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Global scale climate–crop yield relationships and the impacts of recent warming

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Abstract
Changes in the global production of major crops are important drivers of food prices, food security and land use decisions. Average global yields for these commodities are determined by the performance of crops in millions of fields distributed across a range of management, soil and climate regimes. Despite the complexity of global food supply, here we show that simple measures of growing season temperatures and precipitation—spatial averages based on the locations of each crop—explain ~30% or more of year-to-year variations in global average yields for the world's six most widely grown crops. For wheat, maize and barley, there is a clearly negative response of global yields to increased temperatures. Based on these sensitivities and observed climate trends, we estimate that warming since 1981 has resulted in annual combined losses of these three crops representing roughly 40 Mt or $5 billion per year, as of 2002. While these impacts are small relative to the technological yield gains over the same period, the results demonstrate already occurring negative impacts of climate trends on crop yields at the global scale.

Keywords: climate change, crop yield, food production

1. Introduction

Annual global temperatures have increased by ~0.4 °C since 1980, with even larger changes observed in several regions [1]. While many studies have considered the impacts of future climate changes on food production [2–5], the effects of these past changes on agriculture remain unclear. It is likely that warming has improved yields (food production per unit of land area) in some areas, reduced them in others and had negligible impacts in still others. The relative balance of these effects at the global scale is unknown. An understanding of the net global impact of recent climate trends would help to anticipate impacts of future climate changes, as well as to more accurately assess recent technologically driven yield progress.

The six most widely grown crops in the world are wheat, rice, maize, soybeans, barley and sorghum. Production of these crops accounts for over 40% of global cropland area, 55% of non-meat calories and over 70% of animal feed [6]. Yields for all crops increased substantially since 1961 (figure 1), while temperature and precipitation, spatially weighted for each crop, also exhibited several significant trends. Here, we investigate the impact of these climatic trends on yields by developing new empirical/statistical models of global yield response to climate.

2. Methods

Average global yields for 1961–2002 were obtained from the Food and Agriculture Organization [6]. Gridded monthly temperature (minimum and maximum) and rainfall data at 0.5° × 0.5° for the same time period were obtained from the Climate Research Unit (CRU TS 2.1; [7]). Spatially weighted averages of the CRU data were computed for each crop, with weights defined by the spatial distribution of crop area from Leff *et al* [8], resulting in crop-specific monthly time series of 'global' temperatures and rainfall for 1961–2002.

Rather than use annual averages for each climatic variable, we defined an effective 'global growing season' for each crop

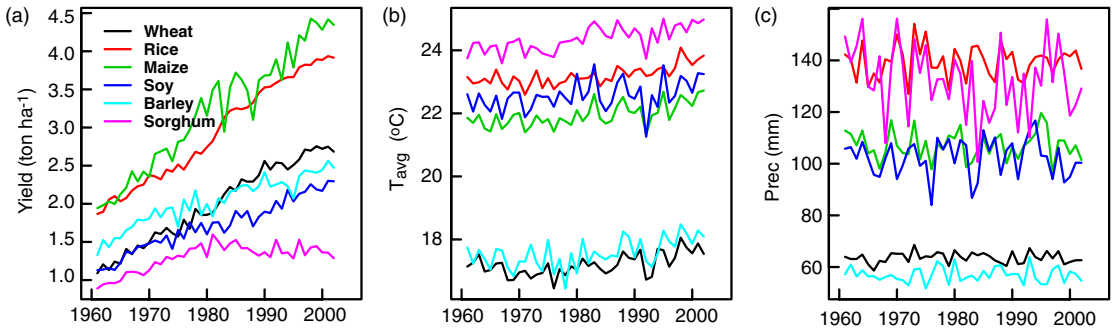

Figure 1. Time series of (a) yields, (b) growing season average monthly temperature and (c) rainfall for 6 crops, 1961–2002.

based on the contiguous months within the growing seasons for the major growing regions [9] that produced the highest model R^2. The selected growing seasons were May–Oct. (wheat), Jan.–Oct. (rice), July–Aug. (maize and soy), May–Aug. (barley) and Aug. (sorghum). Overall, results were fairly insensitive to the choice of growing season months among models that had the highest R^2, so that the particular choice of growing season did not greatly affect results (see section 3).

