Climate trends and global crop production since 1980

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Efforts to anticipate how climate change will affect future food availability can benefit from understanding the impacts of changes to date. Here we show that in the cropping regions and growing seasons of most countries, with the important exception of the United States, temperature trends for 1980-2008 exceeded one standard deviation of historic year-to-year variability. Models that link yields of the four largest commodity crops to weather indicate that global maize and wheat production declined by 3.8% and 5.5%, respectively, compared to a counter-factual without climate trends. For soybeans and rice, winners and losers largely balanced out. Climate trends were large enough in some countries to offset a significant portion of the increases in average yields that arose from technology, CO_2 fertilization, and other factors.

Inflation-adjusted prices for food have shown a significant downward trend over the last century as increases in supply outpaced demand. More recently, food prices have increased rapidly and many observers have attributed this in part to weather episodes, such as the prolonged drought in Australia or the heat waves and wildfires in Russia. However, efforts to model the effects of climate on prices or food availability, even for individual countries, must consider effects throughout the world, given that agricultural commodities are traded worldwide and world market prices are determined by global supply and demand (*1*-*3*).

Global average temperatures have risen by roughly 0.13 ˚C decade^{-1} since 1950 (*4*), yet the impact this has had on agriculture is not well understood (*5*). An even faster pace of roughly 0.2 ˚C decade^{-1} of global warming is expected over the next 2-3 decades, with substantially larger trends likely for cultivated land areas (*4*). Understanding the impacts of past trends can help to gauge the importance of near-term climate change for supply of key food commodities. In addition, identifying which particular crops and regions have been most impacted by recent trends would assist efforts to measure and analyze ongoing efforts to adapt.

We develop a database of yield response models to evaluate the impact of these recent climate trends on major crop yields at the country scale for 1980-2008. Publicly available datasets on crop production, crop locations, growing seasons, and monthly temperature (T) and precipitation (P) were combined in a panel analysis of four crops (maize, wheat, rice, and soybeans) for all countries in the world (*6*). These four crops constitute roughly 75% of the calories that humans directly or indirectly consume (*7*).

Time series of average growing season T and P reveal significant positive trends in temperature since 1980 for nearly all major growing regions of maize, wheat, rice, and soybeans (Fig. 1-2, S1-4). To put the magnitude of trends in context, they are normalized by the historical standard deviation (σ) of year-to-year fluctations (i.e. a T trend of 1.0 means that temperatures at the end of the period were 1.0 σ higher than at the beginning of the period). A notable exception to the warming pattern is the United States, which produces ~40% of global maize and soybean and experienced a slight cooling over the period (Fig. 1). Overall, 65% of countries experienced T trends in growing regions of at least 1σ for maize and rice, with the number slightly higher (75%) for wheat and lower (53%) for soybean. Roughly one-fourth of all countries experienced trends of more than 2σ for each crop (Fig. 2). This distribution of trends stands in marked contrast to the 20 years prior to 1980, for which trends were evenly distributed about zero (Fig. 1). Precipitation trends were more mixed across regions and were significantly smaller relative to historical variability in most places. The number of countries with extreme trends reflected the number expected by chance (Fig. 2), indicating no consistent global shift in growing season average P.

Translating these climate trends into potential yield impacts requires models of yield response. Here, regression analysis of historical data is used to relate past yield outcomes to weather realizations. All models include T and P, their squares, country-specific intercepts to account for spatial variations in crop management and soil quality, and country-specific time trends to account for yield growth due to technology gains (6). Since our models are non-linear, both year-to-year variations in historical weather as well as the average climate are used for the identification of the coefficients (unlike a linear panel which only uses deviations from the average). However, we do not directly estimate the full set of adaptation possibilities that might occur in the long-term under climate change (*8*). For this reason, we prefer to view these not as predictions of actual impacts, but rather as a useful measure of the pace of climate change in the context of agriculture. The greater the estimated impacts, the faster adaptation (or any other action to raise yields) would have to occur to offset potential losses.

