			-2.834^{***}
			(-3.095)
Constant	4.881^{***}	5.021^{***}	10.783^{***}
	(6.341)	(11.755)	(6.121)
Observations	144	27	109
Adjusted R-squared	0.711	0.893	0.713

[a] See footnotes on Table 4. Separate regressions for winter and spring wheat are found in the supplementary material.

When winter and spring wheat are combined, we get statistically significant results on CO_2 and temperature, which provides a much clearer picture of their role. The results from the wheat regression are as expected, except the adverse impact of higher temperatures on yield was expected to be somewhat lower. In the wheat specification, the statistically significant positive quadratic term implies that the heat effect increases at higher temperatures. This is seemingly inconsistent with the literature as there are well-established diminishing effects.

Yield Measure: Grams per Plant

The regression results when yields are measured in g/plant are reported in Table 9. Maize is not included due to too few observations, while separate data for winter and spring wheat are not relevant in these experiments. The effect of CO_2 on yields is statistically insignificant in each of the wheat, rice and soybean regressions, except for the interaction effect between CO_2 and temperature in the wheat regression. It indicates that, when increased atmospheric CO_2 is combined with higher temperatures, wheat yields will increase; however, although the parameter estimate is significant at the 1% level, the impact of CO_2 on yield is quite small even when there is a considerable increase in temperature. The lack of statistical significance for CO_2 implies that we are unable properly to identify the effect in the individual crop regressions when yield is measured in g/plant.

When looking at the temperature effect on wheat yields, we get a statistically significant negative linear term which is more consistent with literature that projects negative effects from global warming (although the magnitude of the estimate is unreasonable). However, given the statistically significant parameter estimate on temperature squared, we find that, contrary to expectation, increases in temperature will cause wheat yields to decline, but after some point, as temperatures continue to rise, yields will increase. For rice, the estimated coefficients on temperature and temperature squared are statistically significant (at 5% and 10% levels, respectively), indicating that yields increase with temperature but at a diminishing rate. These values are more in line with the literature than those associated with the associated t/ha regression in Table 8. Temperature appears to have no statistically significant effect on soybean yields.

Table 9: Regression Analysis of Yields for Wheat, Rice and Soybean, Yield Measured in g/plant[a]

Variables	Wheat	Rice	Soybean
CO_2	-0.005	0.073	-0.336
	(-0.170)	(0.507)	(-1.081)
CO_2-squared	-0.00002	-0.00004	0.0002
	(-0.744)	(-0.368)	(1.065)
Temperature	-106.662***	10.53**	-4.036
	(-11.459)	(2.645)	(-0.290))
Temperature-squared	3.196***	-0.191***	0.021
	(11.336)	(-3.197)	(0.081)
CO_2 × temperature	0.002***	0.0004	0.006
	(3.222)	(0.112)	(0.781)
Laboratory	5.898		
	(1.507)		
Controlled-environment chamber	-81.660***		
	(-9.659)		
Glasshouse	-157.631***	63.983***	17.008*
	(-11.621)	(9.919)	(1.827)
Closed-top container			-30.061**
			(-2.145)
Open-top container	19.555***		107.436***
	(5.019)		(4.221)
Constant	225.558***	-6.854	49.591***
	(12.476)	(-0.631)	(3.367)
Observations	78	82	49
Adjusted R-squared	0.876	0.782	0.825

[a] See footnotes to Table 4.

Marginal Effects

The marginal effects of changes in atmospheric CO_2 concentration and temperature are found in Table 10. To analyze marginal effects and their respective turning points, we need to evaluate them using crop-specific summary statistics for temperature and CO_2, which are found in Table 7. We only report those marginal effects that exhibit statistically significant parameters. It is clear from the summary statistics regarding average yields that imposing a common marginal effect across crops is incorrect and our earlier model is not capturing crop-specific effects.

Table 10: Marginal Effects of CO_2 and Temperature by Crop[a]

Crop	CO_2	Temperature
	Measure of Yield: tonnes per hectare (t/ha)	
Wheat	$0.024 - 0.00004\ CO_2 + 0.00001\ (T - \bar{T})$	$-2.304 + 0.108\ T + 0.00001\ (CO_2 - \overline{CO_2})$
Maize	$-0.027 + 0.00002\ CO_2 + 0.001\ (T - \bar{T})$	$1.956 - 0.108\ T + 0.001\ (CO_2 - \overline{CO_2})$
Rice	$0.007 + 0.00000\ CO_2 - 0.0003\ (T - \bar{T})$	$1.889 - 0.082\ T - 0.0003\ (CO_2 - \overline{CO_2})$
	Measure of Yield: grams per plant (g/plant)	
Wheat	$-0.005 - 0.00004\ CO_2 + 0.002\ (T - \bar{T})$	$-106.662 + 6.392\ T - 0.002\ (CO_2 - \overline{CO_2})$
Rice	$0.073 - 0.00008\ CO_2 + 0.0004\ (T - \bar{T})$	$10.53 - 0.382\ T - 0.0004\ (CO_2 - \overline{CO_2})$
Soybean	$-0.336 + 0.0002\ CO_2 + 0.006\ (T - \bar{T})$	$-4.036 + 0.042\ T - 0.006\ (CO_2 - \overline{CO_2})$