To evaluate the relationship between the time series for yield and climate, we used a common approach [10, 11] based on the first-difference time series for yield and climate (i.e. the difference in values from one year to the next). The use of first differences minimizes the influence of slowly changing factors such as crop management. We then performed multiple linear regressions with first differences in yield ($\Delta Yield$) as the response variable, and first differences of minimum temperature ($\Delta t_{\min}$), maximum temperature ($\Delta t_{\max}$) and precipitation (Δppt) as predictor variables. Methods of detrending the time series other than first-differences were evaluated and produced qualitatively similar results (see section 3).

While an empirical study cannot attribute directions of causality, we assume that climate variations caused yield changes, and not vice versa. This analysis also assumes that year-to-year management changes were either uncorrelated with climate, or were themselves caused by climate [12], and thus did not bias the interpretation of the climate's influence on yields, and that errors in FAO global yield data are independent of temperature and rainfall.

To estimate the role of climate in recent yield trends, we applied the regression models to observed trends in climate variables for each decade since 1961. The uncertainty in the relationship between yields and average growing season climate due to a finite historical sample was estimated and propagated by bootstrap resampling of the historical data (with 100 bootstrap samples) and re-calibration of the regression model for each sample.

While these empirical/statistical models do not attempt to capture details of plant physiology or crop management, they do capture the net effect of the entire range of processes by which climate affects yields, including the effects of poorly modelled processes (e.g. pest dynamics). In addition, these empirical/statistical models enable a quantitative evaluation of uncertainties [13].

An important assumption in using models derived from year-to-year variations to compute impacts of climate trends is that crop yields respond similarly to rapid and gradual climate variations. In theory, farmers would adapt cropping systems as climate changes, thus minimizing or possibly reversing the adverse effects of warming [14–16]. Our estimates of climate impacts can therefore be viewed as an upper bound on the impacts of recent trends. However, while some studies have documented recent trends in management practices, these changes were not driven by climate [17]. In addition, adaptation is expected to lag several years behind climate trends, because of the difficulty of distinguishing climate trends from natural variability and the disaggregated nature of farmer decisions [18].

3. Results

3.1. Global scale climate–yield relationships

At least 29% of the variance in year-to-year yield changes was explained by the predictors for all crops (table 1). For some crops, such as rice and soybeans, much of the model's explanatory power came from a positive relationship with precipitation (figure 2). For other crops, however, temperature provided most of the explanatory power. The inferred temperature sensitivities were negative for all crops (figure 2; table 1), in agreement with several previous assessments [2–5]. Mechanisms likely responsible for the observed relationships include increases in crop development rates, water stress and canopy respiration with warmer temperatures [19]. However, the relative importance of these different mechanisms cannot be determined from the empirical relationships.

That roughly half to two-thirds of global yield variance was unexplained by these models reflects the importance of variables omitted from this analysis. These are likely to include regional variations in growing seasons and climate responses, variations in climate statistics other than growing season averages, and changes in economic and other conditions that influence crop management. Consideration of these factors would likely improve model performance. However, that roughly one-third to half of variance was explained signifies that a simple, integrated measure of global climate variations for each crop provides substantial information on global crop yield changes. This weighted global average importantly

