

1 The influence of climate change on global crop productivity

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5

6 Abstract

7 Climate trends over the past few decades have been fairly rapid in many agricultural regions around the
8 world, and increases in atmospheric carbon dioxide (CO₂) and ozone (O₃) levels have also been
9 ubiquitous. The virtual certainty that climate and CO₂ will continue to trend in the future raises many
10 questions related to food security, one of which is whether the aggregate productivity of global
11 agriculture will be affected. We outline the mechanisms by which these changes affect crop yields and
12 present estimates of past and future impacts of climate and CO₂ trends. The review focuses on global
13 scale grain productivity, notwithstanding the many other scales and outcomes of interest to food
14 security. Over the next few decades, CO₂ trends will likely increase global yields by roughly 1.8% per
15 decade. At the same time, warming trends are likely to reduce global yields by roughly 1.5% per decade
16 without effective adaptation, with a plausible range from roughly 0% to 4%. The upper end of this range
17 is half of the expected 8% rate of gain from technological and management improvements over the next
18 few decades. Thus, effective adaptation that avoids climate-induced yield losses could play an important
19 role in strategies to sustain global yield growth. Many global change factors that will likely challenge
20 yields, including higher O₃ and greater rainfall intensity, are not considered in most current assessments.

21

22 1. Introduction

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

31 Sources of growth in agricultural productivity are also multifaceted, and include levels of funding for
32 public and private research and development, changes in soil quality, availability and cost of mineral
33 fertilizers, atmospheric concentrations of carbon dioxide (CO₂) and ozone (O₃), and changes in
34 temperature (T) and precipitation (P) conditions. This Update focuses on changes in weather, CO₂ and O₃
35 in agricultural areas, and how that has and will affect crop productivity. In doing so, we recognize that
36 this is only part of the fuller story on crop productivity, which in turn is only part of the fuller story on

37 future food security. For example, the Update is silent on the many ways that global change can
38 influence food security via pathways other than agricultural productivity, such as by influencing human
39 disease incidence or income growth rates.

40 The main question of interest here is “How important will climate change and CO₂ be in shaping future
41 crop yields at the global scale, relative to the many other factors that influence productivity?” This
42 question helps to set the challenge of climate adaptation in context. We are less concerned, for
43 example, with whether impacts are statistically distinguishable from zero, than whether they are costly
44 enough to justify a major acceleration of investment in agriculture in order to reach target growth rates.

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

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

65 The next section (2) describes some of the observed and projected climate changes of relevance to
66 agriculture, which provide a foundation for understanding past and future impacts. Section 3 describes
67 the various mechanisms by which climate, CO₂, and O₃ changes can affect crop productivity. Section 4
68 then integrates the understanding of climate trends and response mechanisms to discuss the likely past
69 and future impacts of climate, CO₂, and O₃ changes on global crop productivity. Finally, sections 5 and 6
70 discuss some pending issues and conclusions. Throughout the paper, we emphasize changes and
71 impacts not only in the future, but also for the recent past. The main rationale for this approach is that
72 past trends are a reasonable starting point for what to expect in the next decades. For example, the
73 rates of warming in most climate models are roughly linear for the 1980-2050 period, both at global and
74 regional scales (Solomon et al., 2007).

75 2. Climate trends in crop regions

76 2-1. Observed trends

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

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

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

101 Atmospheric CO₂ concentrations have been rising rapidly since the start of the industrial era, with an
102 average rate of growth of ~2 ppm/year in the 2000's (Peters et al., 2011). The 2010 global average
103 concentration of 390 ppm was 39% higher than at the start of the Industrial revolution (i.e. 278 ppm in
104 1750; GCP, 2011). Global average tropospheric O₃ concentrations have also increased from ~10-15 ppb
105 in the pre-industrial era to ~35 ppb at current levels due to emissions of ozone precursors associated
106 with industrial activity. Regional spikes due to air pollution events can increase concentrations to over
107 100 ppb (Wilkinson et al., 2011). Recent emission control efforts have had some success in reducing
108 peak levels, which are particularly damaging to crops (see below), although background levels have
109 continued to rise (Oltmans et al., 2006). "Solar dimming" was also observed around the globe from
110 1950 to 1980, associated with increasing air pollution and aerosol loads (Wild, 2012). However, since
111 then, global trends in radiation have been more neutral, with continued dimming in some areas (e.g.
112 India and East Asia), and brightening in others (e.g. North America and Europe).

