UCRL-JRNL-221905

Global crop yield losses from recent warming

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June 9, 2006

Environmental Research Letters

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Abstract

Global yields of the world's six most widely grown crops – wheat, rice, maize, soybeans, barley, sorghum – have increased since 1961. Year-to-year variations in growing season minimum temperature, maximum temperature, and precipitation explain 30% or more of the variations in yield. Since 1991, climate trends have significantly decreased yield trends in all crops but rice, leading to foregone production since 1981 of about 12 million tons per year of wheat or maize, representing an annual economic loss of \$1.2 to \$1.7 billion. At the global scale, negative impacts of climate trends on crop yields are already apparent.

Annual global temperatures have increased by ~0.4 ºC 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 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 this balance would help to anticipate impacts of future climate changes, as well as to more accurately assess recent (and thereby project future) technologically driven yield progress.

Separating the contribution of climate from concurrent changes in other factors – such as crop cultivars, management practices, soil quality, and atmospheric carbon dioxide (CO_2) levels – requires models that describe the response of yields to climate. Studies of future global impacts of climate change have typically relied on a bottom-up approach, whereby field scale, process-based models are applied to hundreds of representative sites and then averaged (e.g., ref *2*). Such approaches require input data on soil and management conditions, which are often difficult to obtain. Limitations on data quality or quantity can thus limit the utility of this approach, especially at the local scale (*6*-*8*). At the global scale, however, many of the processes and impacts captured by field scale models will tend to cancel out, and therefore simpler empirical/statistical models with fewer input requirements may be as accurate (*8, 9*). Empirical/statistical models also allow the effects of poorly modeled processes (e.g., pest dynamics) to be captured and uncertainties to be readily quantified (*10*).

Here we develop new, empirical/statistical models of global yield responses to climate using datasets on broad-scale yields, crop locations, and climate variability. We focus on global average yields for the six most widely grown crops in the world: wheat, rice, maize, soybeans, barley, and sorghum. Production of these crops accounts for over 40% of global cropland area (11). 55% of non-meat calories, and over 70% of animal feed (12). Yield records for 1961-2002 were obtained from the Food and Agriculture Organization (FAO statistical databases, available at http://apps.fao.org). Gridded monthly temperature (minimum and maximum) and rainfall data at 0.5º x 0.5º for the same time period were obtained from the Climate Research Unit (CRU TS 2.1; (*13*)). 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. (*14*), resulting in crop-specific monthly time series of 'global' temperatures and rainfall for 1961-2002.

Yields for all crops increased substantially over the study period, and temperature and precipitation for several crops also exhibited significant trends (Figure 1). Direct comparison of trends in raw time series can be misleading, however, since factors such as management have also changed. We therefore computed the first-difference time series for yield and climate, and performed linear regressions with first differences in yield (ΔYield) as the response variable, and first differences of minimum temperature (tmin), maximum temperature (tmax), and precipitation (ppt) as predictor variables (*15, 16*). Rather than use annual averages for each climatic variable, we defined an effective "global growing season" for each crop as the range of months that produced the highest model R^2. These growing seasons were Aug-Sep (wheat), Sep-Oct (rice), July-August (maize and soy), Aug (sorghum), and May-Aug (barley). 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, and thus did not bias the interpretation of climate's influence on yields.

At least 40% of yield variance was explained by the predictors for all crops except rice and sorghum, for which the value was roughly one-third (Figure 2, Table S1). For comparison with the full regression models, the analysis was repeated using only average temperatures instead of both tmin and tmax. While this made little difference for several crops, it substantially reduced model accuracies for rice and wheat, with the latter dropping from 49% to 4% (Figure 2). This finding corroborates previous regional studies with rice (*17*) and wheat (*16*), which showed stronger effects of nighttime than daytime temperatures on crop yields, and suggests that differentiation between tmin and tmax in climate datasets and crop and climate models is important for predicting yield responses of these crops to climate changes.