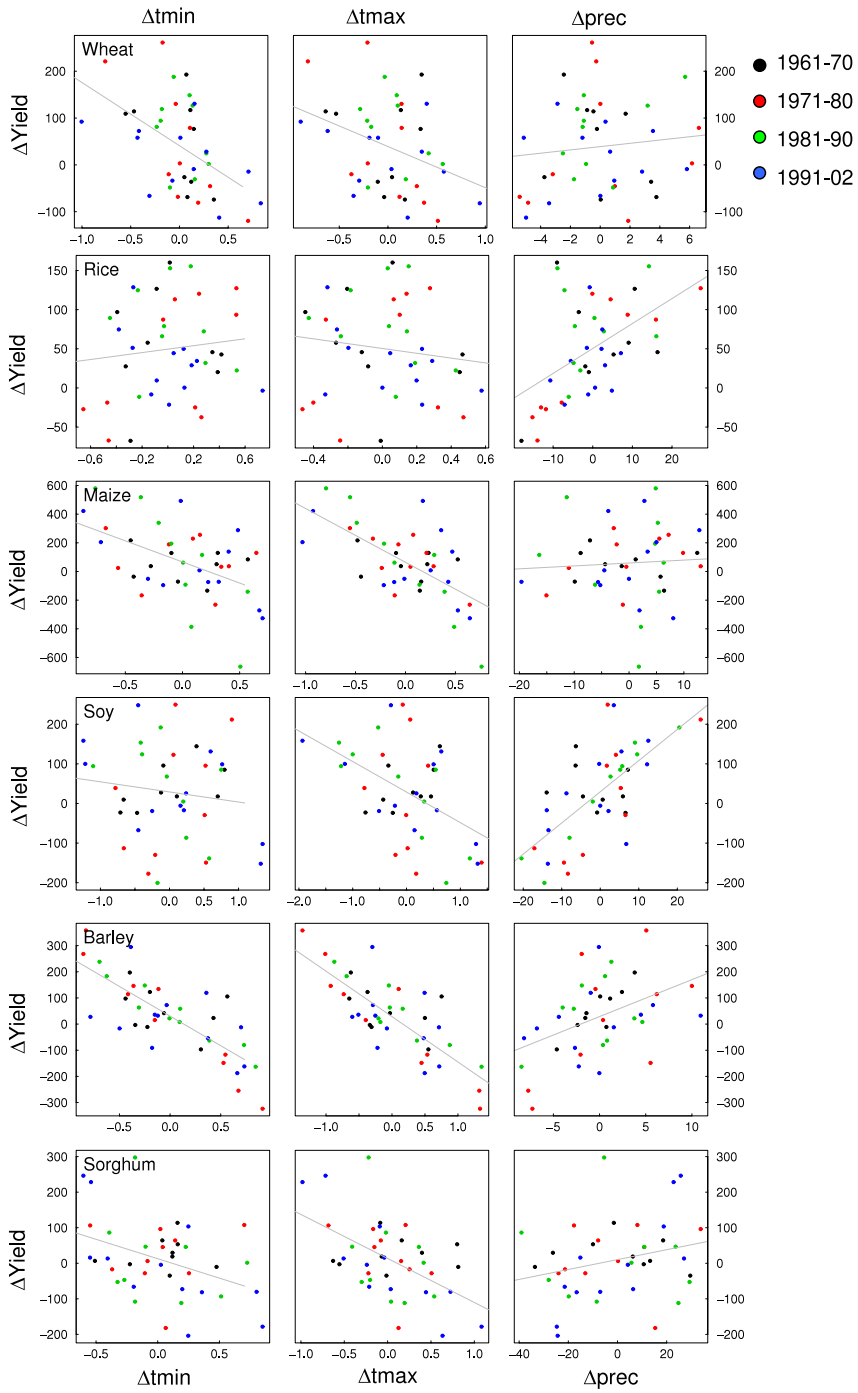

Figure 2. Scatter plots of first-differences of yield (kg ha^{-1}) and first-differences of average monthly minimum and maximum temperatures (°C) and precipitation (mm) during the growing season, along with best-fit linear regression (grey line). Each decade is shown with a different colour, indicating that the relationships do not appear to change through time.

Table 1. Summary statistics of regression models between yield and climate first-differences, 1961–2002.