113 2-2. Projected Trends

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

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

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

134 Of more direct relevance to agriculture than P are changes in soil moisture and surface runoff, which
135 depend on T and intensity of P in addition to total P. Even in regions without significant projected
136 changes in total P, higher T will increase evapotranspiration rates, and along with more intense storms
137 and an associated higher proportion of runoff, this will lead to significant drying trends in soil moisture
138 and a higher risk of agricultural drought in many agricultural land areas in the coming century (Dai,
139 2011). A significant exception is northern North America and Eurasia, where projected increases in
140 precipitation and permafrost thawing should lead to comparable or increased soil moisture.

141 CO₂ levels are anticipated to grow for at least the next century, as emission reductions of roughly 80%
142 would be required to stabilize current atmospheric levels (Meehl et al., 2007). Growth rates of roughly
143 25 ppm per decade can be expected out to 2050, which would cause overall levels to reach 500 ppm
144 around this time (IPCC, 2001). Ozone precursor emissions are also projected to continue rising in the
145 coming decades, particularly in developing countries. Projections of future tropospheric O₃
146 concentrations and radiation levels are highly uncertain due to the uncertainty in emission pathways
147 and air pollution control efforts, as well as the interaction of ozone precursors with a changing climate
148 (Cape, 2008).

149 3. Crop response to global change

150 3-1 Mechanisms

151 This Update focuses on four primary factors that have and will continue to affect crop production in the
152 coming decades: rising T, an intensified hydrological cycle, increasing CO₂, and elevated tropospheric O₃.
153 Here we briefly discuss the various mechanisms by which each of these impacts crop physiology.

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

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

171 Fourth, T extremes can directly damage plant cells. Warming shifts the temperature probability
172 distribution, such that hot and cold extremes become more and less likely, respectively. The reduction
173 of spring and autumn frost risk will lead to a beneficial extension of the frost-free growing season in
174 several temperate and boreal regions. For example, projections indicate a 2-week increase in the
175 growing season for Scandinavia by 2030 compared to the late 20th century (Trnka et al., 2011). Northern
176 China, Russia, and Canada are also expected to see large gains in the frost-free period suitable for crop
177 growth (Ramankutty et al., 2002). On the other end of the spectrum, warming increases the likelihood of
178 heat stress during the critical reproductive period, which can lead to sterility, lower yields and the risk of
179 complete crop failure (Teixeira et al., 2012). Finally, rising temperatures, along with higher atmospheric
180 CO₂, may favor the growth and survival of many pests and diseases specific to agricultural crops (Ziska et
181 al., 2010).

182 An increased incidence of agricultural drought will increase crop water stress. An expansion of irrigation
183 is a likely response in some regions, although many areas lack irrigation infrastructure, and water access
184 can often be curtailed during periods of severe drought. In situations with shallow or medium depth to
185 groundwater, plants may also be able to escape drought by accessing moisture below the surface. In
186 general, though, crop plants will respond to reduced soil moisture by closing their stomates and slowing
187 carbon uptake to avoid water stress, but thereby raising canopy temperatures and potentially increasing

188 heat-related impacts. Water stress during the reproductive period of cereal crops may be particularly
189 harmful (Stone, 2001; Hatfield et al., 2011), while changes in the timing of the rainy season, particularly
190 in tropical areas, may confound traditional techniques for farmers to determine appropriate planting
191 dates. Finally, more intense rainfall events may lead to flooding and waterlogged soils, also pathways
192 for damaged crop production.