The models exhibited statistically significant sensitivities to T and P that are consistent with process-based crop models and the broader agronomic literature (Fig. S6-7). Given the hill-shaped yield-temperature function, predicted decreases are larger the warmer a country is to begin with. In particular, a 1 ˚C rise tended to lower yields by up to 10% except in high latitude countries, where in particular rice gains from warming. Precipitation increases yields for nearly all crops and countries, up to a point at which further rainfall becomes harmful. Tests of alternate climate datasets and groupings of countries identified some important differences but responses for most countries were robust to these model choices (Fig S8).

To estimate yield impacts of climate trends, the statistical models were used to predict annual yields for four scenarios of historical T and P: (i) actual T and actual P for each country for 1980-2008, (ii) actual T and detrended P, (iii) detrended T and actual P, and (iv) detrended T and detrended P. Trends in the difference between (iv) and (i) were used to quantify the impact of historical climate trends, whereas (ii) and (iii) were used to determine the relative contribution of T and P to overall impacts.

At the global scale, maize and wheat exhibited negative impacts for several major producers and global net loss of 3.8% and 5.5% relative to what would have been achieved without the climate trends in 1980-2008 (Fig. 3, Table 1). In absolute terms, these equal the annual production of maize in Mexico (23 MT) and wheat in France (33 MT), respectively. The net impact on rice and soybean was insignificant, with gains in some countries balancing losses in others. Among the largest country-specific losses was wheat in Russia (almost 15%), while the country with largest overall share of crop production (United States) showed no effect due to the lack of significant climate trends.

The majority of impacts were driven by trends in T rather than P (Fig. 3). Precipitation is an important driver of interannual variability of yields, and indeed our models often predict a comparable yield change for a 1σ change in P or T (Fig. S7). However, the magnitude of recent T trends (Fig. 2) is larger than those for P in most situations. This finding is consistent with models of future yield impacts of climate change, which indicate that changes in T are more important than changes in P, at least at the national and regional scales (*9, 10*).

Prior studies for individual countries and at the global scale also found that recent trends have depressed maize and wheat yields (*5*). For example, a recent study of wheat yields in France suggests that climate is an important factor contributing to stagnation of yields since 1990 (*11*). Similarly, warming trends in India have a well understood negative effect on yields, and are thought to explain part of the slowdown in recent yield gains (*12, 13*). For rice, the lack of significant impacts is consistent with a recent study of rice in Asia, which showed that past changes in average T had small effects at large scales, in part because of opposing influence of nighttime and daytime temperatures, and in part because of opposing climate trends in different countries (*14*). The trends reported in the current study are dependent on the time period used, 1980-2008, but adjustments to this time period do not qualitatively affect the results (Fig. S9). Separating the effects of maximum and minimum temperature, or different treatments of the time trend, also did not significantly alter the conclusions (Fig. S10-S11).

Climate is only one factor likely to shape the future (or past) of food supply. It is therefore important to assess how these impacts of climate trends compare to other factors over the same time period. As one measure, we divide the climate-induced yield trend by the overall yield trend for 1980-2008 in each country (Fig. 4). We emphasize that this is a simple metric of the importance of climate relative to all other factors, and does not address the overall pace of yield growth, nor does it separately attribute yield growth to the many technological and environmental factors that influence trends. However, it provides a useful measure of the relative importance of climate, with values of -0.1 indicating that 10 years of climate trend is equivalent to a setback of roughly one year of technology gains.

The ratio exhibits wide variation across countries because of differences in both the growth rate of average yields and climate impacts (Fig. 4). Cases where negative climate impacts represent a large fraction of overall yield gains include wheat in Russia, Turkey, and Mexico, and maize in China. Rice production in high latitude regions appears to have benefitted from warming, but latitudinal gradients are not apparent for other crops. Although temperate systems tend to be hurt less from a given amount of warming in many model assessments (*15*), in reality these systems often have much lower non-climatic constraints, for instance because of high fertilizer rates, which increases their sensitivity to weather (*9*). Moreover, temperate systems tend to warm more quickly than tropics (*16*), and as shown in Fig.1 several high latitude growing regions have seen dramatic warming since 1980.