	Wheat	Rice	Maize	Soybean	Barley	Sorghum
Model R^2	0.41	0.29	0.47	0.52	0.65	0.29
% yield change for $\Delta t_{min} = \Delta t_{max} = 1\,°C$	−5.4	−0.6	−8.3	−1.3	−8.9	−8.4
95% confidence interval	(−8.4, −3.2)	(−1.9, 0.9)	(−12.2, −4.0)	(−2.6, 0.2)	(−11.7, −6.1)	(−11.6, −3.3)

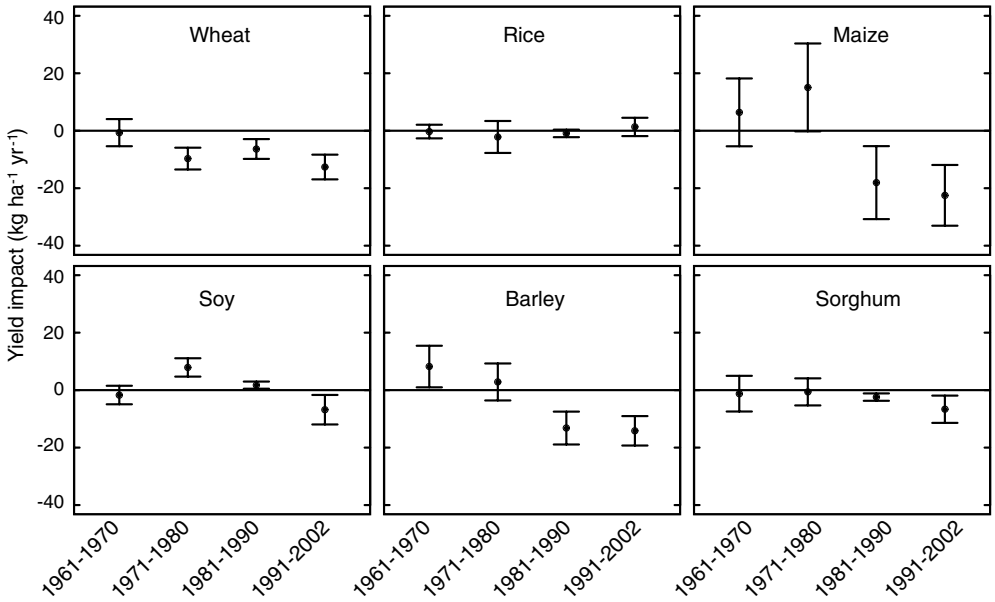

Figure 3. Estimated yield impacts of climate trends by decade. Negative values indicate yield losses. Error bars show 95% confidence interval, and the role of climate is significant in cases where the error bar does not cross the yield impact = 0 line.

Table 2. Global area, production and yield changes for six major crops.

	Wheat	Rice	Maize	Soybean	Barley	Sorghum
2002 Area (Mha)	214	148	139	79	55	42
2002 Production (Mt yr^{-1})	574	578	602	181	137	54
Yield change, 1981–2002 (kg ha^{-1})	846	1109	1178	632	473	−80
Climate-driven yield change, 1981–2002 (kg ha^{-1})	−88.2	−10.5	−90.3	23.1	−144.9	−19.5
Climate-driven production change, 1981–2002 (Mt yr^{-1})	−18.9	−1.6	−12.5	1.8	−8.0	−0.8

accounts for the spatial distribution of each crop. A simple, unweighted average did not perform as well, as expected, since growing regions of these major crops are distinct and yield differences were not highly correlated.

3.2. Yield impacts of recent climate trends

The estimated impacts of climate on yield trends were statistically significant for several crops, especially since 1980 (figure 3, table 2). These inferred impacts reflect only the climate influences that were captured by the empirical models. In cases where much of the yield variance was unexplained by the models (e.g. rice), there are likely important climate influences not accounted for which may have also contributed to yield trends.

For wheat, maize and barley, negative yield impacts for the 1980s and 1990–2002 indicate that recent climate trends have, unless addressed through adaptation measures, suppressed global yield progress for these three crops. Effects are less pronounced for other crops and decades, though with significant yield suppression for soybean and sorghum since 1990, and wheat in the 1970s. All instances of significant yield effects were attributable mainly to warming temperature trends, as precipitation trends had only minor effects on yields (not shown).

While small when expressed as a percentage of current yields, the absolute losses in global production due to warming trends since 1981 were substantial. Wheat, maize and barley production in 2002, for example, would have been roughly 2–3% higher without climate trends since 1981. The foregone production, 19 Mt yr^{-1} for wheat, 12 Mt yr^{-1} for maize and 8 Mt yr^{-1} for barley, translates to annual global losses of $2.6B, $1.2B, and $1.0B, respectively, using 2002 producer prices for the US [6]. The wheat and maize production lost to climate change is roughly equivalent to the total wheat and maize production of Argentina [6].