193 Rising atmospheric CO₂ concentrations provide some counteracting tendencies to the otherwise
194 negative impacts of rising temperatures and reduced soil moisture. First, higher CO₂ has a fertilization
195 effect in C3 species such as wheat, rice, and most fruit and vegetable crops, given that photorespiratory
196 costs in the C3 photosynthesis pathway are alleviated by higher CO₂. Elevated CO₂ also has the benefit
197 of reducing stomatal conductance, and thereby increasing water-use efficiency in both C3 and C4 crops
198 (Ainsworth and Long, 2005). Yields are estimated to be enhanced by e.g. ~15% in C3 plants under a
199 ~200 ppm atmospheric CO₂ increase, although the relative benefit of this effect varies widely between
200 studies, and is still a subject of considerable debate in the scientific literature (Long et al., 2006).
201 Another debate surrounds the concern that CO₂ fertilization may reduce the nutritional quality of crops,
202 especially in nutrient-poor cropping systems, through reduced nitrate assimilation and lower protein
203 concentrations in harvestable yield (Taub et al., 2008).

204 Air pollutants such as NO_x, CO and CH₄ react with OH in the presence of sunlight to form tropospheric
205 O₃, which causes oxidative damage to photosynthetic machinery in all major crop plants (Wilkinson et
206 al., 2011). Aerosols from air pollution can also reduce plant-available radiation. These pollution-related
207 impacts are likely to be highest in agricultural areas downwind of urban regions, but O₃ precursors can
208 also be transported across continents. In fact, tropospheric O₃ concentrations above pre-industrial levels
209 are currently found in most agricultural regions of the globe (Van Dingenen et al., 2009). Interaction
210 effects may also occur between O₃ and elevated CO₂. For example, reduced stomatal conductance
211 under elevated CO₂ will reduce O₃ uptake by crop plants, thereby limiting damage to the plant and
212 maintaining biomass production (McKee et al., 2000). However, empirical evidence is mixed regarding
213 the ability of elevated CO₂ to reduce the impact of O₃ on final yields (McKee et al., 1997). A related
214 concern is that variety improvement in crops such as wheat has favored increased stomatal
215 conductance, given that higher transpiration fluxes are generally associated with increased
216 photosynthesis rates and final yields (Reynolds et al., 1994). However, a higher stomatal conductance
217 implies more uptake of O₃, increasing sensitivity of more recent varieties to O₃ damage (Biswas et al.,
218 2008).

219 In summary, while the individual mechanisms enumerated above are relatively well-understood (e.g.,
220 faster development at higher temperatures, or higher photosynthesis rates at elevated CO₂ in C3 crops),
221 the interactions between various global change factors under field conditions create substantial
222 complexity that is not currently well understood. For example, heat-induced shortening of the grain
223 filling stage could limit the benefits from higher CO₂, or conversely, improved water use efficiency from
224 higher CO₂ may help to reduce negative impacts of VPD increases or rainfall declines. Decades of plot-
225 level (e.g., Kim et al., 2007; Shimono et al., 2007; Markelz et al., 2011) and open-air field experiments
226 (e.g., Long et al., 2006; Wall et al., 2006; Zhu et al., 2011), as well as simulation modeling exercises (e.g.,
227 Long, 1991; Brown and Rosenberg, 1997; Grant et al., 2004) have been dedicated towards

228 understanding the net impact of interactions between competing global change mechanisms at small
229 scales. However, results have not always been conclusive, especially at regional scales relevant for
230 projecting the future response of overall crop production to changing environmental conditions.