Any model has its limitations, and we recognize a few caveats that are common to statistical models. Our approach may be overly pessimistic as it does not fully incorporate long-term adaptations that may occur once farmers adjust their expectations of future climate. Examples of this would include expansion of crop area into cooler regions, switches to new varieties (*17*), or shifts towards earlier planting dates, although there is little evidence that the latter is happening beyond what is expected from historical responses to warm years (*18*). Moreover, the incentives to innovate have been limited in most of our sample period as prices have been low. On the other hand, our estimates may be overly optimistic because data limitations prevent us from explicitly modeling effects of extreme temperature or precipitation events within the growing season, which can have disproportionately large impacts on final yields (*19*). For example, while we capture the decline in growing season total precipitation for wheat in India, there has also been a trend towards increased fraction of rain in heavy events which is likely harmful to wheat yields (*20*).

Finally, we note that the current study does not consider the direct effect of elevated CO_2 on crop yields that are captured in the smooth time trends. Atmospheric CO_2 concentrations at Mauna Loa, Hawaii have increased from 339 ppm in 1980 to 386 ppm in 2008 (www.esrl.noaa.gov/gmd/ccgg/trends/). Free-air CO_2 enrichment (FACE) experiments for C_3 crops (i.e., wheat, rice, and soybean) show an average yield increase of 14% in 583 ppm compared to 367 ppm (or 0.065% increase per ppm (*21*)). This suggests that the 47 ppm increase since 1980 would have boosted yields by roughly 3%. Impacts of higher CO_2 on maize were likely much smaller because its C_4 photosynthetic pathway is unresponsive to elevated CO_2 (*22*). Thus, the net effects of higher CO_2 and climate change since 1980 have likely been slightly positive for rice and soybean, and negative for wheat and maize (Table 1).

The fact that climate impacts often exceed 10% of the rate of yield change indicates that climate changes are already exerting a considerable drag on yield growth. To further put this in perspective, we have calculated the impact of climate trends on global prices using recent estimates of price elasticities for global supply and demand of calories (*23*). The estimated changes in crop production excluding and including CO_2 fertilization (columns (5) and (7) of Table 1, respectively) translate into average commodity price increases of 18.9% and 6.4% when we use the same bootstrap procedure as Table 3 in (22).

The current study considers production of four major commodities at national scales. There are many important questions at sub-national scales that our models cannot address, many important foods beyond the four modeled here, and many important factors that determine food security besides food production. Nonetheless, we contend that periodic assessments of how climate trends are affecting global food production can provide some useful insights for scientists and policy makers. Much needed to compliment this type of analysis are studies that evaluate the true pace and effectiveness of adaptation responses around the world, particularly for wheat and maize. By identifying countries where the pace of climate change and associated yield pressures are especially fast, this study should facilitate these future analyses. Without successful adaptation, and given the persistent rise in demand for maize and wheat, the sizable yield setback from climate change is likely incurring large economic and health costs.

Figures:

1) Maps of the 1980-2008 linear trend in (a) temperature and (b) precipitation for the growing season of the predominant crop (among maize, wheat, rice, and soybean) in each 0.5 x 0.5 grid cell. Trends are expressed as the ratio of the total trend for the 29-year period (e.g. ˚C per 29 years) divided by the historical standard deviation for the 1960-2000 period. For clarity, only cells with at least 1% area

covered by either maize, wheat, rice, or soybean are shown. Temperature trends exceed more than twice the historical standard deviation in many locations, whereas precipitation trends have been less dramatic.