That roughly half of global yield variance was unexplained by these models reflects the importance of variables omitted from this analysis. These likely include regional variations in climate responses, variations in climate statistics other than growing season averages, and changes in economic and other conditions that influence crop management. However, that roughly half of variance was explained signifies that a simple, integrated measure of global climate for each crop provides substantial information on global crop yields. This weighted global average importantly accounts for the spatial distribution of each crop. A simple, un-weighted average would not perform as well, as indicated by the fact that yield differences were in general not highly correlated, except for crops with similar growing regions such as maize-soybean and wheat-barley (Table S2).

To evaluate the role of climate in past yield trends, we applied the regression models to observed trends in climate variables for each decade since 1961, thereby estimating the climate-driven yield trend in each decade. The uncertainty due to sampling errors was estimated by bootsrap resampling of the historical data (with 100 bootstrap samples) and re-calibration of the regression model for each sample. Subtraction of the climate-driven yield trend from the observed yield trends revealed statistically significant differences for several crops, especially since 1980 (Figure 3). Importantly, these differences 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, yield trends after accounting for climate are significantly larger than observed yield trends in the 1980's and 1990-2002, indicating that recent climate changes have suppressed global yield progress for these three crops. Effects are less pronounced for other crops and decades, with yield suppression also seen for soybean and sorghum since 1990 (19).

Overall, the net effect of trends in the model climate variables since 1981 has been to reduce yield growth of all crops except soybean (Table 1). While small when expressed as a percentage of current yields, the absolute losses in global production were substantial. Wheat and maize production in 2002, for example, would have each been roughly 2% or 12 Mt higher without climate changes since 1981. This is roughly equivalent to the maize and wheat production of Argentina (*20, 21*). Using current global prices (*20*), this totals roughly \$1.2B and \$1.7B in annual global losses for maize and wheat, respectively, relative to no climate change. Climate trends since 1981 reduced 2002 barley production by roughly 8 Mt, or $1.0B per year.

The results suggest that recent climate changes, likely in part the result of human activity, have had a discernible negative impact on global production of several major crops. The temperature sensitivities estimated here were negative for all crops (Figure S1), in agreement with previous assessments that predict negative yield impacts of future warming. The impact of warming will likely be offset to some extent by increased CO_2 levels, although recent experimental results suggest this effect is smaller than previously believed (*22, 23*). We were unable to reliably estimate CO_2 effects in this study when including CO_2 as a predictor variable, as year-to-year changes of CO_2 were too small to result in a measurable yield signal (Table S1; *24*). If one assumes that each additional ppm of CO_2 results in ~0.05% yield increase for C_3 crops (*22*), then the ~35 ppm increase since 1981 corresponds to a roughly 1.75% yield increase. This is roughly the same magnitude as the 2% decrease in wheat yield due to climate changes over this period estimated above. Thus, we estimate that the effects of CO_2 and climate changes have largely cancelled each other over the past two decades, with a small net effect on yields. This challenges the conclusions of model assessments that suggest global CO_2 benefits will exceed temperature related losses up to ~2° warming (1).

All models of crop yield are scale dependent, and the global empirical/statistical models (Table S1) cannot reliably predict responses at sub-global scales. 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 (*20*)), or when the range of future temperatures exceeds those for which the models were calibrated.

Nonetheless, the empirical/statistical models point to the clear conclusion that recent warming has partially negated global yield gains from technological advances, rising CO_2, and other non-climatic factors.

Notes and References:

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19. These conclusions are somewhat sensitive to the break-points defined for each decade. For example, if maize yields are analyzed for the 1982-1998 period used in (18), the net effect of climate trends switched to slightly positive, in agreement with the findings of that study. For further details, see Figure S1.
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25. This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48. This research was supported by a Lawrence Fellowship from LLNL to DBL and by the Carnegie Institution of Washington.