[a] Computed as the partial derivative of yield with respect to CO_2 and temperature, respectively. The marginal effects of CO_2 (temperature) can be evaluated at the mean of temperature (CO_2) such that we can evaluate the marginal effect without the interaction effect.

For the t/ha regression analysis in Table 10, we get properly signed CO_2-fertilization effects for wheat and rice, and maize and rice for temperature effects. For the g/plant analysis, we only get a proper sign for the CO_2-fertilization and temperature effect for rice. Thus, it may not be appropriate to evaluate tipping points from a statistical point given the available data. This is further exhibited by lack of coverage with respect to the interaction between CO_2 and temperature (see supplementary material). It is not likely that underlying functional relationships between CO_2, temperature, and crop yields are systematically different. Rather, it is more plausible that there are differences in the extent to which CO_2 and temperature affect crop yields and we are unable to properly uncover these effects in all crops. For those that we do, the substantive CO_2-fertilization effect is clearly of importance.

5. DISCUSSION

Current research on climate change focuses on the negative impact that climate change will have on crop yields. What seems to be downplayed in the discussion is the windfall gains from rising atmospheric CO_2 – the benefits of CO_2-fertilization. While there are negative effects from amplified CO_2 levels, there are beneficial impacts for the agricultural sector. As demonstrated in this study, increases in atmospheric CO_2 and temperatures in line with what the IPCC [50] has projected are likely to improve food security. Only if temperatures rise beyond current projections will the negative effect of higher temperatures offset the beneficial effect from CO_2 fertilization. At current temperatures, the CO_2-fertilization effect on yield appears unbounded, although its impact diminishes with increases in the concentration of CO_2 in the atmosphere. Overall, yields of some major crops are likely to increase within the range of CO_2 concentrations and temperatures projected by the IPCC. 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. In particular, there will be genetic modifications that tailor new species of crops to the changing climate and allow for further improvement in yields.

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. They show a sheer lack of overlap between deciles of both our CO_2 and temperature data.

The extent of missing data reported in g/plant is starker than t/ha; however, the t/ha data still have severe limitations. Without having more data from varied experiments, the interaction effects of CO_2 and temperature on crop yields are hard to quantify as we do not have a complete analysis of these two explanatory variables across different levels. This reinforces our point that more research needs to be devoted to this area so that we can better quantitatively and qualitatively evaluate the risk that climate change poses for food security.

The analysis in this study demonstrates the importance of taking the CO_2-fertilization effect into account, and the need to incorporate it within future analyses of food security. It indicates the need for more research on crop yields in developing countries and areas most at risk from global warming. One possible avenue is to adopt FACE experiments more broadly as they simulate elevated CO_2 under ordinary field conditions. Such experiments are likely ideal for evaluating the future impacts of rising CO_2 and the potential for mitigating the projected negative effects of global warming.

6. AUTHOR CONTRIBUTIONS

Conceptualization: GCVK

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Formal Analysis: BM, GCVK, ZZ

Funding Acquisition: GCVK

Investigation: BM, ZZ

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Project administration: GCVK

Supervision: GCVK

Validation: BM, GCVK

Writing: BM, GCVK, ZZ

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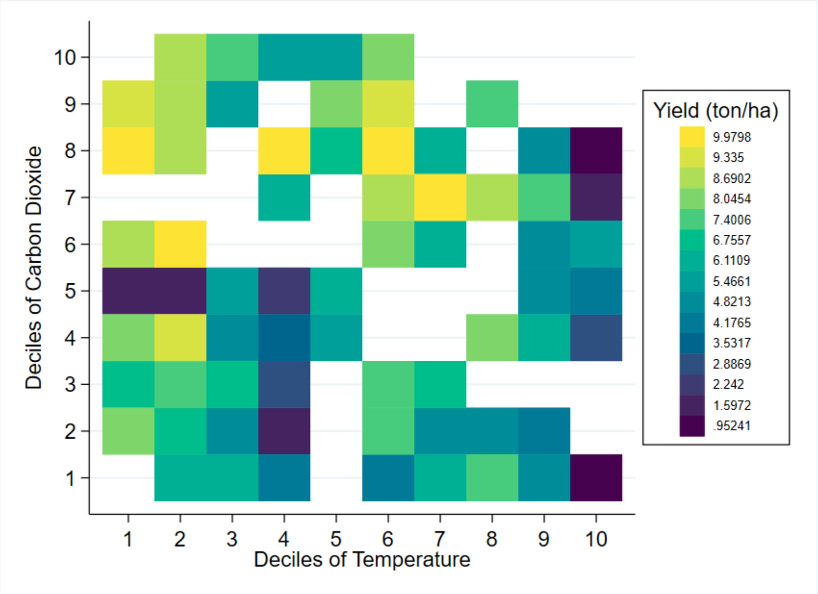
9. SUPPLEMENTARY MATERIAL