The sensitivity of results to the method of detrending was evaluated by repeating the analysis with several different approaches: (i) first-differences (as used above); (ii) removal of a linear time trend; (iii) removal of a cubic-spline trend, which allows for nonlinear technological trends; (iv) inclusion of a time trend in the regression between (non-detrended) yields and climate. In addition, the effect of using t_{min} and t_{max} as separate variables was evaluated by repeating the analyses using only average temperature (t_{avg}). All approaches resulted in negative estimates for total impacts of climate trends since

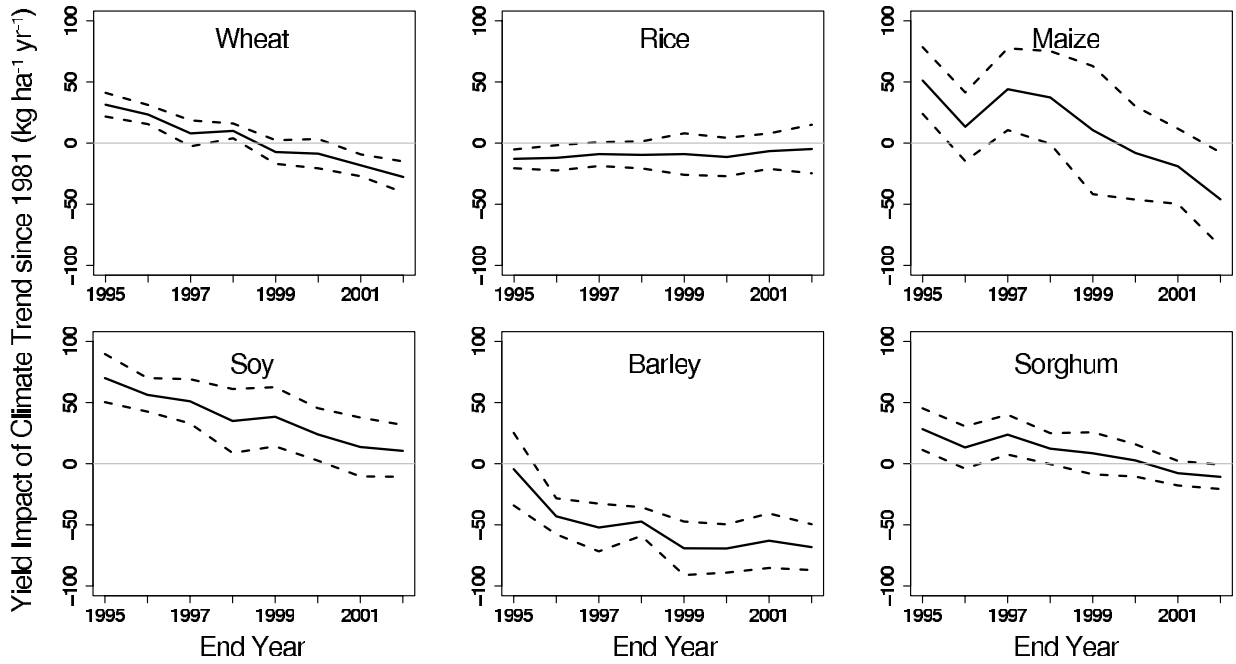

Figure 4. The effect of time period on the inferred effect of climate on yield trends, estimated by re-computing trends for all possible ending years using 1981 as a starting year. The solid line shows the mean estimate of climate effect on yield trends from 1981 to the year shown on the x axis. Dotted lines indicate 95% confidence interval. The effect of climate trend becomes clearly negative for maize only when including all data up to 2002. Other crops (e.g. barley) were less sensitive to the time period.