Table 1. Global area, production, and yield changes for six major world crops

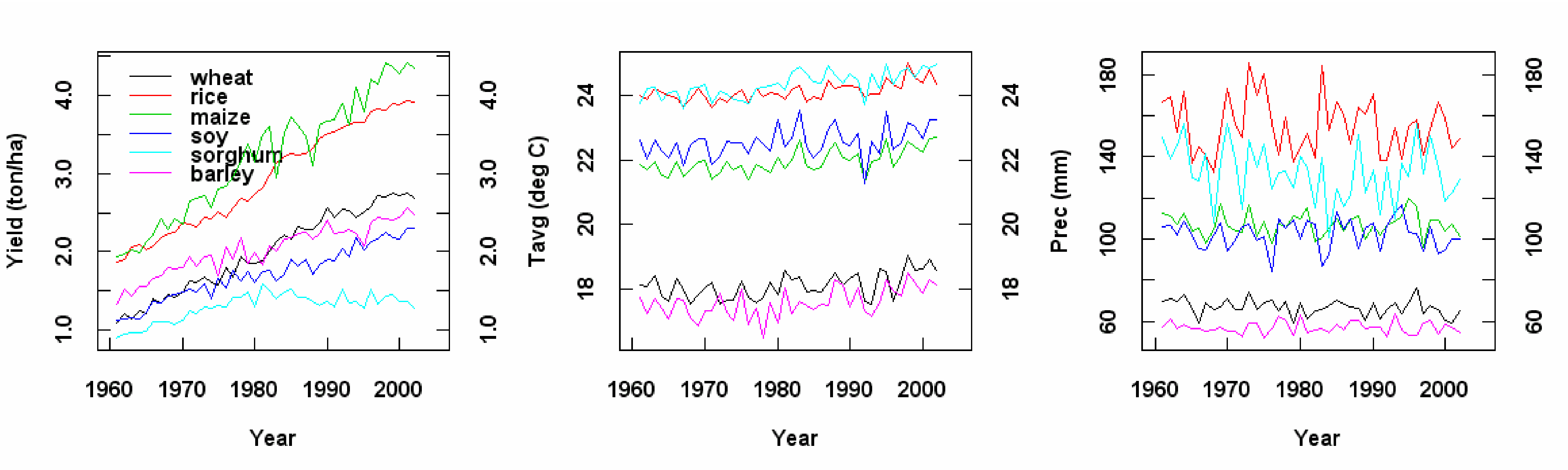
	Wheat	Rice	Maize	Soybean	Barley	Sorghum
2002 Area (Mha)	214	148	139	79	55	42
2002 Production (Mt yr^{-1})	574	578	602	181	137	54
Yield change, 1981-2002 (kg/ha)	846	1109	1178	632	473	-80
Climate driven yield change, 1981-2002 (kg/ha)	-60.1	-6.5	-89.5	23.1	-140.3	-20.0
Climate driven production change, 1981-2002 (Mt yr^{-1})	-12.9	-1.0	-12.4	1.8	-7.8	-0.8