Heat Maps

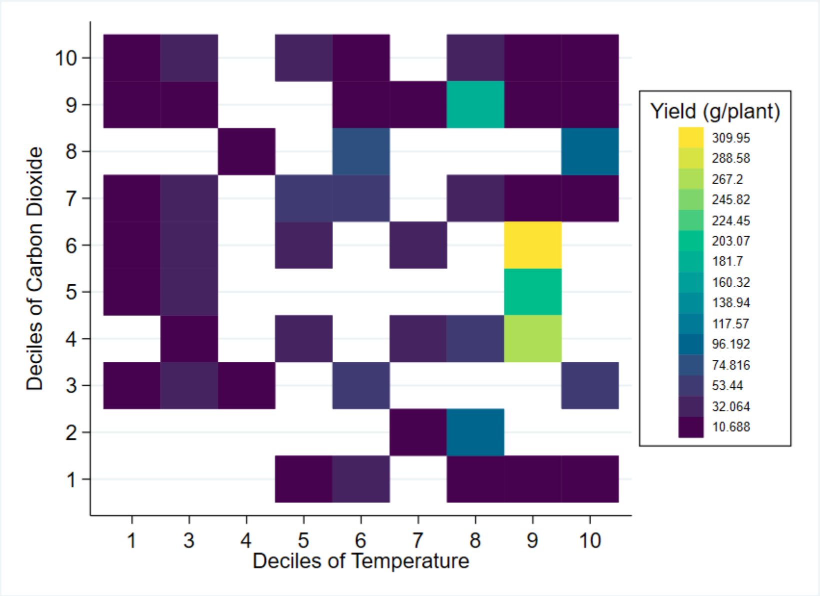
When we separate levels of CO_2 and temperature into deciles and generate a heat map, we see a severe lack of coverage. This leads us to believe that we cannot accurately interpret the interaction effect between CO_2 and temperature on crop yields as we miss a large portion of the *combinations* between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



Deciles of Carbon Dioxide
10
9
8
7
6
5
4
3
2
1
Deciles of Temperature
1
2
3
4
5
6
7
8
9
10
Yield (ton/ha)
9.9798
9.335
8.6902
8.0454
7.4006
6.7557
6.1109
5.4661
4.8213
4.1765
3.5317
2.8869
2.242
1.5972
.95241

677

678



Deciles of Carbon Dioxide
10
9
8
7
6
5
4
3
2
1
Deciles of Temperature
1
3
4
5
6
7
8
9
10
Yield (g/plant)
309.95
288.58
267.2
245.82
224.45
203.07
181.7
160.32
138.94
117.57
96.192
74.816
53.44
32.064
10.688

Spring versus Winter Wheat

In the analysis, spring and winter wheat yield data have been combined in the crop-level regressions. From Figure S1, it is clear that there is no statistically-significant 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.

