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The influence of climate change on global crop productivity

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Abstract

Climate trends over the past few decades have been fairly rapid in many agricultural regions around the world, and increases in atmospheric carbon dioxide (CO_2) and ozone (O_3) levels have also been ubiquitous. The virtual certainty that climate and CO_2 will continue to trend in the future raises many questions related to food security, one of which is whether the aggregate productivity of global agriculture will be affected. We outline the mechanisms by which these changes affect crop yields and present estimates of past and future impacts of climate and CO_2 trends. The review focuses on global scale grain productivity, notwithstanding the many other scales and outcomes of interest to food security. Over the next few decades, CO_2 trends will likely increase global yields by roughly 1.8% per decade. At the same time, warming trends are likely to reduce global yields by roughly 1.5% per decade without effective adaptation, with a plausible range from roughly 0% to 4%. The upper end of this range is half of the expected 8% rate of gain from technological and management improvements over the next few decades. Thus, effective adaptation that avoids climate-induced yield losses could play an important role in strategies to sustain global yield growth. Many global change factors that will likely challenge yields, including higher O_3 and greater rainfall intensity, are not considered in most current assessments.

1. Introduction

Many factors will shape global food security over the next few decades, including changes in rates of human population growth, income growth and distribution, dietary preferences, disease incidence, increased demand for land and water resources for other uses (i.e., bioenergy production, carbon sequestration, and urban development), and rates of improvement in agricultural productivity. This latter factor, which we define here simply as crop yield (I.e., metric tons of grain production per ha of land), is a particular emphasis of the plant science community, as researchers and farmers seek to sustain the impressive historical gains associated with improved genetics and agronomic management of major food crops.

Sources of growth in agricultural productivity are also multifaceted, and include levels of funding for public and private research and development, changes in soil quality, availability and cost of mineral fertilizers, atmospheric concentrations of carbon dioxide (CO_2) and ozone (O_3), and changes in temperature (T) and precipitation (P) conditions. This Update focuses on changes in weather, CO_2 and O_3 in agricultural areas, and how that has and will affect crop productivity. In doing so, we recognize that this is only part of the fuller story on crop productivity, which in turn is only part of the fuller story on future food security. For example, the Update is silent on the many ways that global change can influence food security via pathways other than agricultural productivity, such as by influencing human disease incidence or income growth rates.

The main question of interest here is "How important will climate change and CO_2 be in shaping future crop yields at the global scale, relative to the many other factors that influence productivity?" This question helps to set the challenge of climate adaptation in context. We are less concerned, for example, with whether impacts are statistically distinguishable from zero, than whether they are costly enough to justify a major acceleration of investment in agriculture in order to reach target growth rates.

Two spatial scales are of primary interest when discussing impacts of climate change on food security. One is the global scale, because most major sources of human calories (e.g., maize or wheat) are international commodities whose prices are determined by the balance of global supply and demand. In this context, individual regions are only of interest to the extent that they contribute to global supply. However, it is equally true that not all areas are fully integrated into global markets. In fact, many of the poorest and most food insecure areas currently lack the infrastructure and institutions needed to fully participate in global (and sometimes even regional) markets. Although most of these areas are more integrated into global markets than they used to be, and will be even more so over the next few decades, it is important that assessments of global food security consider local and regional impacts in addition to those at the global scale. If nothing else, transport costs will always make local supply more closely tied than global supply to local prices. For brevity and focus, this Update discusses mainly global scale issues.

Similarly, climate impact assessments must make choices about which crops to consider. By far the most common crops considered in published studies to date are (in order) wheat, maize, rice, and soybean (White et al., 2011). These crops are the main sources of human and livestock calories globally, as well as in many regions (Fig. 1a). They also directly or indirectly (via livestock) provide the bulk of protein in many regions (Fig. 1b). However, many other crops are important sources of calories (e.g., starchy roots in Africa, non-soybean vegetable oils, and sugar) or protein (e.g., pulses and seafood), yet there is relatively little known about their responses to climate change. Here we focus on the main grain crops that are most well studied, but also discuss other crops where possible.

The next section (2) describes some of the observed and projected climate changes of relevance to agriculture, which provide a foundation for understanding past and future impacts. Section 3 describes the various mechanisms by which climate, CO_2, and O_3 changes can affect crop productivity. Section 4 then integrates the understanding of climate trends and response mechanisms to discuss the likely past and future impacts of climate, CO_2, and O_3 changes on global crop productivity. Finally, sections 5 and 6 discuss some pending issues and conclusions. Throughout the paper, we emphasize changes and impacts not only in the future, but also for the recent past. The main rationale for this approach is that past trends are a reasonable starting point for what to expect in the next decades. For example, the rates of warming in most climate models are roughly linear for the 1980-2050 period, both at global and regional scales (Solomon et al., 2007).

2. **Climate trends in crop regions**

2-1. Observed trends

In the past several decades, air temperatures have been warming in most of the major cereal cropping regions around the world. As an illustration, Figure 2 shows the linear trend in growing season average maximum and minimum T (Tmax and Tmin, respectively) for 1980-2011, with the growing season defined based on crop calendars from (Sacks et al., 2010) for the predominant crop near the station location. Average trends were roughly 0.3 ˚C/ decade for Tmax and 0.2 ˚C/ decade for Tmin. There is a larger range in trends for Tmax as compared to Tmin (Fig 3, c & d), due to the greater impact of changes in cloudiness and radiation (associated with both natural variability and air pollution) on daytime relative to nighttime T (Lobell et al., 2007).

The trends in Figure 2 are consistent with those seen in a recent analysis of gridded temperature data (Lobell et al., 2011), which showed T trends from 1980 to 2008 higher than one standard deviation of historical variability in most cropping regions and growing seasons around the world, with the exception of the United States. Trends in mean T are also associated with an increased incidence of hot extremes and a reduced incidence of cold extremes (Alexander et al., 2006), which affect crop production through different mechanisms as discussed in section 2-2.

In contrast to T, historical changes in total growing season P have been more mixed and generally not significant relative to natural variability (Lobell et al., 2011). The intensity of P, however, has increased significantly in many parts of the world (Alexander et al., 2006). Soil moisture, of great direct relevance to agriculture, is influenced by changes in T (which affect evapotranspiration), and changes in the intensity and seasonal accumulation of P. Although long term measurements of soil moisture are rare, models can be used to estimate historical trends in agricultural drought occurrence and intensity based on changes in T, P, radiation, and other factors. In general, estimated moisture changes are not statistically significant in most regions, although since 1970 significant increases in drought extent and severity have been estimated for Africa, southern Europe, east and south Asia, and eastern Australia (Sheffield and Wood, 2008; Dai, 2011).

Atmospheric CO_2 concentrations have been rising rapidly since the start of the industrial era, with an average rate of growth of ~2 ppm/year in the 2000's (Peters et al., 2011). The 2010 global average concentration of 390 ppm was 39% higher than at the start of the Industrial revolution (i.e. 278 ppm in 1750; GCP, 2011). Global average tropospheric O_3 concentrations have also increased from ~10-15 ppb in the pre-industrial era to ~35 ppb at current levels due to emissions of ozone precursors associated with industrial activity. Regional spikes due to air pollution events can increase concentrations to over 100 ppb (Wilkinson et al., 2011). Recent emission control efforts have had some success in reducing peak levels, which are particularly damaging to crops (see below), although background levels have continued to rise (Oltmans et al., 2006). "Solar dimming" was also observed around the globe from 1950 to 1980, associated with increasing air pollution and aerosol loads (Wild, 2012). However, since then, global trends in radiation have been more neutral, with continued dimming in some areas (e.g. India and East Asia), and brightening in others (e.g. North America and Europe).

2-2. Projected Trends

The most robust feature of global warming in agricultural areas will continue to be T increases. Figure 3 shows projected changes from 16 climate models over a 50 year period (2040-2060 vs. 1990-2010) in June-August average T and P averaged over crop areas by continent. The average model projected rates of warming are similar to the mean observed rates since 1980 of roughly 0.3 °C/decade (Figure 2). There is no clear consensus on whether Tmin will warm faster or slower than Tmax (Lobell et al., 2007).