Figure Legends

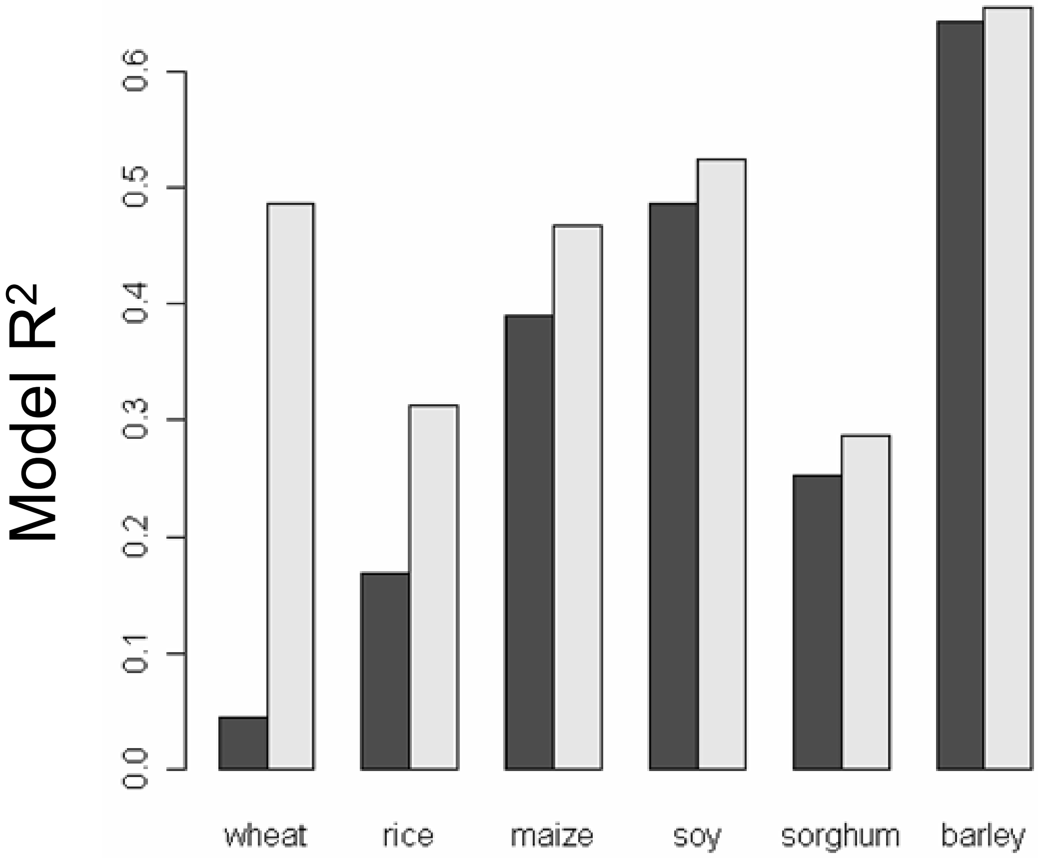
Figure 1. Time series of (a) yields and (b) growing season average monthly temperature and (c) rainfall for 6 crops, 1961-2002.