231 **3-2 Cropping systems and crop-specific responses to global change**

232 Global change factors will have varying impacts on cropping systems around the world, due to regional
233 differences in rates of day and night-time warming, changes to the timing, frequency and intensity of
234 precipitation, and exposure to O₃ and air pollution sources. Most aspects of farm management, such as
235 the specific crops grown and level of inputs, also differ considerably by region and play an important
236 role in shaping the impact of weather and climate change. Farmers are also likely to change these
237 practices in response to climate change, for instance by sowing different crops or varieties, changing the
238 timing of field operations, or expanding irrigation, and the socioeconomic capacity to make these
239 adaptive changes will differ by region. Even atmospheric CO₂ increases, which will be uniform around
240 the world, will have regionally disparate effects because of different mixtures of crop types and
241 moisture conditions. Rather than attempt a review of observed or expected impacts, this section briefly
242 discusses some important distinctions in cropping systems that drive much of the variation in net
243 impacts:

- 244 • *Irrigated versus rainfed conditions:* Irrigated systems are generally less harmed than rainfed
245 systems by higher T_{max}, primarily because irrigation prevents effects of warming on water
246 stress, and greater transpiration rates help to cool canopies and prevent losses related to direct
247 temperature damage. For example, maize in the western United States, which is predominately
248 irrigated, is much less sensitive to extreme heat than in eastern counties (Schlenker and
249 Roberts, 2009). Because some crops, such as rice or sugarcane, tend to be more irrigated than
250 others, irrigation also goes a long way towards explaining the relatively low sensitivity of certain
251 crops to warming. For example, rice actually benefits from higher T_{max} in many locations, at
252 least until T_{max} exceeds values that cause direct heat damage, whereas higher T_{min} is harmful
253 (Welch et al., 2010). Rainfed crops growing in very wet areas will behave similarly to irrigated
254 crops.
- 255 • *Crop type:* Different crop species have different T optima, as well as different sensitivities to CO₂
256 and O₃. One useful distinction is between crops that originated in temperate environments,
257 such as wheat and barley, vs. crops from tropical environments such as cassava or sorghum. A
258 recent synthesis of the literature (Hatfield et al., 2011) identified optimal season average
259 temperatures of 15 °C for wheat, 18 °C for maize, 22°C for soybean, 23 °C for rice and bean, and
260 25°C for cotton and sorghum. (For some crops, Hatfield et al. report a range, from which we
261 take the lowest value). An important distinction for CO₂ sensitivity is between C4 grains (least
262 responsive), C3 grains (more responsive) and root and tuber crops (most responsive). For
263 example, a recent field study of cassava showed roughly a doubling of dry mass for a CO₂
264 increase from 385 to 585 ppm (Rosenthal et al., 2012).

- 265 • *Current temperatures relative to optimum*: A simple but often overlooked factor that
266 determines regional or global average yield responses is the geographic distribution of crop
267 production relative to optimum T. Figure 4 presents data on average growing season T and
268 average yield for individual countries over the past two decades taken from (Lobell et al., 2011).
269 The size of dots in the figure indicates the relative contribution to global production of the
270 given crop (e.g., China has the biggest dot for rice, United States for maize). A lot of scatter is
271 apparent because many factors affect yields other than T. However, for several crops, there is a
272 clear tendency for yields to decline after the optimum T, which is shown in the thick gray line
273 based on the numbers from Hatfield et al. (2011). (Note: barley is not reported in Hatfield et al.
274 (2011), so we use the same value as for wheat, since barley should have a similar or slightly
275 lower optimum T (Todd, 1982).) Also evident in Figure 4 is that, for some crops, most large
276 producers have average season T that is above optimum. Even though warming would likely
277 benefit countries to the left of the optimum, total global production will therefore tend to
278 decrease for warming.
- 279 • *High vs. low nutrient status*: In high input systems with sufficient fertilizer, there may be more
280 sensitivity to weather changes, given the lack of other limiting factors (Schlenker and Lobell,
281 2010). At the same time, high input systems will also be better able to take advantage of CO₂
282 fertilization in C3 crops while maintaining nutritional quality (Ainsworth and Long, 2005). For
283 low fertility systems with minimal fertilizers, such as exist in many tropical areas, higher
284 atmospheric CO₂ should help to maintain biomass production under drought conditions, but
285 higher CO₂ is also more likely to decrease protein levels without additional N inputs into the
286 system (Taub et al., 2008). Capacities will also differ between well-capitalized, high-input vs.
287 subsistence-level, low-input farms in their ability to cope with, finance, and proactively plan for
288 environmental change.