Although the expected rate of warming is similar to the past rate, it is also plausible that rates could be significantly higher or lower for any 10 or 20 year period. For example, global mean surface T (which includes both ocean and land) did not increase for the 10 year period following the strong 1998 El Niño, a fact that can be explained by natural variability counteracting the greenhouse driven trend (Easterling and Wehner, 2009). Conversely, it is plausible that we could observe 10-year trends of as much as 1°C in global mean T, which translates to as much as 2°C for major agricultural regions, because land warms faster than oceans (Easterling and Wehner, 2009).

Model projections of seasonal P accumulation indicate changes for continent-scale averages from -20% to +10% by 2050. Most of the spread in P projections, such as those in Figure 3, results from different realizations of natural variability in different model simulations, and reflects the substantial amount of P variability that comes from internal dynamics of the climate system (Hawkins and Sutton, 2009). The clearest consequence of greenhouse gas emissions will be increased P in high latitudes and decreased P in subtropical areas, such as the southwest US, Central America, Southern Africa, and the Mediterranean basin (i.e. southern Europe & north Africa) (Meehl et al., 2007). In other regions, most models do not predict changes in P that are large relative to natural variability, even by 2100 (Tebaldi et al., 2011).

Of more direct relevance to agriculture than P are changes in soil moisture and surface runoff, which depend on T and intensity of P in addition to total P. Even in regions without significant projected changes in total P, higher T will increase evapotranspiration rates, and along with more intense storms and an associated higher proportion of runoff, this will lead to significant drying trends in soil moisture and a higher risk of agricultural drought in many agricultural land areas in the coming century (Dai, 2011). A significant exception is northern North America and Eurasia, where projected increases in precipitation and permafrost thawing should lead to comparable or increased soil moisture.

CO_2 levels are anticipated to grow for at least the next century, as emission reductions of roughly 80% would be required to stabilize current atmospheric levels (Meehl et al., 2007). Growth rates of roughly 25 ppm per decade can be expected out to 2050, which would cause overall levels to reach 500 ppm around this time (IPCC, 2001). Ozone precursor emissions are also projected to continue rising in the coming decades, particularly in developing countries. Projections of future tropospheric O_3 concentrations and radiation levels are highly uncertain due to the uncertainty in emission pathways and air pollution control efforts, as well as the interaction of ozone precursors with a changing climate (Cape, 2008).

3. Crop response to global change

3-1 Mechanisms

This Update focuses on four primary factors that have and will continue to affect crop production in the coming decades: rising T, an intensified hydrological cycle, increasing CO_2, and elevated tropospheric O_3. Here we briefly discuss the various mechanisms by which each of these impacts crop physiology.

Temperatures affect yields through five main pathways. First, higher T causes faster crop development and thus shorter crop duration, which in most cases is associated with lower yields (Stone, 2001). Second, T impacts the rates of photosynthesis, respiration and grain-filling. Crops with C4 photosynthetic pathway (e.g., maize, sugarcane) have higher optimum T for photosynthesis than C3 crops (e.g., rice, wheat), but even C4 crops see declines in photosynthesis at high T (Crafts-Brandner and Salvucci, 2002). Warming during day can increase or decrease net photosynthesis (photosynthesis – respiration), depending on the current T relative to optimum, whereas warming at night raises respiration costs without any potential benefit for photosynthesis.

Third, warming leads to an exponential increase in the saturation vapor pressure of air. Assuming a constant relative humidity, warming therefore raises the vapor pressure deficit (VPD) between air and the leaf, which is defined as the simple difference between the saturation vapor pressure and the actual vapor pressure of the air. Relative humidity has remained roughly constant in recent decades over large spatial scales (Willett et al., 2007), and is projected to change minimally in the future as well. Increased VPD leads to reduced water use efficiency, because plants lose more water per unit carbon gain (Ray et al., 2002). Plants respond to very high VPD by closing their stomates, but at the cost of reduced photosynthesis rates and an increase in canopy temperatures, which in turn may increase heat-related impacts.

Fourth, T extremes can directly damage plant cells. Warming shifts the temperature probability distribution, such that hot and cold extremes become more and less likely, respectively. The reduction of spring and autumn frost risk will lead to a beneficial extension of the frost-free growing season in several temperate and boreal regions. For example, projections indicate a 2-week increase in the growing season for Scandinavia by 2030 compared to the late 20th century (Trnka et al., 2011). Northern China, Russia, and Canada are also expected to see large gains in the frost-free period suitable for crop growth (Ramankutty et al., 2002). On the other end of the spectrum, warming increases the likelihood of heat stress during the critical reproductive period, which can lead to sterility, lower yields and the risk of complete crop failure (Teixeira et al., 2012). Finally, rising temperatures, along with higher atmospheric CO_2, may favor the growth and survival of many pests and diseases specific to agricultural crops (Ziska et al., 2010).

An increased incidence of agricultural drought will increase crop water stress. An expansion of irrigation is a likely response in some regions, although many areas lack irrigation infrastructure, and water access can often be curtailed during periods of severe drought. In situations with shallow or medium depth to groundwater, plants may also be able to escape drought by accessing moisture below the surface. In general, though, crop plants will respond to reduced soil moisture by closing their stomates and slowing carbon uptake to avoid water stress, but thereby raising canopy temperatures and potentially increasing heat-related impacts. Water stress during the reproductive period of cereal crops may be particularly harmful (Stone, 2001; Hatfield et al., 2011), while changes in the timing of the rainy season, particularly in tropical areas, may confound traditional techniques for farmers to determine appropriate planting dates. Finally, more intense rainfall events may lead to flooding and waterlogged soils, also pathways for damaged crop production.

Rising atmospheric CO_2 concentrations provide some counteracting tendencies to the otherwise negative impacts of rising temperatures and reduced soil moisture. First, higher CO_2 has a fertilization effect in C3 species such as wheat, rice, and most fruit and vegetable crops, given that photorespiratory costs in the C3 photosynthesis pathway are alleviated by higher CO_2. Elevated CO_2 also has the benefit of reducing stomatal conductance, and thereby increasing water-use efficiency in both C3 and C4 crops (Ainsworth and Long, 2005). Yields are estimated to be enhanced by e.g. ~15% in C3 plants under a ~200 ppm atmospheric CO2 increase, although the relative benefit of this effect varies widely between studies, and is still a subject of considerable debate in the scientific literature (Long et al., 2006). Another debate surrounds the concern that CO_2 fertilization may reduce the nutritional quality of crops, especially in nutrient-poor cropping systems, through reduced nitrate assimilation and lower protein concentrations in harvestable yield (Taub et al., 2008).

Air pollutants such as NO_x, CO and CH_4 react with OH in the presence of sunlight to form tropospheric O_3, which causes oxidative damage to photosynthetic machinery in all major crop plants (Wilkinson et al., 2011). Aerosols from air pollution can also reduce plant-available radiation. These pollution-related impacts are likely to be highest in agricultural areas downwind of urban regions, but O_3 precursors can also be transported across continents. In fact, tropospheric O_3 concentrations above pre-industrial levels are currently found in most agricultural regions of the globe (Van Dingenen et al., 2009). Interaction effects may also occur between O_3 and elevated CO_2. For example, reduced stomatal conductance under elevated CO_2 will reduce O_3 uptake by crop plants, thereby limiting damage to the plant and maintaining biomass production (McKee et al., 2000). However, empirical evidence is mixed regarding the ability of elevated CO_2 to reduce the impact of O_3 on final yields (McKee et al., 1997). A related concern is that variety improvement in crops such as wheat has favored increased stomatal conductance, given that higher transpiration fluxes are generally associated with increased photosynthesis rates and final yields (Reynolds et al., 1994). However, a higher stomatal conductance implies more uptake of O_3, increasing sensitivity of more recent varieties to O_3 damage (Biswas et al., 2008).

In summary, while the individual mechanisms enumerated above are relatively well-understood (e.g., faster development at higher temperatures, or higher photosynthesis rates at elevated CO_2 in C3 crops), the interactions between various global change factors under field conditions create substantial complexity that is not currently well understood. For example, heat-induced shortening of the grain filling stage could limit the benefits from higher CO_2, or conversely, improved water use efficiency from higher CO_2 may help to reduce negative impacts of VPD increases or rainfall declines. Decades of plot-level (e.g., Kim et al., 2007; Shimono et al., 2007; Markelz et al., 2011) and open-air field experiments (e.g., Long et al., 2006; Wall et al., 2006; Zhu et al., 2011), as well as simulation modeling exercises (e.g., Long, 1991; Brown and Rosenberg, 1997; Grant et al., 2004) have been dedicated towards understanding the net impact of interactions between competing global change mechanisms at small scales. However, results have not always been conclusive, especially at regional scales relevant for projecting the future response of overall crop production to changing environmental conditions.