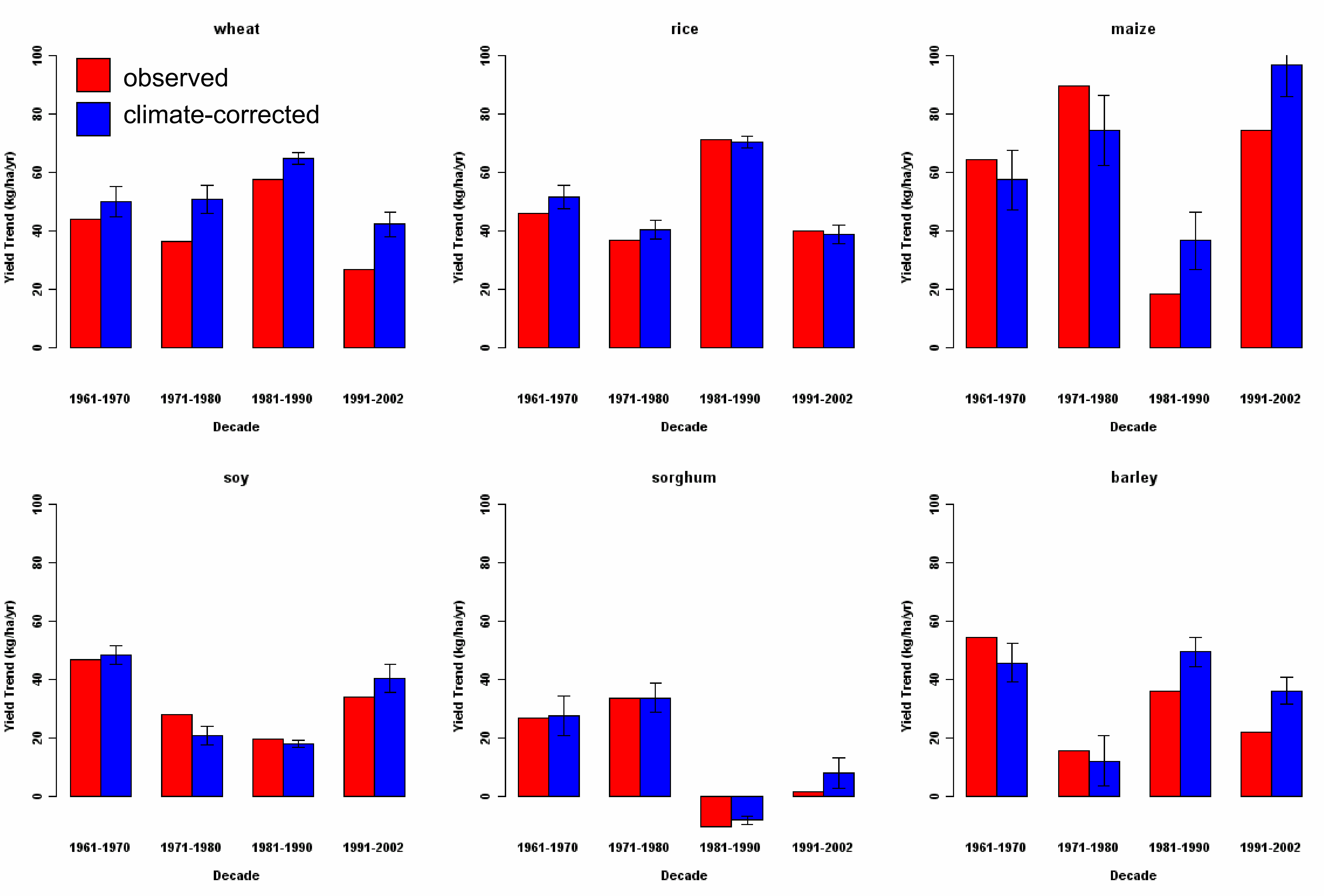
Figure 2. Coefficient of determination (R^2) of each model. Dark bar is using tavg, light bar using tmin and tmax.