Table 3. The estimated impacts of climate trends since 1981 on 2002 production levels (Mt) using different detrending methods and temperature variables. The methods are (i) first-differences (as used in table 2); (ii) removal of a linear time trend; (iii) removal of a cubic-spline trend, which allows for nonlinear technological trends; (iv) inclusion of a time trend in the regression between (non-detrended) yields and climate.

		Estimated change in 2002 production (Mt) due to 1981–2002 climate trends						
Method	Temperature variables	Wheat	Rice	Maize	Soybean	Barley	Sorghum	Total
i	t_{min}, t_{max}	−18.9	−1.6	−12.5	1.8	−8.0	−0.8	−40.0
i	t_{avg}	−14.8	−1.5	−20.7	−1.6	−8.3	−1.0	−48.0
ii	t_{min}, t_{max}	−13.5	1.1	−5.6	2.8	−5.1	−1.2	−21.5
ii	t_{avg}	−10.8	−1.0	−18.4	−0.7	−6.2	−1.2	−38.3
iii	t_{min}, t_{max}	−13.5	−3.4	−9.3	2.6	−5.2	−0.6	−29.4
iii	t_{avg}	−10.8	−0.6	−19.1	−1.2	−6.1	−0.6	−38.4
iv	t_{min}, t_{max}	−13.2	−1.2	−5.2	4.4	−6.6	−1.5	−23.3
iv	t_{avg}	−11.0	−1.0	−15.2	−1.0	−6.6	−1.8	−36.5

1981 (table 3), with most close to the value of 40 Mt reported above. Inferred impacts were consistently higher for wheat when using t_{min} and t_{max} separately than when using t_{avg} for two reasons. First, wheat yields were more sensitive to t_{min} than t_{max}. Second, observed trends in t_{min} were more positive than for t_{max}. For maize, yield impacts were greater when using t_{avg} because maize yields were more sensitive to t_{max}, which exhibited smaller trends than t_{min} for 1981–2000.

Estimates of lost production due to climate change are also potentially sensitive to the time period analysed. We addressed this by re-computing trends for all possible ending years, using 1981 as a starting year. Omitting the last 3–4 years of the study period had significant effects on inferred wheat and maize losses, with less sensitivity for barley (figure 4). For example, when maize yields were analysed for the 1982–98 period used in a previous study [20], the net effect of climate trends switched to slightly positive, in agreement with the conclusion of that study that part of the 1982–98 yield trend in the US resulted from a period of regional cooling. These sensitivities indicate that warming since 1998 had high leverage on the estimated impacts of climate trends. This study did not consider years after 2002, because of a lack of gridded climate data, but warming effects have likely been more substantial over this time period, since 2003–5 represent three of the warmest five years in the past century [21].

A final sensitivity test was performed to evaluate how results depended on the choice of growing season. For each possible growing season definition (i.e. range of months),