3-2 Cropping systems and crop-specific responses to global change

Global change factors will have varying impacts on cropping systems around the world, due to regional differences in rates of day and night-time warming, changes to the timing, frequency and intensity of precipitation, and exposure to O_3 and air pollution sources. Most aspects of farm management, such as the specific crops grown and level of inputs, also differ considerably by region and play an important role in shaping the impact of weather and climate change. Farmers are also likely to change these practices in response to climate change, for instance by sowing different crops or varieties, changing the timing of field operations, or expanding irrigation, and the socioeconomic capacity to make these adaptive changes will differ by region. Even atmospheric CO_2 increases, which will be uniform around the world, will have regionally disparate effects because of different mixtures of crop types and moisture conditions. Rather than attempt a review of observed or expected impacts, this section briefly discusses some important distinctions in cropping systems that drive much of the variation in net impacts:

- *Irrigated versus rainfed conditions:* Irrigated systems are generally less harmed than rainfed systems by higher Tmax, primarily because irrigation prevents effects of warming on water stress, and greater transpiration rates help to cool canopies and prevent losses related to direct temperature damage. For example, maize in the western United States, which is predominately irrigated, is much less sensitive to extreme heat than in eastern counties (Schlenker and Roberts, 2009). Because some crops, such as rice or sugarcane, tend to be more irrigated than others, irrigation also goes a long way towards explaining the relatively low sensitivity of certain crops to warming. For example, rice actually benefits from higher Tmax in many locations, at least until Tmax exceeds values that cause direct heat damage, whereas higher Tmin is harmful (Welch et al., 2010). Rainfed crops growing in very wet areas will behave similarly to irrigated crops.

- *Crop type:* Different crop species have different T optima, as well as different sensitivities to CO_2 and O_3. One useful distinction is between crops that originated in temperate environments, such as wheat and barley, vs. crops from tropical environments such as cassava or sorghum. A recent synthesis of the literature (Hatfield et al., 2011) identified optimal season average temperatures of 15 °C for wheat, 18 °C for maize, 22°C for soybean, 23 °C for rice and bean, and 25°C for cotton and sorghum. (For some crops, Hatfield et al. report a range, from which we take the lowest value). An important distinction for CO_2 sensitivity is between C4 grains (least responsive), C3 grains (more responsive) and root and tuber crops (most responsive). For example, a recent field study of cassava showed roughly a doubling of dry mass for a CO_2 increase from 385 to 585 ppm (Rosenthal et al., 2012).

- *Current temperatures relative to optimum*: A simple but often overlooked factor that determines regional or global average yield responses is the geographic distribution of crop production relative to optimum T. Figure 4 presents data on average growing season T and average yield for individual countries over the past two decades taken from (Lobell et al., 2011). The size of dots in the figure indicates the relative contribution to global production of the given crop (e.g., China has the biggest dot for rice, United States for maize). A lot of scatter is apparent because many factors affect yields other than T. However, for several crops, there is a clear tendency for yields to decline after the optimum T, which is shown in the thick gray line based on the numbers from Hatfield et al. (2011). (Note: barley is not reported in Hatfield et al. (2011), so we use the same value as for wheat, since barley should have a similar or slightly lower optimum T (Todd, 1982).) Also evident in Figure 4 is that, for some crops, most large producers have average season T that is above optimum. Even though warming would likely benefit countries to the left of the optimum, total global production will therefore tend to decrease for warming.

- *High vs. low nutrient status*: In high input systems with sufficient fertilizer, there may be more sensitivity to weather changes, given the lack of other limiting factors (Schlenker and Lobell, 2010). At the same time, high input systems will also be better able to take advantage of CO_2 fertilization in C3 crops while maintaining nutritional quality (Ainsworth and Long, 2005). For low fertility systems with minimal fertilizers, such as exist in many tropical areas, higher atmospheric CO2 should help to maintain biomass production under drought conditions, but higher CO2 is also more likely to decrease protein levels without additional N inputs into the system (Taub et al., 2008). Capacities will also differ between well-capitalized, high-input vs. subsistence-level, low-input farms in their ability to cope with, finance, and proactively plan for environmental change.

4. The relative role of climate and CO_2 trends in past and future productivity trends

Given an understanding of observed and projected trends in climate, CO_2, and O_3 (section 2), as well as knowledge of crop yield sensitivities to these factors (section 3), it becomes possible to estimate the net impact of changes in these factors on global crop productivity. It is necessary to estimate these impacts, rather than directly measure them, even when considering past trends, because it is simply not possible to observe a counterfactual world in which climate was not changing. Before turning to impacts of climate and other trends, however, it is useful to understand the context of overall productivity growth in agriculture.

4-1 Global trends in crop productivity

Yields of most major crops have increased markedly over the past half century, largely due to greater use of irrigation, chemical inputs, and modern crop varieties. Figure 5 shows average global yields for the six most important crops in terms of calorie production, as well as linear trends by decade. At the global scale, yield growth has been fairly linear over the past 50 years, with the exception of sorghum which has not improved since 1980. Of course, this linear growth rate translates to a declining percent increase over time (Figure 5c). The global aggregate also masks a lot of important differences between countries, with many high yielding countries already showing evidence of slowing growth rates (Cassman, 1999). Nonetheless, the global story has largely been one of sustained improvement in yields at a fairly steady rate over the last half century.

An important point when considering observed trends is that they reflect the combined impact of all factors influencing yield, including changes in climate and CO_2. Often, historical trends are used simply as an estimate for technology growth, but they are more correctly viewed as the result of various factors, the most important of which is usually, but not always, technology growth.

4-2 Estimating the impact of past climate and CO_2 trends

A growing number of studies have attempted to quantify impacts of recent climate trends on crop production. Here we present the main results from a global-scale study, which estimated impacts for the 1980-2008 period (Lobell et al., 2011). Warming trends were estimated to have lowered wheat and maize yields by roughly 6% and 4%, respectively, over the 29 year period, with relatively small impacts of P trends. Global soybean and rice yields were deemed to be relatively unaffected by changes so far. Figure 6 summarizes the results from Lobell et al. (2011), with results for barley and sorghum added for comparison with Figures 4 and 5. Yields for barley, maize, and wheat all increased substantially since 1980, but not as much as they would have if climate had remained stable. Yields for a counterfactual of no climate and no CO_2 trend are also shown, illustrating the benefit of higher CO_2 for C3 crops (estimated as roughly 3% for the 49 ppm increase over this time period).

The results in Figure 6 are almost entirely driven by increased T, as changes in P were small at the global scale. The impact of climate can therefore be easily understood as the straightforward consequence of the warming shown in Figure 2, and the fact that most barley, wheat, and maize areas are beyond their optimum T (Figure 4).

All crops in Figure 6 show a much larger difference between yields in 1980 and 2008 than between the observed and counterfactual yields in 2008. A casual observer might interpret this as evidence that climate has a very small impact on global food production or food security. However, food demand has also increased greatly since 1980, and so global prices and food security continue to be sensitive to small fluctuations in supply. For example, the roughly 3% loss in calories due to climate trends since 1980 (computed as a calorie- weighted average of the individual crop impacts), was estimated to translate to a roughly 20% increase in commodity prices relative to a counterfactual with no warming (Lobell et al., 2011). It is also worth noting that by ending in 2008, the study did not consider recent years that included several major climate events (Russian heat wave in 2010, United States drought in 2012), which had significant effects on food supply and prices.

4-3 Estimating the impact of future climate and CO_2 trends

Numerous studies have projected impacts of climate and CO_2 changes on future crop yields. Reviews and syntheses of these studies are available (e.g., Easterling et al., 2007), and point to a general conclusion that the benefits of CO_2 at the global scale will eventually be outweighed by the harm from climate change induced by CO_2 and other greenhouse gases. There is considerable debate about exactly when net impacts will become negative. As mentioned above, there is evidence that net global impacts for 1980-2008 were negative (Lobell et al., 2011) due to climate trends during this historical period, although that study focused on actual warming rather than just the amount of warming due to greenhouse gases.