289 **4. The relative role of climate and CO₂ trends in past and future productivity trends**

290 Given an understanding of observed and projected trends in climate, CO₂, and O₃ (section 2), as well as
291 knowledge of crop yield sensitivities to these factors (section 3), it becomes possible to estimate the net
292 impact of changes in these factors on global crop productivity. It is necessary to estimate these impacts,
293 rather than directly measure them, even when considering past trends, because it is simply not possible
294 to observe a counterfactual world in which climate was not changing. Before turning to impacts of
295 climate and other trends, however, it is useful to understand the context of overall productivity growth
296 in agriculture.

297 **4-1 Global trends in crop productivity**

298 Yields of most major crops have increased markedly over the past half century, largely due to greater
299 use of irrigation, chemical inputs, and modern crop varieties. Figure 5 shows average global yields for
300 the six most important crops in terms of calorie production, as well as linear trends by decade. At the
301 global scale, yield growth has been fairly linear over the past 50 years, with the exception of sorghum
302 which has not improved since 1980. Of course, this linear growth rate translates to a declining percent

303 increase over time (Figure 5c). The global aggregate also masks a lot of important differences between
304 countries, with many high yielding countries already showing evidence of slowing growth rates
305 (Cassman, 1999). Nonetheless, the global story has largely been one of sustained improvement in yields
306 at a fairly steady rate over the last half century.

307 An important point when considering observed trends is that they reflect the combined impact of all
308 factors influencing yield, including changes in climate and CO₂. Often, historical trends are used simply
309 as an estimate for technology growth, but they are more correctly viewed as the result of various
310 factors, the most important of which is usually, but not always, technology growth.

311 **4-2 Estimating the impact of past climate and CO₂ trends**

312 A growing number of studies have attempted to quantify impacts of recent climate trends on crop
313 production. Here we present the main results from a global-scale study, which estimated impacts for
314 the 1980-2008 period (Lobell et al., 2011). Warming trends were estimated to have lowered wheat and
315 maize yields by roughly 6% and 4%, respectively, over the 29 year period, with relatively small impacts
316 of P trends. Global soybean and rice yields were deemed to be relatively unaffected by changes so far.
317 Figure 6 summarizes the results from Lobell et al. (2011), with results for barley and sorghum added for
318 comparison with Figures 4 and 5. Yields for barley, maize, and wheat all increased substantially since
319 1980, but not as much as they would have if climate had remained stable. Yields for a counterfactual of
320 no climate and no CO₂ trend are also shown, illustrating the benefit of higher CO₂ for C3 crops
321 (estimated as roughly 3% for the 49 ppm increase over this time period).

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

326 All crops in Figure 6 show a much larger difference between yields in 1980 and 2008 than between the
327 observed and counterfactual yields in 2008. A casual observer might interpret this as evidence that
328 climate has a very small impact on global food production or food security. However, food demand has
329 also increased greatly since 1980, and so global prices and food security continue to be sensitive to small
330 fluctuations in supply. For example, the roughly 3% loss in calories due to climate trends since 1980
331 (computed as a calorie- weighted average of the individual crop impacts), was estimated to translate to
332 a roughly 20% increase in commodity prices relative to a counterfactual with no warming (Lobell et al.,
333 2011). It is also worth noting that by ending in 2008, the study did not consider recent years that
334 included several major climate events (Russian heat wave in 2010, United States drought in 2012), which
335 had significant effects on food supply and prices.