2) The frequency distribution of country level growing season temperature (top) and precipitation (bottom) trends for 1960-1980 (left), and 1980-2008 (right) for four major crops, with trends expressed as the total trend for the period (e.g. ˚C per 29 years), divided by the historical standard deviation for the 1960-2000 period. The null distribution (derived from 10,000 runs with simulated random noise) is shown by gray line, reflecting the frequency of different trends expected by chance. The distribution across countries of precipitation trends for both 1960-1980 and 1980-2008, and temperature trends for 1960-1980, do not appear different than expected from random variation. In contrast, the temperature distribution for 1980-2008 is shifted relative to the null distribution, with temperature trends often two or more times larger than the historical standard deviation.

3) Estimated net impact of climate trends for 1980-2008 on crop yields for major producers and for global production. Values are expressed as percent of average yield. Gray bars show median estimate and error bars show 5-95% confidence interval from bootstrap resampling with 500 replicates. Red and blue dots show median estimate of impact for T trend and P trend, respectively.

4) Estimated net impact of climate trends for 1980-2008 on crop yields by country, divided by the overall yield trend per year for 1980-2008. Values represent the climate effect in the equivalent number of years of overall yield gains. Negative (positive) values indicate that the climate trend slowed (sped up) yield trends relative to what would have occurred without trends in climate.