We present in Table 1 a simple summary of how two key global change factors affecting global productivity (T and CO_2) could evolve over the next few decades. These numbers are intended as rough estimates of the overall impact on calorie supply from all major crops, averaged over the next 30 years. A likely scenario in the near-term is that warming will slow global yield growth by about 1.5% per decade, while CO_2 increases will raise yields by roughly the same amount. This balance is broadly consistent with the global picture emerging from many studies and major assessments. Past mid-century, it is likely that CO_2 benefits will diminish and climate effects will be larger (Easterling et al., 2007).

Table 1 also displays the range of plausible outcomes in the near term, which receive far less attention in the literature than the most likely outcome. It is plausible that the net effects of warming and CO_2 could be as negative as -3% per decade, or as positive as +2% per decade, depending on how fast T and CO_2 change and how responsive crop yields turn out to be. To consider whether 3% is a large number, one comparison is rates of yield growth in recent decades, which vary around an average of roughly 15% per decade (Figure 5C). Looking forward, projections that ignore climate and CO_2 effects anticipate a roughly linear continuation of recent yield in absolute terms, resulting in a lower percent growth rate of roughly 8% per decade to 2050 (Bruinsma, 2009). Thus, losses or gains of 2-3% per decade represent a significant fraction of past and, especially, future yield growth.

An important issue often overlooked in discussions of climate change impacts on agriculture is that the relevant quantity depends on the particular question at hand. There are at least three distinct perspectives on global scale productivity impacts, even without mentioning the much broader set of questions related to crop- or region- specific effects. Traditionally, people have focused on the question of the net effect of greenhouse gas emissions in order to inform mitigation policies. In that case, of most relevance is the combined effect of CO_2 plus all associated climate changes. However, if one is focused on policies related to adaptation to T and P changes, the effects of climate changes are of interest in themselves, regardless of potential benefits of CO_2. If one is instead interested in the question of how to account for climate and CO_2 in projections of overall productivity growth, the relevant issue is how much the effects of climate and CO_2 will change from one decade to the next, because historical yield trends include the effects of past climate and CO_2 trends.

5. Pending Issues

Improved estimates of global change impacts on global scale crop yield trends will require several scientific advances. Some, such as predicting rates of global T increase or behavior of farmers in the face of gradual trends, are beyond the scope of the traditional plant physiology community. Here we briefly mention three that seem particularly relevant to the audience of this journal.

First, the importance of interactions of elevated CO_2 and high T are still not well known. For example, how much does high CO_2 help reduce water stress associated with warming, and how much does it increase susceptibility to heat damage because of reduced cooling from transpiration? Conversely, how much does high T reduce the benefits of CO_2 by increasing pollen sterility and lowering grain numbers?

Second, as evident in the above discussion, the effects of O_3 are still not incorporated into most studies of global change impacts. Improved understanding of how O_3 affects yields by itself and in combination with high T and CO_2, and improved representation of current understanding in existing crop models are both needed.

Third, what are the benefits and limits of physiological changes relative to other adaptation strategies, such as encouraging migration of agricultural areas toward higher latitudes, or encouraging conservation agriculture and rainwater harvesting as a way to enhance soil moisture? What are the potential synergies between crop genetic changes and agronomic shifts, and what is the appropriate balance between investments in each?

6. Conclusions

Growth rates in aggregate crop productivity to 2050 will continue to be mainly driven by technological and agronomic improvements, just as they have for the past century. Even in the most pessimistic scenarios, it is highly unlikely that climate change would result in a net decline in global yields. Instead, the relevant question at the global scale is how much of a headwind climate change could present in the perpetual race to keep productivity growing as fast as demand. Overall, the net effect of climate change and CO_2 on global average supply of calories is likely to be fairly close to zero over the next few decades, but could be as large as 20-30% of overall yield trends. Of course, this global picture hides many changes at smaller scales that could be of great relevance to food security, even if global production is maintained (Easterling et al., 2007).

To reduce uncertainties in global impacts, better estimates of rates of global warming, and responsiveness of crop yields to warming and CO_2 (and their combination) would be particularly useful. We note that the responsiveness of yields will depend partly on the crops themselves, including any genetic improvements made to reduce sensitivity to T or improve responsiveness to CO_2, as well as adaptive management changes by farmers in choosing what, when, where, and how to grow their crops. Effects of changes in O_3 are currently much less understood but could also represent a significant impact at the global scale.

It will never be possible to unambiguously measure the effect of changes in climate, CO_2, and O_3, given the scale of global food production and the fact that agriculture is always changing in multiple ways. However, the best available science related to climate change and crop physiology indicates that climate change represents a credible threat to sustaining global productivity growth at rates necessary to keep up with demand. Increasing the scale of investments in crop improvement, and increasing the emphasis of these investments on global change factors, will help to sustain yield growth over the next few decades.

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References

Ainsworth EA, Long SP (2005) What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy. New Phytologist **165:** 351-371

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank A, Haylock M, Collins D, Trewin B, Rahimzadeh F (2006) Global observed changes in daily climate extremes of temperature and precipitation. J. Geophys. Res **111:** D05109, doi:05110.01029/02005JD006290

Biswas DK, Xu H, Li YG, Sun JZ, Wang XZ, Han XG, Jiang GM (2008) Genotypic differences in leaf biochemical, physiological and growth responses to ozone in 20 winter wheat cultivars released over the past. Global Change Biology **14:** 46-59

Brown RA, Rosenberg NJ (1997) Sensitivity of crop yield and water use to change in a range of climatic factors and CO2 concentrations: A simulation study applying EPIC to the central USA. Agricultural and Forest Meteorology **83:** 171-203

Bruinsma J (2009) The resource outlook to 2050. *In* Expert Meeting on How to Feed the World in 2050. Food and Agriculture Organization of the United Nations, Rome, Italy

Cape JN (2008) Surface ozone concentrations and ecosystem health: Past trends and a guide to future projections. Science of the Total Environment **400:** 257-269

Cassman KG (1999) Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. Proceedings of the National Academy of Sciences **96:** 5952-5959

Crafts-Brandner SJ, Salvucci ME (2002) Sensitivity of photosynthesis in a C4 plant, maize, to heat stress. Plant Physiology **129:** 1773-1780

Dai A (2011) Characteristics and trends in various forms of the Palmer Drought Severity Index during 1900–2008. Journal of Geophysical Research **116**

Dai A (2011) Drought under global warming: a review. Wiley Interdisciplinary Reviews: Climate Change **2:** 45-65

Easterling DR, Wehner MF (2009) Is the climate warming or cooling. Geophys. Res. Lett **36:** L08706

Easterling W, Aggarwal P, Batima P, Brander K, Erda L, Howden M, Kirilenko A, Morton J, Soussana JF, Schmidhuber J, Tubiello F (2007) Chapter 5: Food, Fibre, and Forest Products. *In* ML Parry, OF Canziani, JP Palutikof, PJvd Linden, CE Hanson, eds, Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., pp 273-313

FAO (2012) Food and Agriculture Organization of the United Nations (FAO), FAO Statistical Databases. *In*,

Grant RF, Kimball BA, Wall GW, Triggs JM, Brooks TJ, Pinter PJ, Conley MM, Ottman MJ, Lamorte RL, Leavitt SW, Thompson TL, Matthias AD (2004) Modeling Elevated Carbon Dioxide Effects on Water Relations, Water Use, and Growth of Irrigated Sorghum. Agronomy journal **96:** 1693-1705

Hatfield JL, Boote KJ, Kimball BA, Ziska LH, Izaurralde RC, Ort D, Thomson AM, Wolfe D (2011) Climate Impacts on Agriculture: Implications for Crop Production. Agron. J. **103:** 351-370

Hawkins E, Sutton R (2009) The Potential to Narrow Uncertainty in Regional Climate Predictions. Bulletin of the American Meteorological Society **90:** 1095-1107

IPCC (2001) Intergovernmental Panel on Climate Change Working Group 1, Climate Change 2001: The Scientific Basis. Appendix II - SRES Tables. *In*. IPCC Working Group 1