336 **4-3 Estimating the impact of future climate and CO₂ trends**

337 Numerous studies have projected impacts of climate and CO₂ changes on future crop yields. Reviews
338 and syntheses of these studies are available (e.g., Easterling et al., 2007), and point to a general
339 conclusion that the benefits of CO₂ at the global scale will eventually be outweighed by the harm from

340 climate change induced by CO₂ and other greenhouse gases. There is considerable debate about exactly
341 when net impacts will become negative. As mentioned above, there is evidence that net global impacts
342 for 1980-2008 were negative (Lobell et al., 2011) due to climate trends during this historical period,
343 although that study focused on actual warming rather than just the amount of warming due to
344 greenhouse gases.

345 We present in Table 1 a simple summary of how two key global change factors affecting global
346 productivity (T and CO₂) could evolve over the next few decades. These numbers are intended as rough
347 estimates of the overall impact on calorie supply from all major crops, averaged over the next 30 years.
348 A likely scenario in the near-term is that warming will slow global yield growth by about 1.5% per
349 decade, while CO₂ increases will raise yields by roughly the same amount. This balance is broadly
350 consistent with the global picture emerging from many studies and major assessments. Past mid-
351 century, it is likely that CO₂ benefits will diminish and climate effects will be larger (Easterling et al.,
352 2007).

353 Table 1 also displays the range of plausible outcomes in the near term, which receive far less attention
354 in the literature than the most likely outcome. It is plausible that the net effects of warming and CO₂
355 could be as negative as -3% per decade, or as positive as +2% per decade, depending on how fast T and
356 CO₂ change and how responsive crop yields turn out to be. To consider whether 3% is a large number,
357 one comparison is rates of yield growth in recent decades, which vary around an average of roughly 15%
358 per decade (Figure 5C). Looking forward, projections that ignore climate and CO₂ effects anticipate a
359 roughly linear continuation of recent yield in absolute terms, resulting in a lower percent growth rate of
360 roughly 8% per decade to 2050 (Bruinsma, 2009). Thus, losses or gains of 2-3% per decade represent a
361 significant fraction of past and, especially, future yield growth.

362 An important issue often overlooked in discussions of climate change impacts on agriculture is that the
363 relevant quantity depends on the particular question at hand. There are at least three distinct
364 perspectives on global scale productivity impacts, even without mentioning the much broader set of
365 questions related to crop- or region- specific effects. Traditionally, people have focused on the question
366 of the net effect of greenhouse gas emissions in order to inform mitigation policies. In that case, of most
367 relevance is the combined effect of CO₂ plus all associated climate changes. However, if one is focused
368 on policies related to adaptation to T and P changes, the effects of climate changes are of interest in
369 themselves, regardless of potential benefits of CO₂. If one is instead interested in the question of how
370 to account for climate and CO₂ in projections of overall productivity growth, the relevant issue is how
371 much the effects of climate and CO₂ will change from one decade to the next, because historical yield
372 trends include the effects of past climate and CO₂ trends.

373 **5. Pending Issues**

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

378 First, the importance of interactions of elevated CO₂ and high T are still not well known. For
379 example, how much does high CO₂ help reduce water stress associated with warming, and how much
380 does it increase susceptibility to heat damage because of reduced cooling from transpiration?
381 Conversely, how much does high T reduce the benefits of CO₂ by increasing pollen sterility and lowering
382 grain numbers?

383 Second, as evident in the above discussion, the effects of O₃ are still not incorporated into most
384 studies of global change impacts. Improved understanding of how O₃ affects yields by itself and in
385 combination with high T and CO₂, and improved representation of current understanding in existing
386 crop models are both needed.

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

392

393 **6. Conclusions**

394 Growth rates in aggregate crop productivity to 2050 will continue to be mainly driven by
395 technological and agronomic improvements, just as they have for the past century. Even in the most
396 pessimistic scenarios, it is highly unlikely that climate change would result in a net decline in global
397 yields. Instead, the relevant question at the global scale is how much of a headwind climate change
398 could present in the perpetual race to keep productivity growing as fast as demand. Overall, the net
399 effect of climate change and CO₂ on global average supply of calories is likely to be fairly close to zero
400 over the next few decades, but could be as large as 20-30% of overall yield trends. Of course, this global
401 picture hides many changes at smaller scales that could be of great relevance to food security, even if
402 global production is maintained (Easterling et al., 2007).