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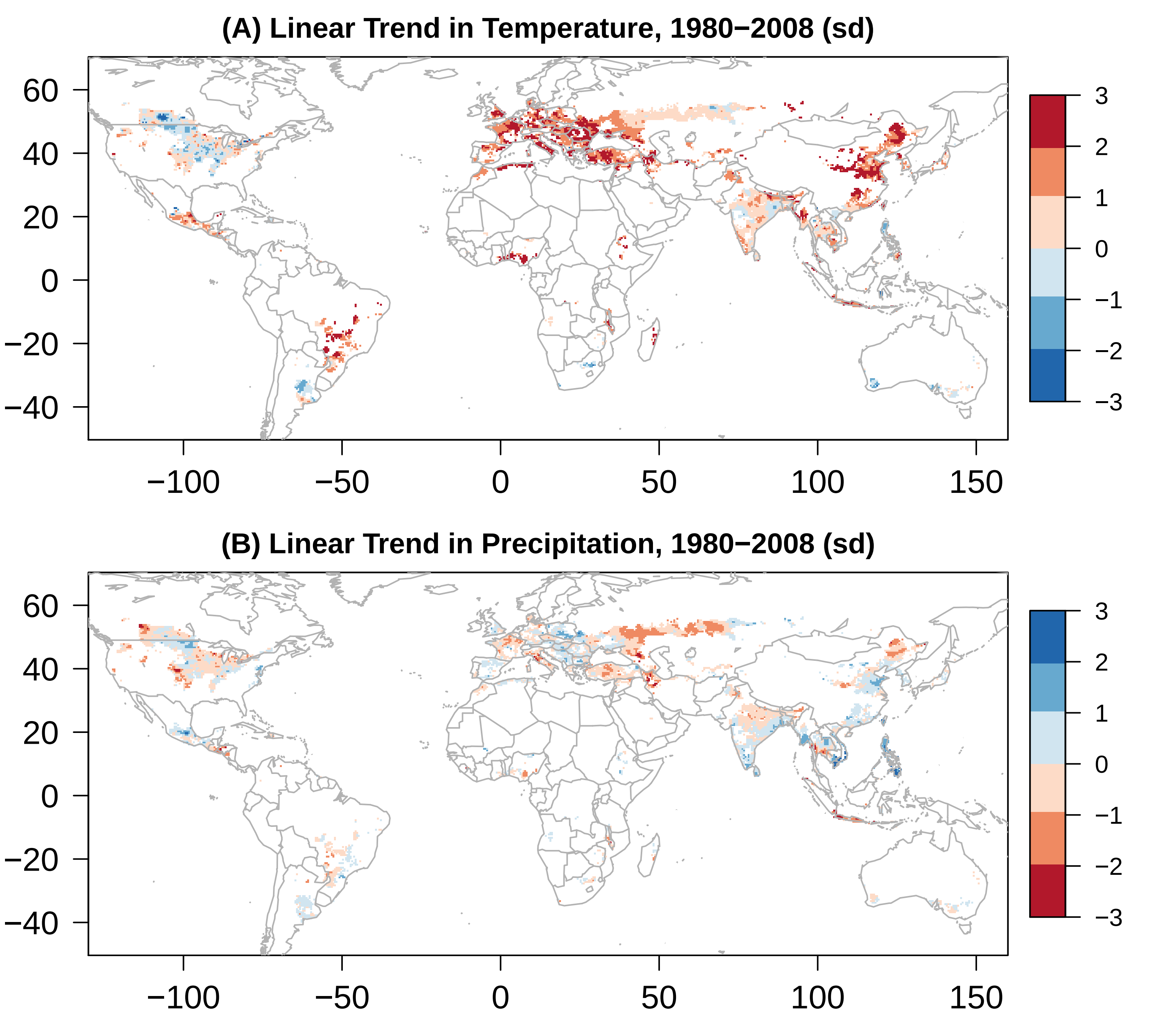
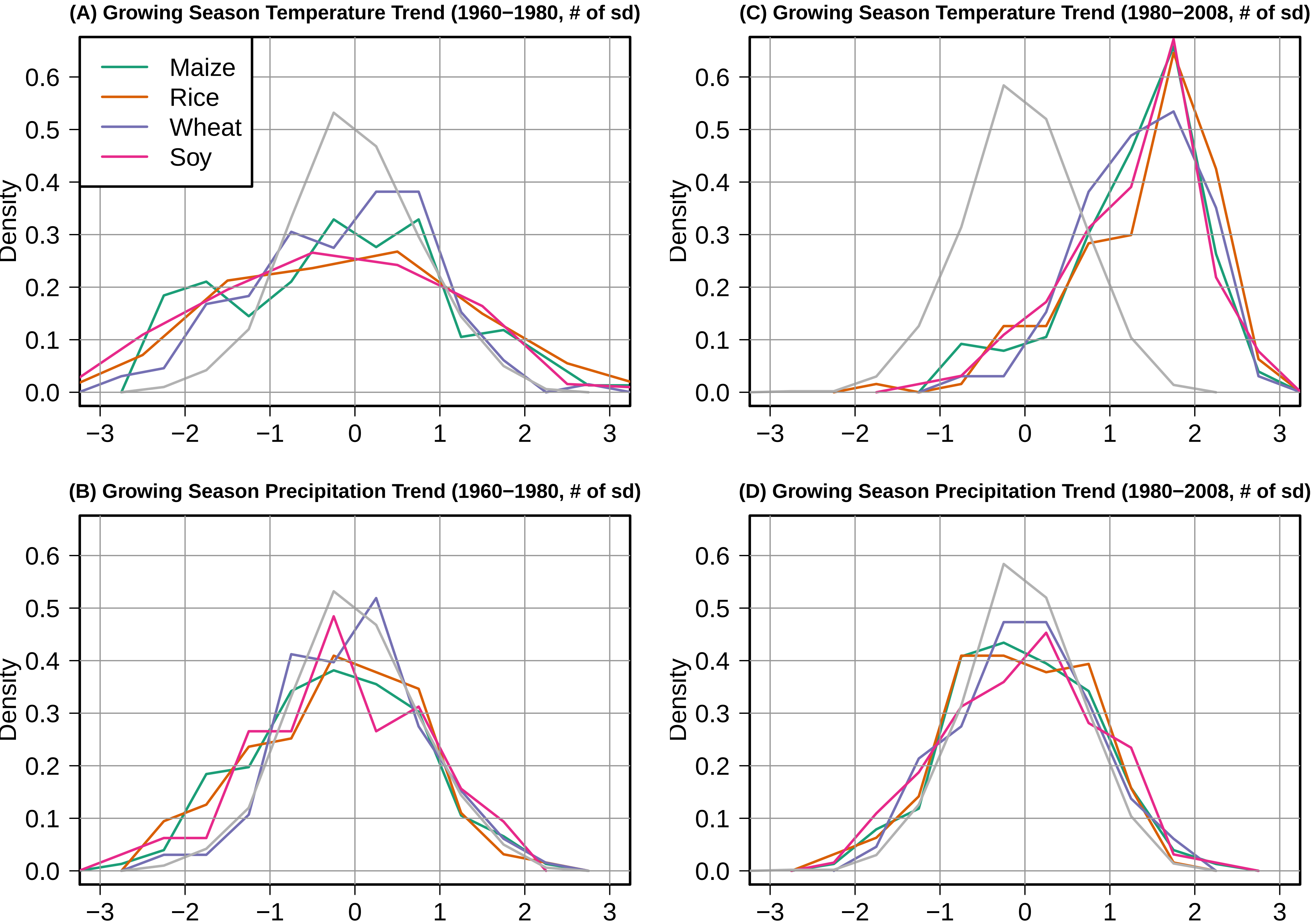
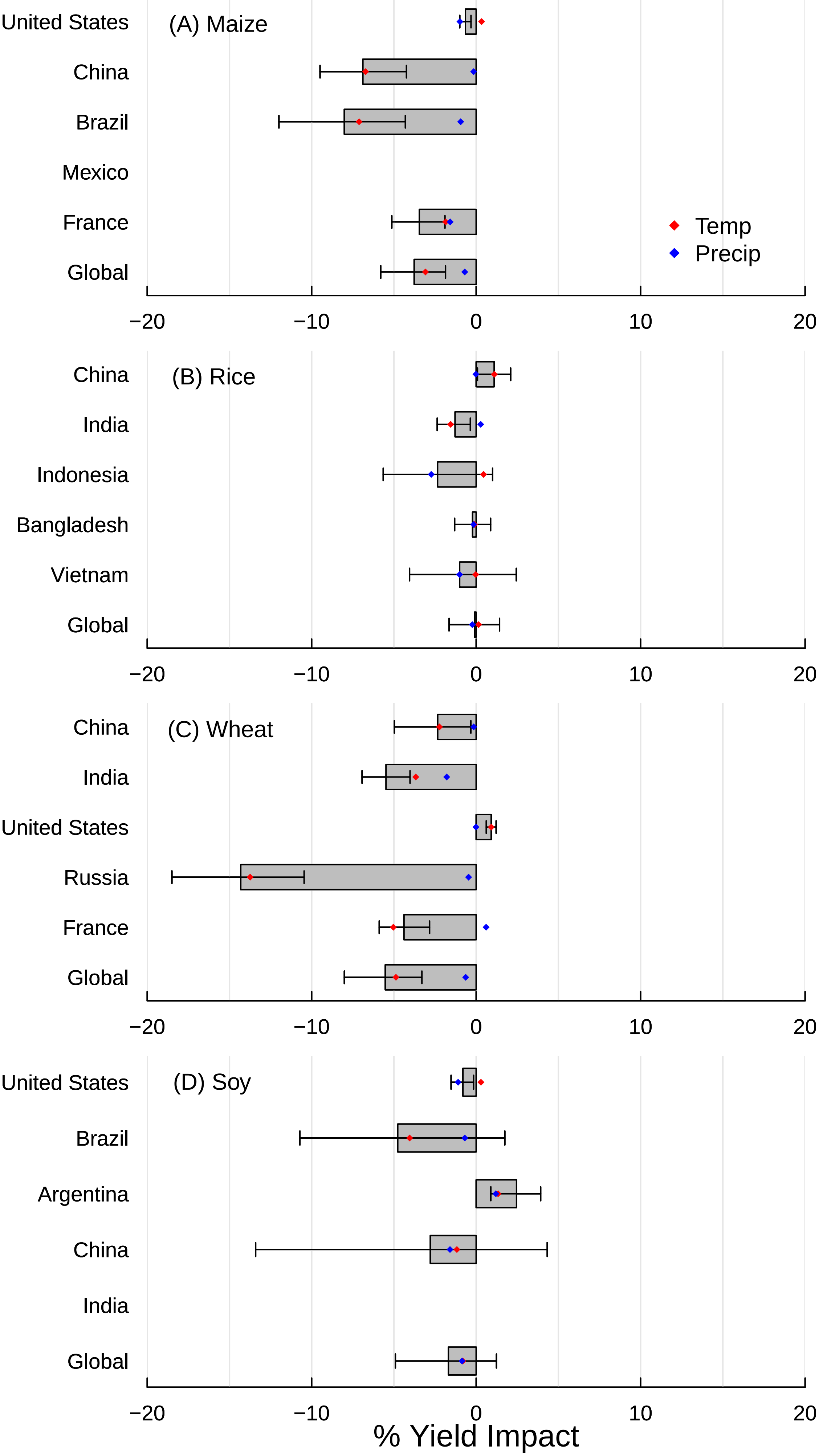
Table 1. Median estimates from this study of global impacts of temperature and precipitation trends, 1980-2008, on average yields for four major crops. Estimates of the 47 ppm increase in CO_2 over the time period were derived from data in (*21*). Values in parentheses show 5th-95th percentile confidence interval estimated by bootstrap resampling over all samples.