Figure 3. Observed yield trends by decade and estimated yield trends after removing modeled effect of temperature and rainfall. Error bars show 95% confidence interval for climate-corrected yield trends.



wheat
rice
maize
soy
sorghum
barley
Yield (ton/ha)
1.0
2.0
3.0
4.0
1960
1970
1980
1990
2000
Year
Tavg (deg C)
18
20
22
24
1960
1970
1980
1990
2000
Year
Prec (mm)
60
100
140
180
1960
1970
1980
1990
2000
Year


Model R²
0.0
0.1
0.2
0.3
0.4
0.5
0.6
wheat
rice
maize
soy
sorghum
barley


wheat
rice
maize
soy
sorghum
barley
observed
climate-corrected
Yield Trend (kg/ha/yr)
0
20
40
60
80
100
1961-1970
1971-1980
1981-1990
1991-2002
Decade

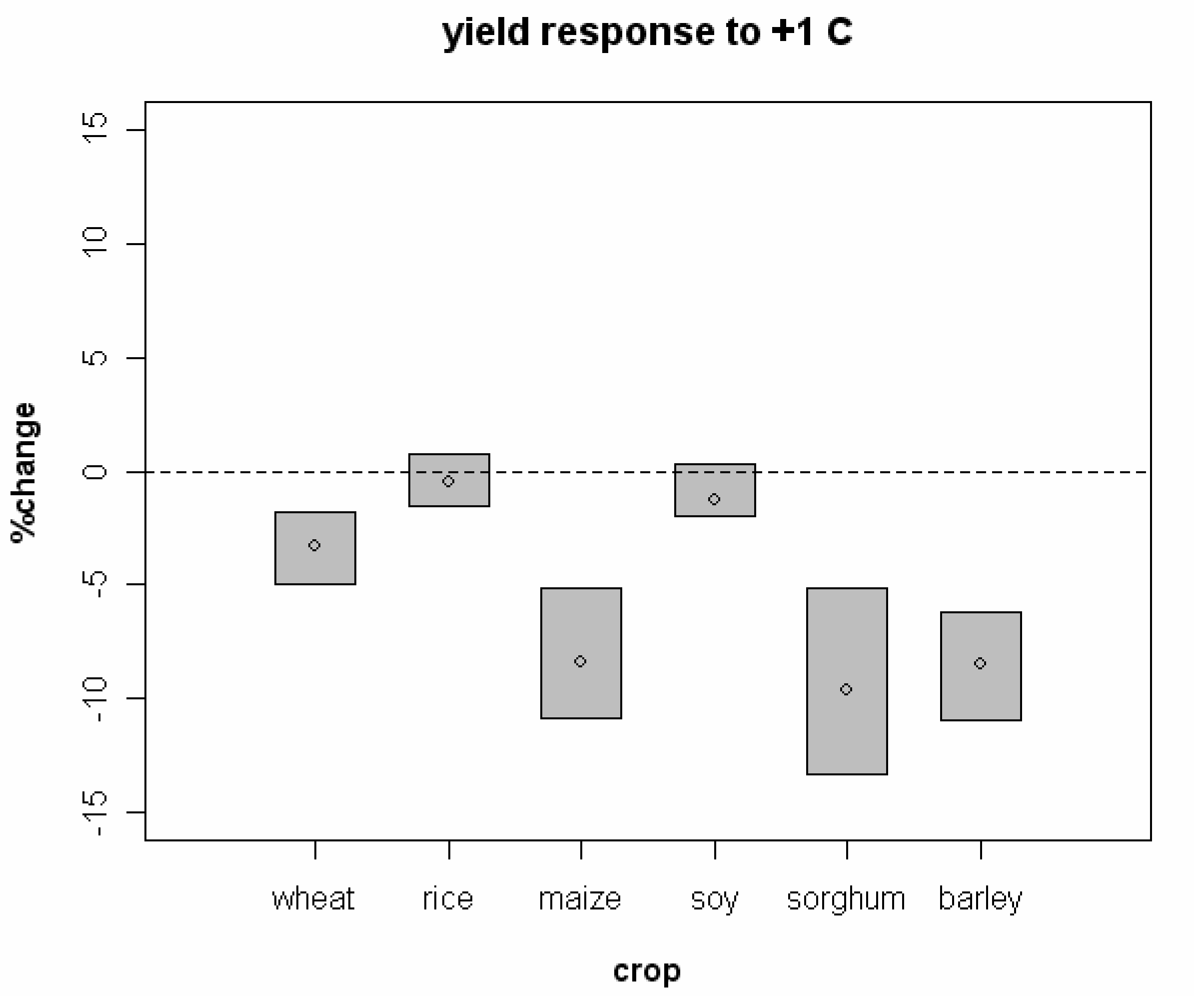


Figure S1. The inferred response of global yields for six crops to a 1 ºC temperature increase. Dots and bars show medians and 90% confidence intervals, respectively.