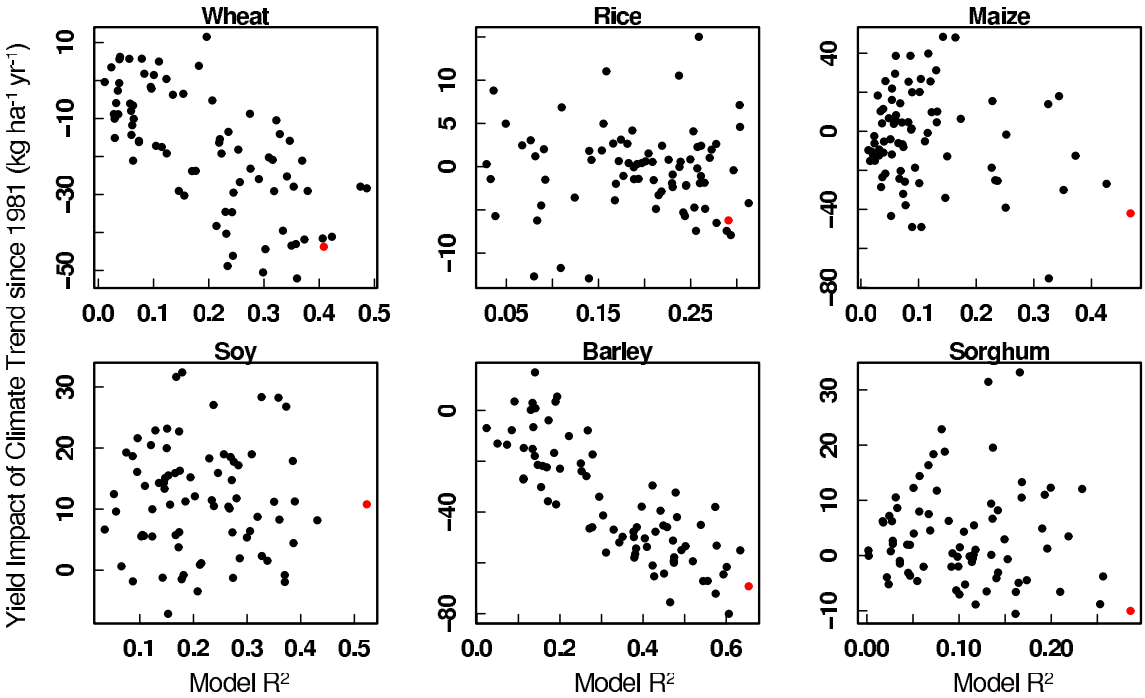

Figure 5. The inferred impact of climate trends for 1981–2002 on yields versus the R^2 of the regression model used to estimate impacts. Each point represents a different definition of growing season months, with all possible combinations of starting and ending months. Models with high R^2, assumed to represent the most plausible growing season, tended to have similar estimates of yield effects for wheat, maize and barley. The red point indicates the growing season definition reported in the paper.

a regression between climate and yields was developed and applied to observed climate trends. All models with high R^2, assumed to represent the most plausible growing seasons, tended to have similar estimates of yield effects for wheat, maize and barley (figure 5). Thus, the inferred effect of climate trends on yields appears relatively insensitive to the particular choice of growing season.

4. Conclusions

The results suggest that recent climate trends, attributable to human activity [22], have had a discernible negative impact on global production of several major crops. The impact of warming was likely offset to some extent by fertilization effects of increased CO_2 levels, although the magnitude of these effects are uncertain and the subject of much debate [23–25]. We attempted to estimate CO_2 effects using the same approach we used for temperature, but year-to-year differences in the size of the CO_2 increment were too small to result in a measurable yield signal. If each additional ppm of CO_2 results in ∼0.1% yield increase for C_3 crops (a yield increase of 17% for a concentration increase from the current 380 ppm to the frequently studied 550 ppm) [23, 24], then the ∼35 ppm increase since 1981 corresponds to a roughly 3.5% yield increase, about the same as the 3% decrease in wheat yield due to climate trends over this period. Thus, the effects of CO_2 and climate trends have likely largely cancelled each other over the past two decades, with a small net effect on yields. This conclusion, while tempered by the substantial uncertainty in yield response to CO_2, challenges model assessments that suggest global CO_2 benefits will exceed temperature related losses up to ∼2° warming (1).

Potential impacts of temperature increases may have also been countered by adaptation measures taken by farmers, such as changes in planting dates or use of different cultivars. Any such gradual changes would not have been captured by the statistical models, which utilized detrended data. Thus, the yield impacts of climate trends reported here can be viewed as the expectation in the absence of explicit recognition of, and adaptation to, climate trends since 1980. The extent to which farmers adapt to climate trends is thus a source of uncertainty in estimating impacts of past climate change, as it is for projecting future impacts [1–5].

All models of crop yield are scale-dependent, and the global empirical/statistical models cannot reliably predict responses at sub-global scales. For example, the conclusion that climate trends have reduced global yield trends does not preclude the possibility that yield growth was enhanced by climate in some regions. In addition, these models are limited in their ability to simulate future yield responses when cropping areas shift (as evidenced by the recent expansion of soybean area in Brazil [6]), or when the range of future temperatures exceeds those for which the models were calibrated. Nonetheless, the historical temperature–yield relationships indicate that, at the global scale, warming from 1981 to 2002 very likely offset some of the yield gains from technological advances, rising CO_2 and other non-climatic factors.

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