Kim S, Gitz D, Sicher R, Baker J, Timlin D, Reddy V (2007) Temperature dependence of growth, development, and photosynthesis in maize under elevated CO2. Environmental and Experimental Botany **61:** 224-236

Lobell DB, Bonfils C, Duffy PB (2007) Climate change uncertainty for daily minimum and maximum temperatures: a model inter-comparison. Geophysical Research Letters **34:** L05715, doi:05710.01029/02006GL028726

Lobell DB, Field CB (2007) Global scale climate-crop yield relationships and the impacts of recent warming. Environmental Research Letters **2:** 004000 (004007pp)

Lobell DB, Schlenker WS, Costa-Roberts J (2011) Climate trends and global crop production since 1980. Science **333:** 616-620

Long S (1991) Modification of the Response of Photosynthetic Productivity to Rising Temperature by Atmospheric Co2 Concentrations - Has Its Importance Been Underestimated. Plant Cell and Environment **14:** 729-739

Long SP, Ainsworth EA, Leakey ADB, Nosberger J, Ort DR (2006) Food for Thought: Lower-Than-Expected Crop Yield Stimulation with Rising CO2 Concentrations. Science **312:** 1918-1921

Markelz RJC, Strellner RS, Leakey ADB (2011) Impairment of C4 photosynthesis by drought is exacerbated by limiting nitrogen and ameliorated by elevated [CO2] in maize. Journal of Experimental Botany **62:** 3235-3246 %U http://jxb.oxfordjournals.org/lookup/doi/3210.1093/jxb/err3056

McKee IF, Bullimore JF, Long SP (1997) Will elevated CO2 concentrations protect the yield of wheat from O-3 damage? Plant Cell and Environment **20:** 77-84

McKee IF, Mulholland BJ, Craigon J, Black CR, Long SP (2000) Elevated concentrations of atmospheric CO2 protect against and compensate for O3 damage to photosynthetic tissues of field-grown wheat. New Phytologist **146:** 427-435

Meehl GA, Stocker TF, Collins WD, Friedlingstein P, Gaye AT, Gregory JM, Kitoh A, Knutti R, Murphy JM, Noda A, Raper SCB, Watterson IG, Weaver AJ, Zhao Z-C (2007) Global Climate Projections. *In* S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor, HL Miller, eds, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Monfreda C, Ramankutty N, Foley JA (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Global Biogeochem. Cycles **22**

Oltmans SJ, Lefohn AS, Harris JM, Galbally I, Scheel HE, Bodeker G, Brunke E, Claude H, Tarasick D, Johnson BJ, Simmonds P, Shadwick D, Anlauf K, Hayden K, Schmidlin F, Fujimoto T, Akagi K, Meyer C, Nichol S, Davies J, Redondas A, Cuevas E (2006) Long-term changes in tropospheric ozone. Atmospheric Environment **40:** 3156-3173

Peters GP, Marland G, Le Quéré C, Boden T, Canadell JG, Raupach MR (2011) Rapid growth in CO2 emissions after the 2008-2009 global financial crisis. Nature Climate Change **2:** 2-4

Ramankutty N, Evan A, Monfreda C, Foley JA (2008) Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Global Biogeochem. Cycles **22**

Ramankutty N, Foley JA, Norman J, McSweeney K (2002) The global distribution of cultivable lands: Current patterns and sensitivity to possible climate change. Global Ecology and Biogeography **11:** 377-392

Ray JD, Gesch RW, Sinclair TR, Hartwell Allen L (2002) The effect of vapor pressure deficit on maize transpiration response to a drying soil. Plant and Soil **239:** 113-121

Reynolds MP, Balota M, Delgado M, Amani I, Fischer RA (1994) Physiological and Morphological Traits Associated with Spring Wheat Yield Under Hot, Irrigated Conditions. Australian Journal of Plant Physiology **21:** 717-730

Rosenthal DM, Slattery RA, Miller RE, Grennan AK, Cavagnaro TR, Fauquet CM, Gleadow RM, Ort DR (2012) Cassava about-FACE: Greater than expected yield stimulation of cassava (Manihot esculenta) by future CO2 levels. Global Change Biology**:** n/a-n/a

Sacks WJ, Deryng D, Foley JA, Ramankutty N (2010) Crop planting dates: An analysis of global patterns. . Global Ecology and Biogeography **19:** 607-620

Schlenker W, Lobell DB (2010) Robust negative impacts of climate change on African agriculture. Environmental Research Letters**:** 014010 (014018pp)

Schlenker W, Roberts MJ (2009) Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proceedings of the National Academy of Sciences **106:** 15594-15598

Sheffield J, Wood EF (2008) Global trends and variability in soil moisture and drought characteristics, 1950-2000, from observation-driven simulations of the terrestrial hydrologic cycle. Journal of Climate **21:** 432-458

Shimono H, Okada M, Yamakawa Y, Nakamura H, Kobayashi K, Hasegawa T (2007) Rice yield enhancement by elevated CO2 is reduced in cool weather. Global Change Biology **14:** 276-284

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (2007) IPCC, climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. *In*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp

Stone P (2001) The effects of heat stress on cereal yield and quality. *In* AS Basra, ed, Crop responses and adaptations to temperature stress. Food Products Press, Binghamton, NY, p 302

Taub DR, Miller B, Allen H (2008) Effects of elevated CO 2 on the protein concentration of food crops: a meta-analysis. Global Change Biology **14:** 565-575

Tebaldi C, Arblaster JM, Knutti R (2011) Mapping model agreement on future climate projections. Geophysical Research Letters **38:** L23701

Teixeira EI, Fischer G, van Velthuizen H, Walter C, Ewert F (2012) Global hot-spots of heat stress on agricultural crops due to climate change. Agricultural and Forest Meteorology http://dx.doi.org/10.1016/j.agrformet.2011.09.002**:** in press

Trnka M, Olesen JE, Kersebaum KC, Skjelvåg AO, Eitzinger J, Seguin B, PELTONEN-SAINIO P, Rötter R, Iglesias A, Orlandini S (2011) Agroclimatic conditions in Europe under climate change. Global Change Biology **17:** 2298-2318

Van Dingenen R, Dentener FJ, Raes F, Krol MC, Emberson L, Cofala J (2009) The global impact of ozone on agricultural crop yields under current and future air quality legislation. Atmospheric Environment **43:** 604-618

Wall GW, Garcia RL, Kimball BA, Hunsaker DJ, Pinter PJ, Long SP, Osborne CP, Hendrix DL, Wechsung F, Wechsung G, Leavitt SW, LaMorte RL, Idso SB (2006) Interactive effects of elevated carbon dioxide and drought on wheat. Agronomy journal **98:** 354-381

Welch JR, Vincent JR, Auffhammer M, Moya PF, Dobermann A, Dawe D (2010) Rice yields in tropical/subtropical Asia exhibit large but opposing sensitivities to minimum and maximum temperatures. Proceedings of the National Academy of Sciences **107:** 14562

White JW, Hoogenboom G, Kimball BA, Wall GW (2011) Methodologies for simulating impacts of climate change on crop production. Field Crops Research **124:** 357-368

Wild M (2012) Enlightening Global Dimming and Brightening. Bulletin of the American Meteorological Society **93:** 27-37

Wilkinson S, Mills G, Illidge R, Davies WJ (2011) How is ozone pollution reducing our food supply? Journal of Experimental Botany **63:** 527-536

Willett KM, Gillett NP, Jones PD, Thorne PW (2007) Attribution of observed surface humidity changes to human influence. Nature **449:** 710-712

Zhu X, Feng Z, Sun T, Liu X, Tang H, Zhu J, Guo W, Kobayashi K (2011) Effects of elevated ozone concentration on yield of four Chinese cultivars of winter wheat under fully open-air field conditions. Global Change Biology **17:** 2697-2706

Ziska LH, Blumenthal DM, Runion GB, Hunt ER, Diaz-Soltero H (2010) Invasive Species and Climate Change: An Agronomic Perspective. Climatic Change **in press**

Table 1. Estimates for the response of global average crop yields to warming and CO_2 changes over the next decades. The most likely values and plausible ranges are both shown. Estimates are based on authors' interpretation of various sources (IPCC, 2001; Long et al., 2006; Lobell and Field, 2007; Meehl et al., 2007; Lobell et al., 2011).