403 To reduce uncertainties in global impacts, better estimates of rates of global warming, and
404 responsiveness of crop yields to warming and CO₂ (and their combination) would be particularly useful.
405 We note that the responsiveness of yields will depend partly on the crops themselves, including any
406 genetic improvements made to reduce sensitivity to T or improve responsiveness to CO₂, as well as
407 adaptive management changes by farmers in choosing what, when, where, and how to grow their crops.
408 Effects of changes in O₃ are currently much less understood but could also represent a significant impact
409 at the global scale.

410 It will never be possible to unambiguously measure the effect of changes in climate, CO₂, and O₃,
411 given the scale of global food production and the fact that agriculture is always changing in multiple
412 ways. However, the best available science related to climate change and crop physiology indicates that
413 climate change represents a credible threat to sustaining global productivity growth at rates necessary
414 to keep up with demand. Increasing the scale of investments in crop improvement, and increasing the
415 emphasis of these investments on global change factors, will help to sustain yield growth over the next
416 few decades.

417 **Acknowledgments**

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419

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567

568 Table 1. Estimates for the response of global average crop yields to warming and CO₂ changes over the
 569 next decades. The most likely values and plausible ranges are both shown. Estimates are based on
 570 authors' interpretation of various sources (IPCC, 2001; Long et al., 2006; Lobell and Field, 2007; Meehl et
 571 al., 2007; Lobell et al., 2011).

Global crop area	ΔT (°C) per decade* x	Δ Yield per °C =	Δ Yield per decade
Likely value	.3	-5 %	-1.5%
Plausible range	.1 to .5	-8 to -3 %	-4% to -.3%
	Δ CO ₂ (ppm) per decade x	Δ Yield per ppm ** =	
Likely value	25 ppm	.07 %	1.8%
Plausible range	20 to 30 ppm	.05% to .09%	1.0% to 2.7%