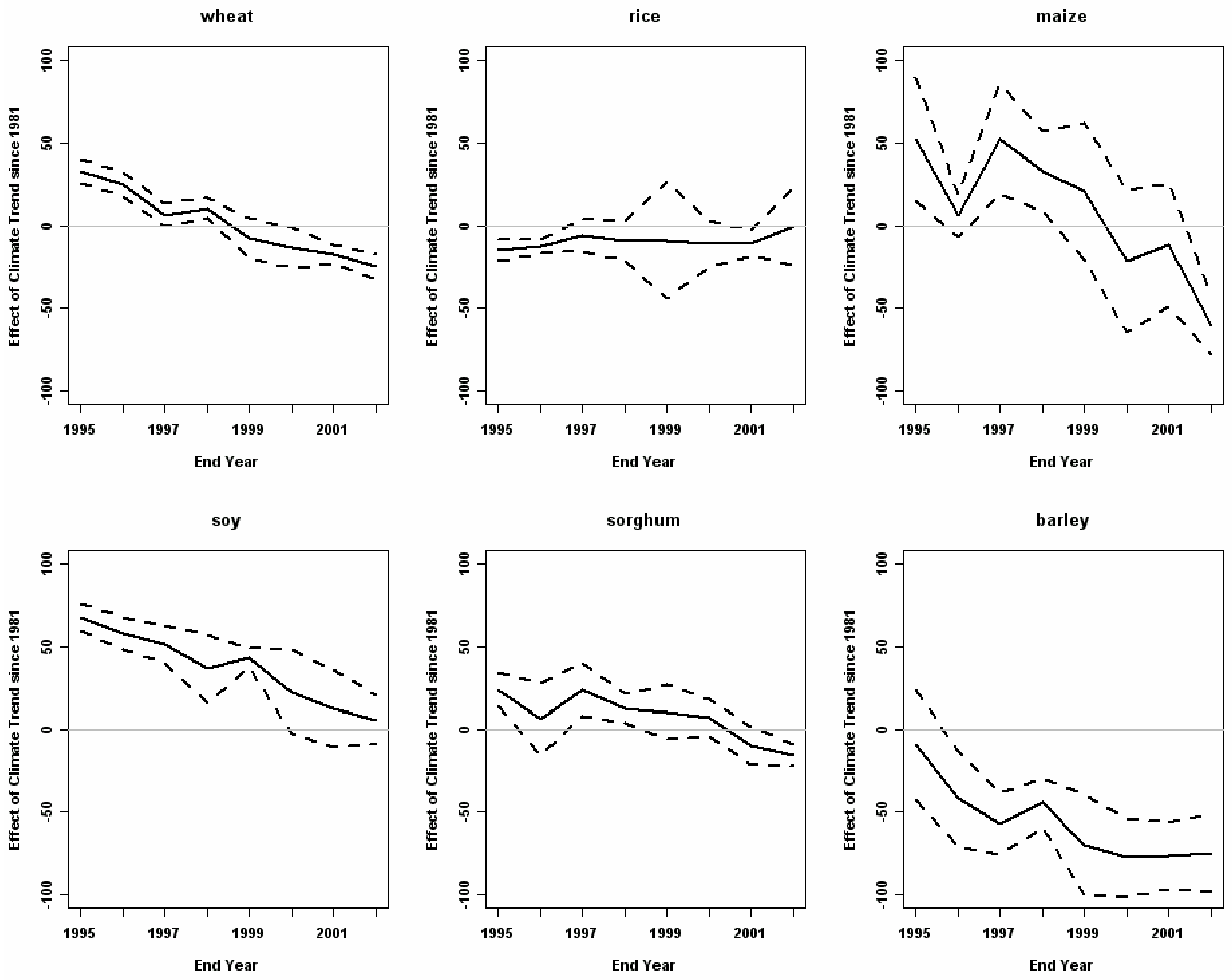


Figure S2. The effect of time period on the inferred effect of climate trends on yield trends. Solid line shows the mean estimate of climate effect on yield trends from 1981 to the year shown on the x-axis. Dotted lines indicate 95% confidence interval. The effect of climate trend becomes clearly negative for maize only when including all data up to 2002. Other crops (e.g., barley) were less sensitive to the time period.

Table S1: Regression equations for year-to-year yield differences. All units are Mg ha^{-1}.

	wheat		rice		maize		soy		sorghum		barley	
	estimate	std error	estimate	std error	estimate	std error	estimate	std error	estimate	std error	estimate	std error
intercept	275	256	553	193	31	751	135	307	214	341	197	310
tmin	-3630	644	1043	402	1964	1749	690	529	289	719	-2320	1207
tmax	2623	514	-1283	490	-5671	1666	-1010	521	-1443	681	208	1042
precip	58	24	6	6	3	48	47	21	-1	10	80	56
co2	130	170	-37	128	435	504	105	203	-60	228	85	205

Table S2: Correlation of year-to-year yield differences, 1961-2002

crop	wheat	rice	maize	soy	sorghum	barley
wheat	1	0.15	-0.05	-0.22	0.04	0.71
rice	0.15	1	0.06	0.12	0.14	0.13
maize	-0.05	0.06	1	0.7	0.6	0.12
soy	-0.22	0.12	0.7	1	0.59	-0.19
sorghum	0.04	0.14	0.6	0.59	1	0
barley	0.71	0.13	0.12	-0.19	0	1