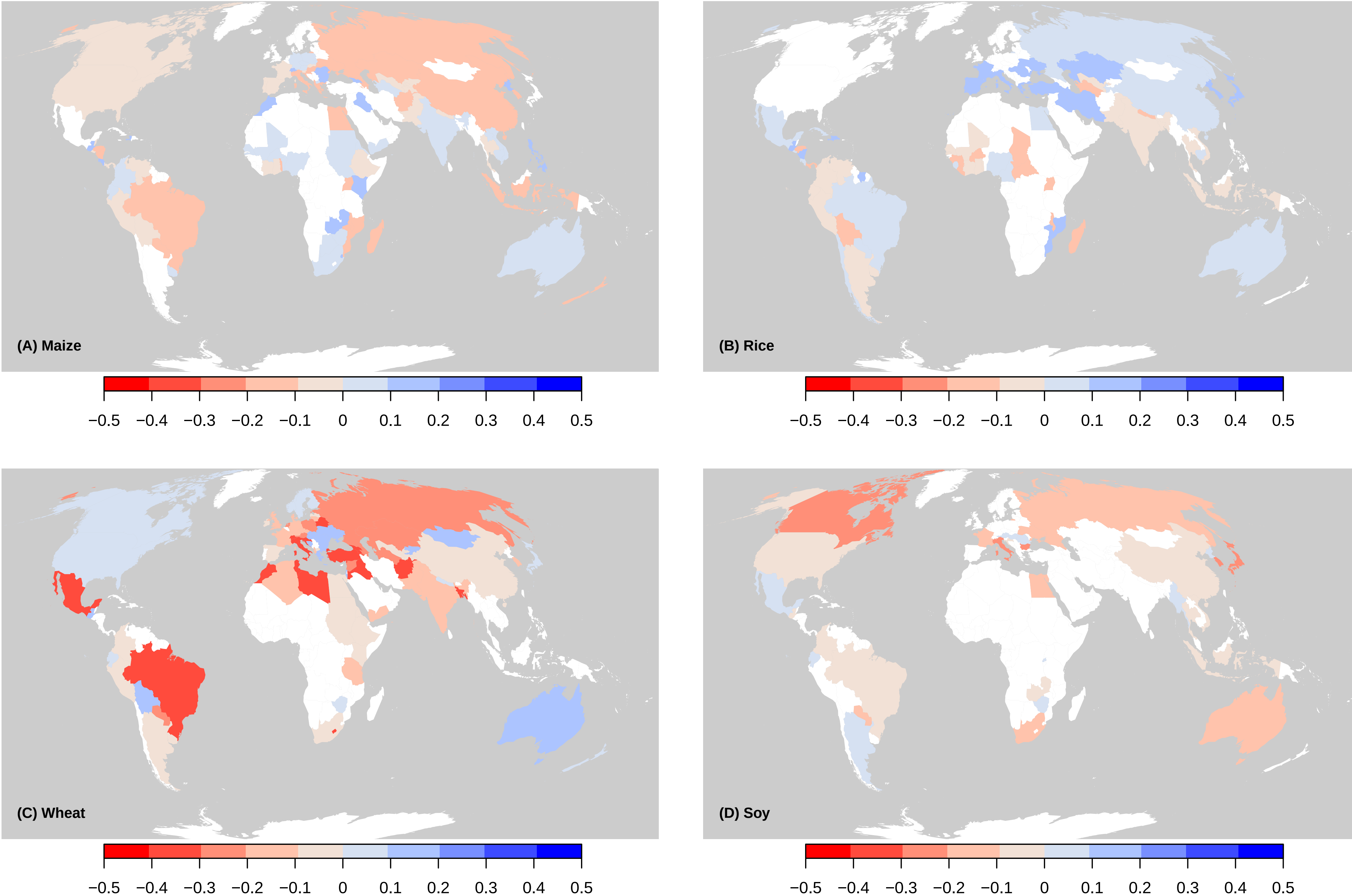
Crop	Global Production (1998-2002 average, million metric tons)	Global yield impact of temperature trends (%)	Global yield impact of precipitation trends (%)	Subtotal	Global yield impact of CO_2 trends (%)	Total
Maize	607	-3.1 (-4.9, -1.4)	-0.7 (-1.2, 0.2)	-3.8 (-5.8, -1.9)	0.0	-3.8
Rice	591	0.1 (-0.9, 1.2)	-0.2 (-1.0, 0.5)	-0.1 (-1.6, 1.4)	3.0	2.9
Wheat	586	-4.9 (-7.2, -2.8)	-0.6 (-1.3, 0.1)	-5.5 (-8.0, -3.3)	3.0	-2.5
Soybean	168	-0.8 (-3.8,1.9)	-0.9 (-1.5, -0.2)	-1.7 (-4.9, 1.2)	3.0	1.3


(A) Linear Trend in Temperature, 1980−2008 (sd)
60
40
20
0
−20
−40
−100
−50
0
50
100
150
3
2
1
0
−1
−2
−3
(B) Linear Trend in Precipitation, 1980−2008 (sd)
60
40
20
0
−20
−40
−100
−50
0
50
100
150
3
2
1
0
−1
−2
−3


(A) Growing Season Temperature Trend (1960−1980, # of sd)
(C) Growing Season Temperature Trend (1980−2008, # of sd)
(B) Growing Season Precipitation Trend (1960−1980, # of sd)
(D) Growing Season Precipitation Trend (1980−2008, # of sd)
Maize
Rice
Wheat
Soy
Density
0.0
0.1
0.2
0.3
0.4
0.5
0.6
−3
−2
−1
0
1
2
3



(A) Maize
United States
China
Brazil
Mexico
France
Global
Temp
Precip
(B) Rice
China
India
Indonesia
Bangladesh
Vietnam
Global
(C) Wheat
China
India
United States
Russia
France
Global
(D) Soy
United States
Brazil
Argentina
China
India
Global
−20
−10
0
10
20
% Yield Impact


(A) Maize
−0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5
(B) Rice
−0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5
(C) Wheat
−0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5
(D) Soy
−0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5