Global crop area	ΔT (°C) per decade* x	ΔYield per °C =	ΔYield per decade
Likely value	.3	-5 %	-1.5%
Plausible range	.1 to .5	-8 to -3 %	-4% to -.3%
	ΔCO2 (ppm) per decade x	ΔYield per ppm ** =	
Likely value	25 ppm	.07 %	1.8%
Plausible range	20 to 30 ppm	.05% to .09%	1.0% to 2.7%

*Averaged over cropland areas

** using value for C3 grains, ignoring differences for C4 grains and non-grain crops, which would be lower and higher, respectively.

Figure Captions

1. Daily (a) calorie consumption and (b) protein supply from various food sources for the globe and eight regions around the world. Data source: (FAO, 2012))

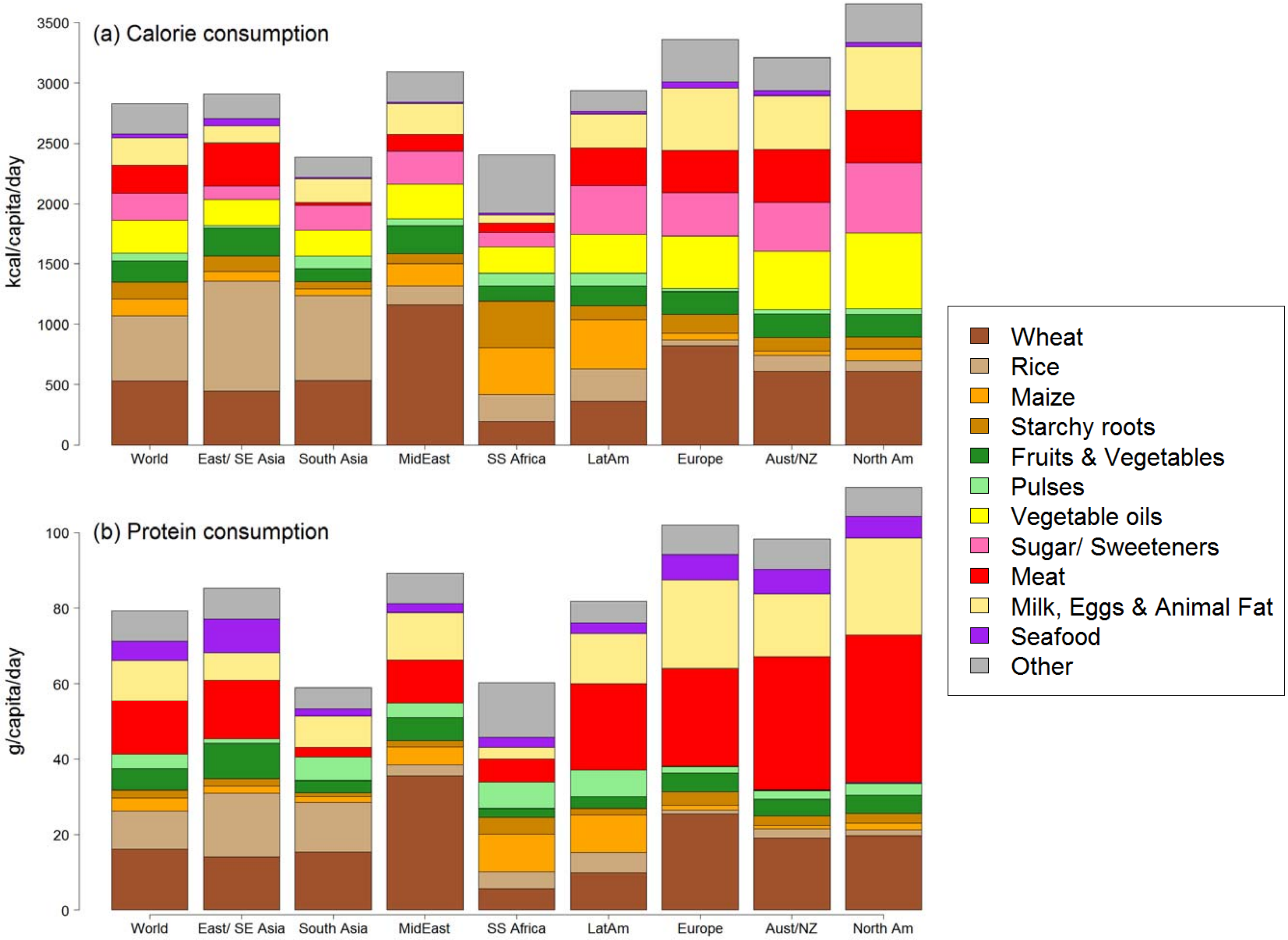
2. Decadal warming trends (˚C/decade) since 1980 in growing season daily minimum and maximum temperatures in major global cereal cropping regions, displayed on maps (a & b), and as histograms (c & d). Temperatures were averaged over the crop season (taken from Sacks et al., 2010) and points were selected randomly from half-degree grid cells having at least 10% harvested area in one of the four major cereal crops (wheat, corn, rice, soy) (based on Monfreda et al., 2008). Weather data were generated by interpolating anomalies of surface weather station data (from www.ncdc.noaa.gov) relative to climate normals in the WorldClim database (www.worldclim.org). Different symbols indicate the predominant crop for each grid cell.

3. Model projected differences between 2040-2060 and 1990-2010 in June-August temperature and precipitation for cropland areas by continent. Each point represents projections from a single model for each region, while hatches indicate model-average for each region. Values are a weighted area average, with weights equal to the fraction of each grid cell with agriculture based on (Ramankutty et al., 2008). (Data source for climate projections: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/)

4. Average yields for six major crops plotted against average growing season temperatures as computed in (Lobell et al., 2011). Each dot represents a single country, with size of dot proportional to total national production for that crop. Gray vertical lines indicate optimal temperature for yields based on experiments, as reported in (Hatfield et al., 2011). The highest national yields are typically observed close to the optimum temperature, with lower average yields for warmer countries. Also apparent is that many countries that are major producers are currently above optimal temperature.

5. (a) Observed global average yields since 1961 for six major crops. (b) Linear rates of yield change per decade for each decade (based on slope of regression line fit to 10-years of data (e.g., 1971-1980). (c) Percentage yield changes per decade for each decade. Data source: (FAO, 2012)

6. Trend yields in 1980 and 2008 (based on regression line fit to annual data for 1980-2008), along with estimated yields for counterfactual scenarios of no climate trends since 1980 or no climate or CO_2 trends since 1980. Based on results from (Lobell et al., 2011).