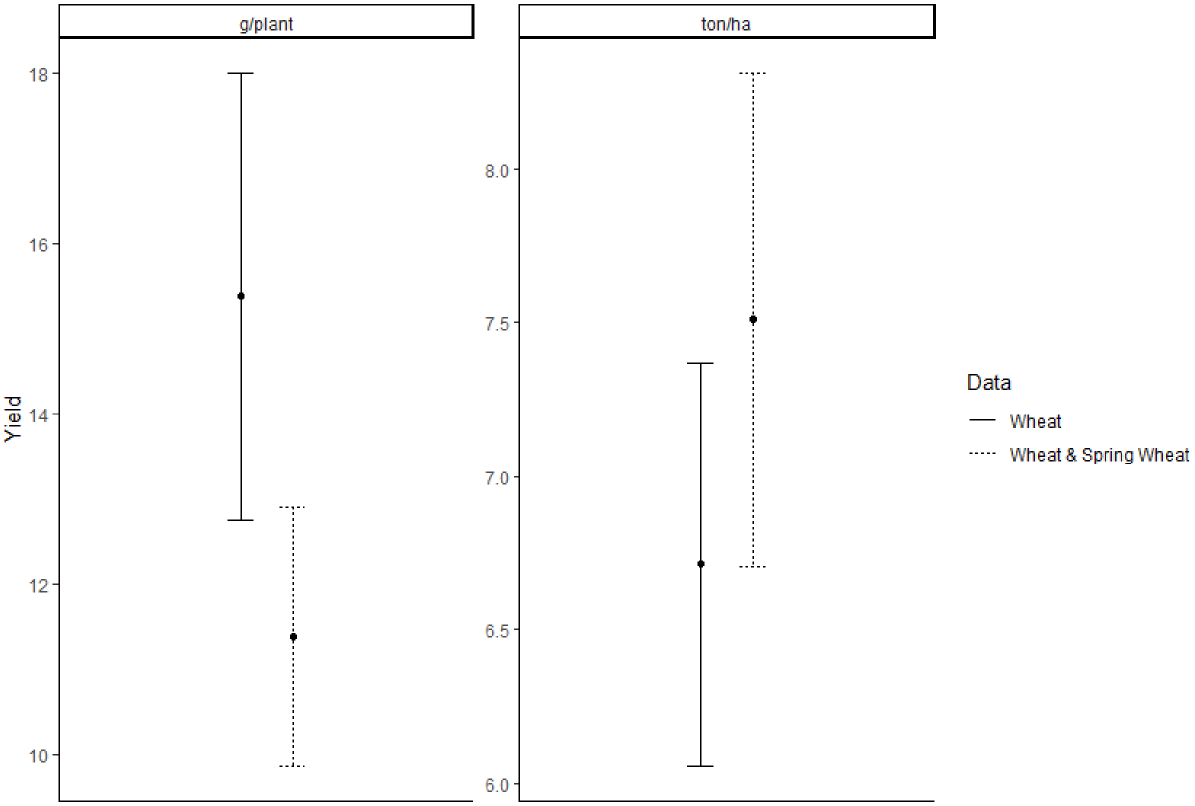


Figure S1: 95% Confidence Intervals for Yields for Wheat (Spring and Winter Wheat Combined)

Consider separate winter wheat and spring wheat regressions; these are indicated in Tables S1 and S2. We again exclude spring wheat from the regression analysis in Table S2 as we are simply asking too much of the model given only 15 observations.

Table S1: Regression Analysis of t/ha Yields for All Wheat, Spring Wheat, and Rice[a]

Variables	Wheat	Spring Wheat	Rice
CO_2	0.027***	0.025	0.007
	(3.591)	(1.405)	(0.173)
CO_2-squared	-0.00002***	-0.00001	-0.00000
	(-3.290)	(-1.037)	(0.113)
Temperature	-3.290***	0.088	1.889*
	(-5.822)	(0.043)	(1.916)
Temperature-squared	0.076***	-0.002	-0.041**
	(5.493)	(-0.035)	(-2.507)
CO_2 × Temperature	0.0001	-0.001	-0.0003
	(0.295)	(-0.980)	(-1.636)
Closed-top container	2.241***		
	(4.122)		
Glasshouse	-0.569		
	(1.023)		
Open-top chamber		-2.177***	-4.596***
		(-3.545)	(-4.784)
Controlled-environment chamber			-2.834***
			(-3.095)
FACE		6.148***	
		(2.856)	
Constant	14.883***	1.262	10.783***
	(9.023)	(0.260)	(6.121)
Observations	89	55	109
Adjusted R-squared	0.611	0.886	0.713

[a] See footnote on Table 4 in the text.

Table S2: Regression Analysis of g/plant Yields for Wheat, Rice, and Soybean[a]

Variables	Wheat	Rice	Soybean
CO_2	-0.011	0.073	-0.336
	(-0.193)	(0.507)	(-1.081)
CO_2-squared	-0.00001	-0.00004	0.0002
	(-0.284)	(-0.368)	(1.065)
Temperature	149.985^{***}	10.530^{**}	-4.036
	(22.986)	(2.645)	(-0.290)
Temperature-squared	-4.770^{***}	-0.191^{***}	0.021
	(-22.986)	(-3.197)	(0.081)
CO_2 × Temperature	0.002^{*}	0.0004	0.006
	(1.801)	(0.112)	(0.781)
Open-top container	-85.563^{***}		107.436^{***}
	(-20.122)		(4.221)
Closed-top container			-30.061^{**}
			(-2.145)
Glasshouse	237.605^{***}	63.983^{***}	17.008^{*}
	(21.913)	(9.919)	(1.827)
Laboratory	-99.176^{***}		
	(-23.549)		
Constant	-291.744^{***}	-6.854	49.591^{***}
	(-21.269)	(-0.631)	(3.367)
Observations	63	82	49
Adjusted R-squared	0.866	0.782	0.825

[a] See footnote to Table 4 in the text.