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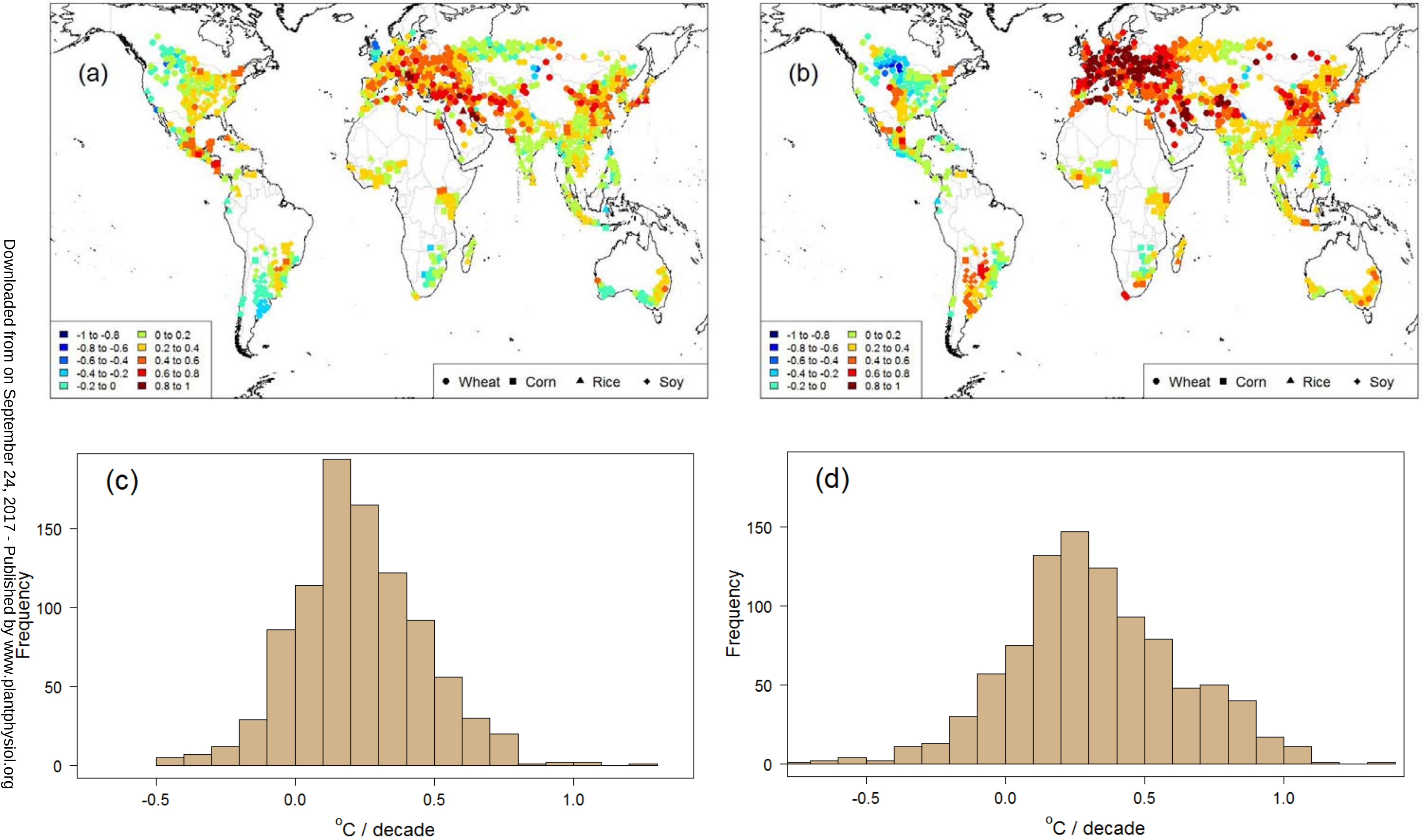

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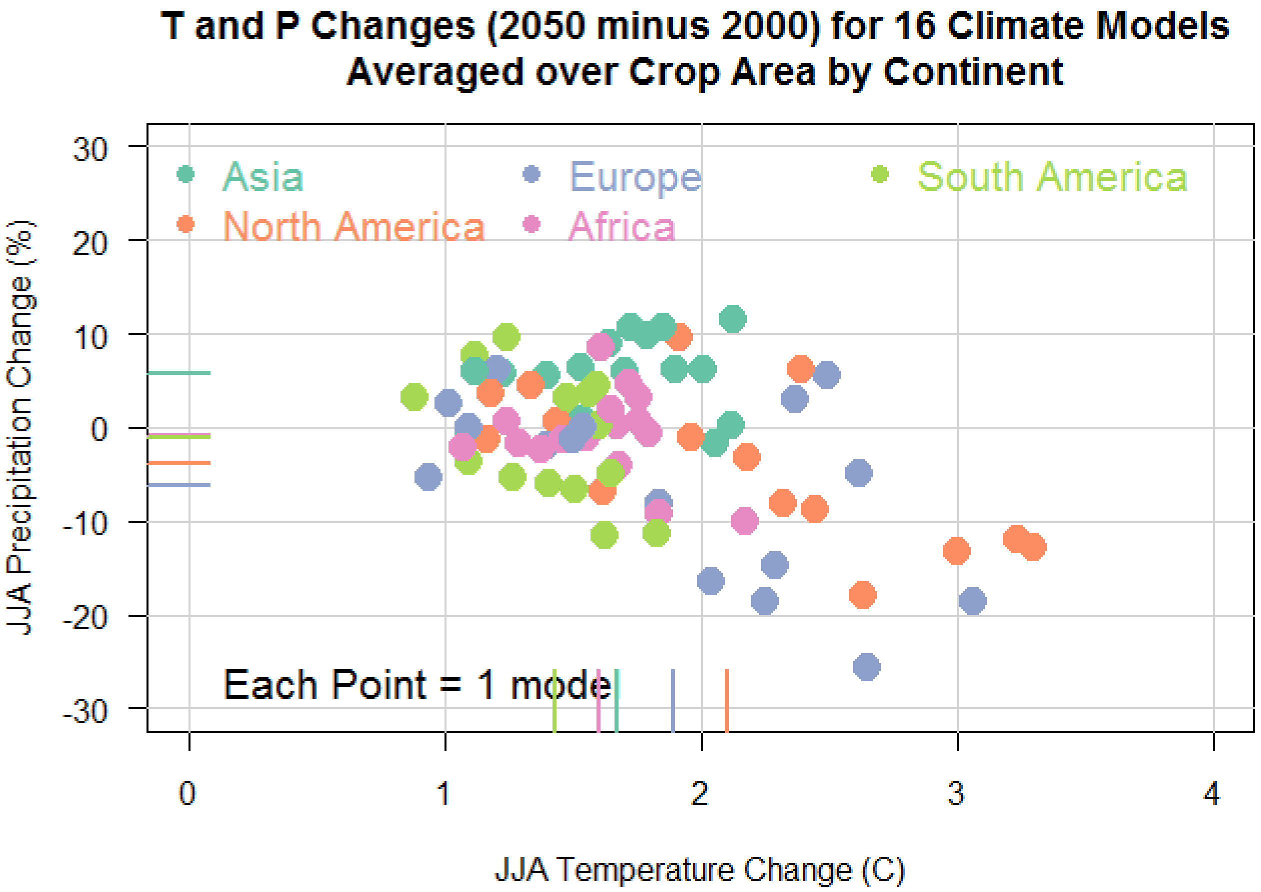

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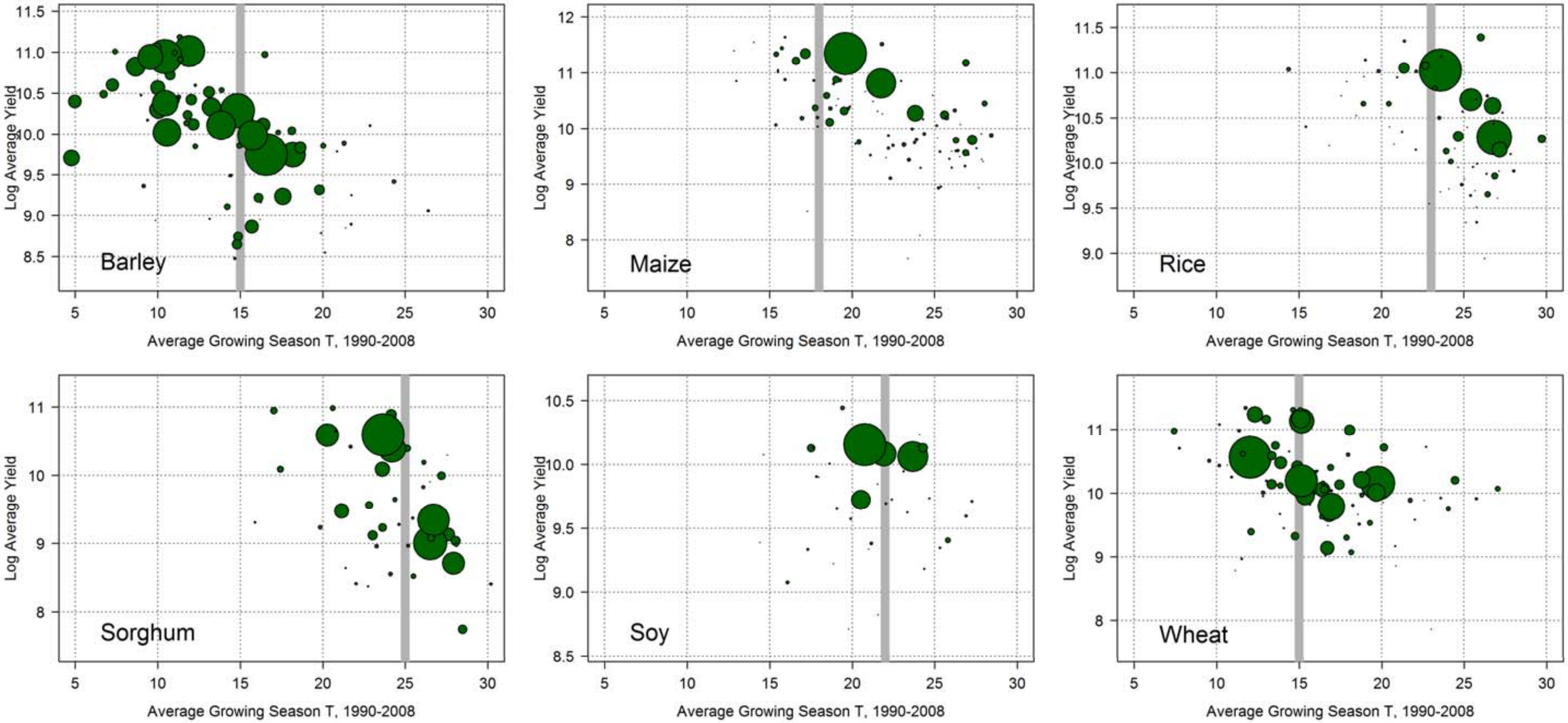

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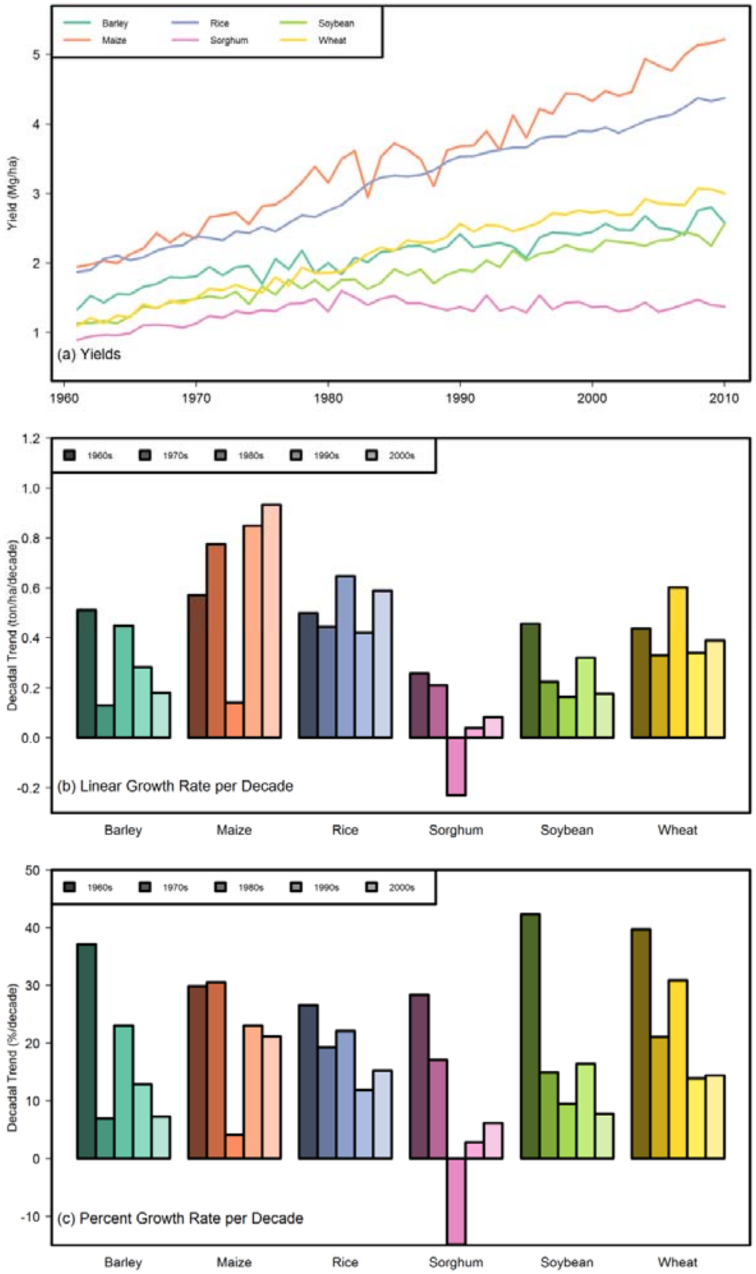

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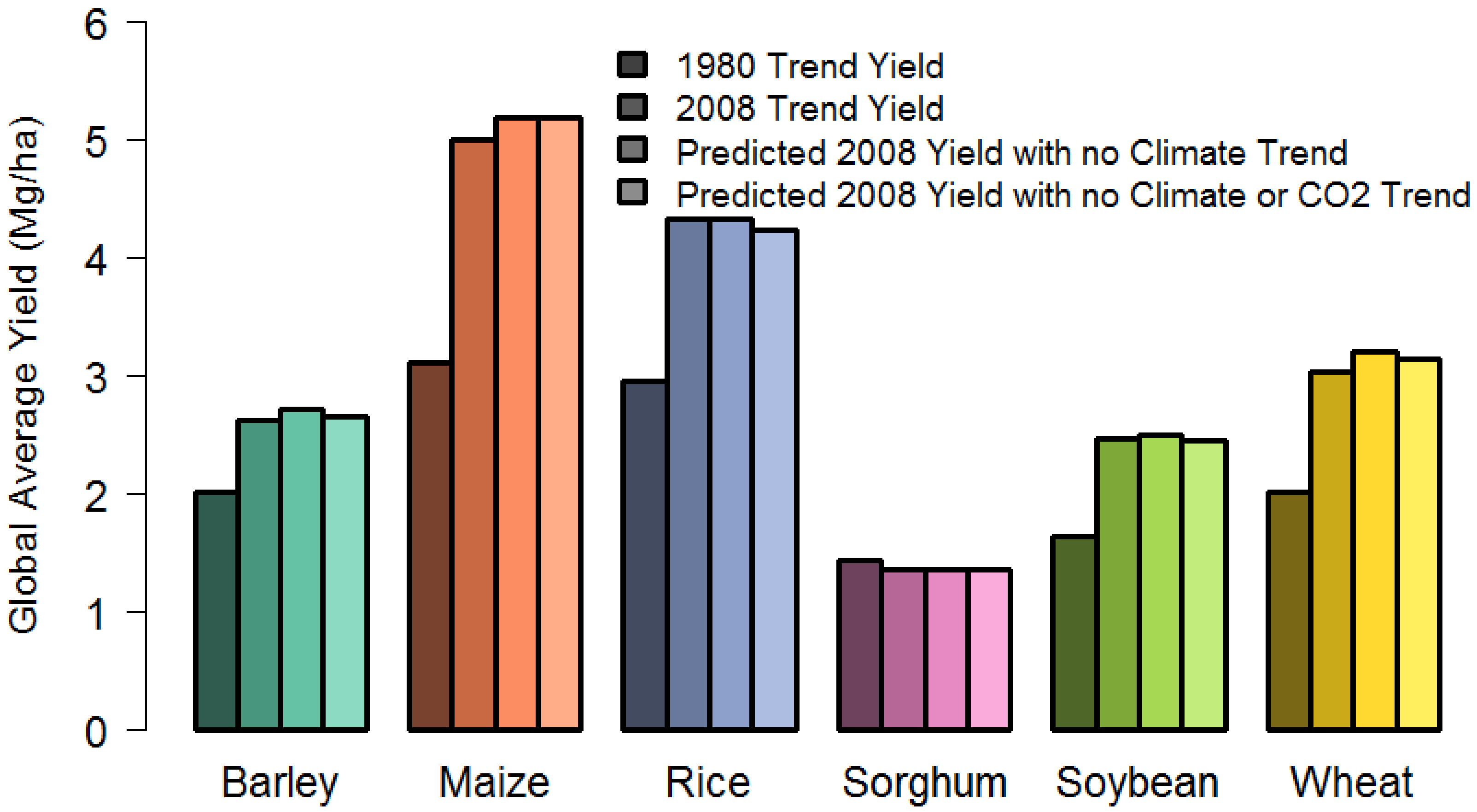

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