572 *Averaged over cropland areas

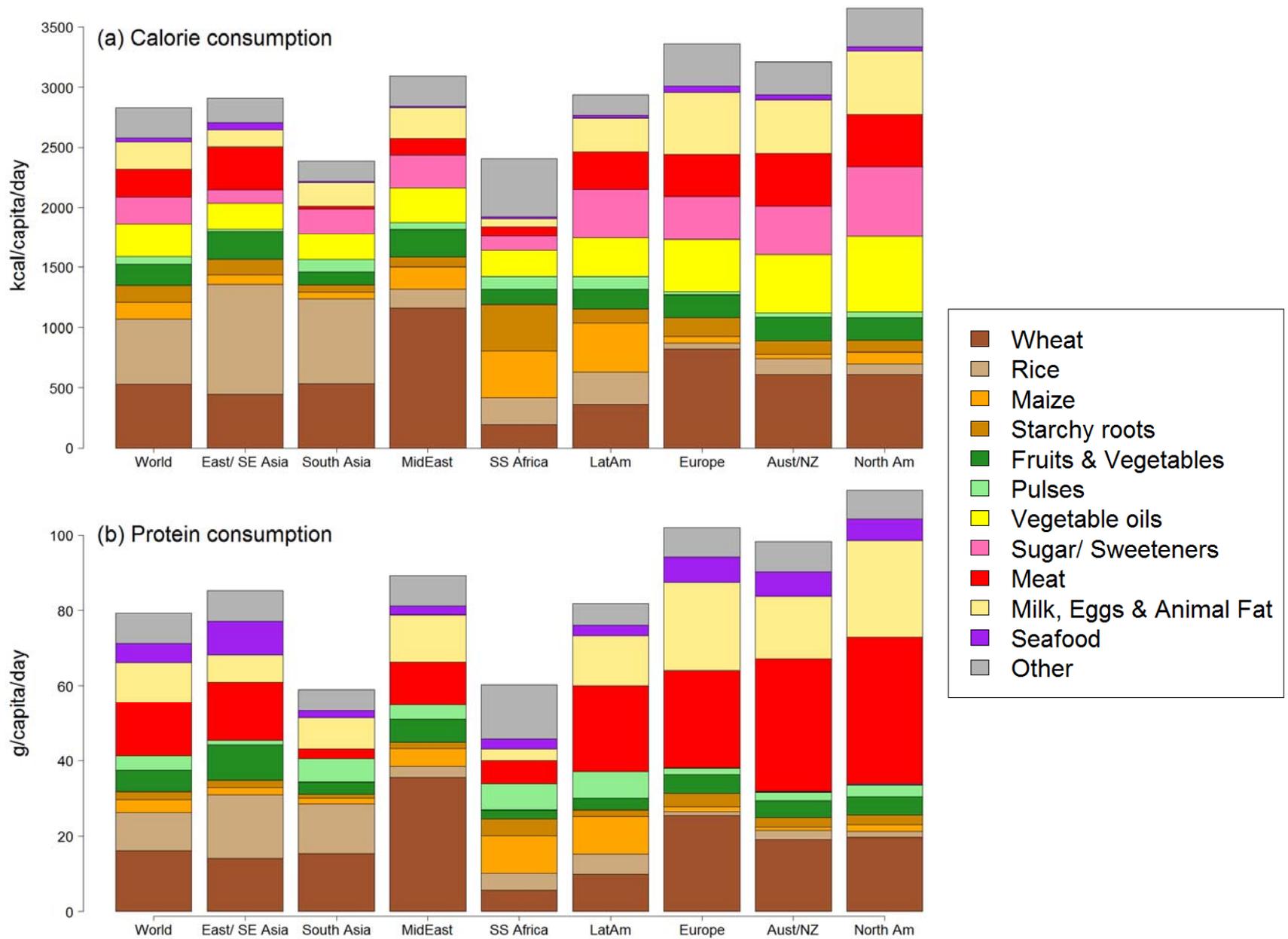
573 ** using value for C3 grains, ignoring differences for C4 grains and non-grain crops, which would be
 574 lower and higher, respectively.

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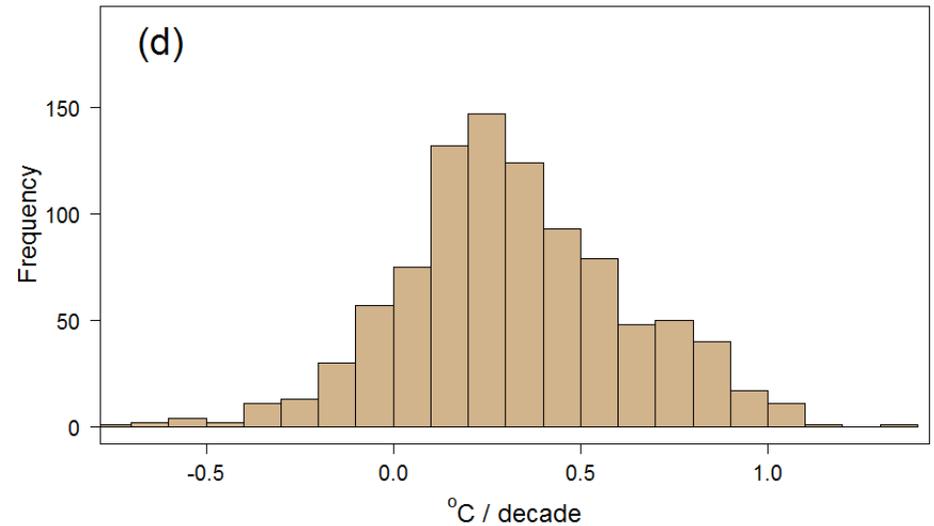
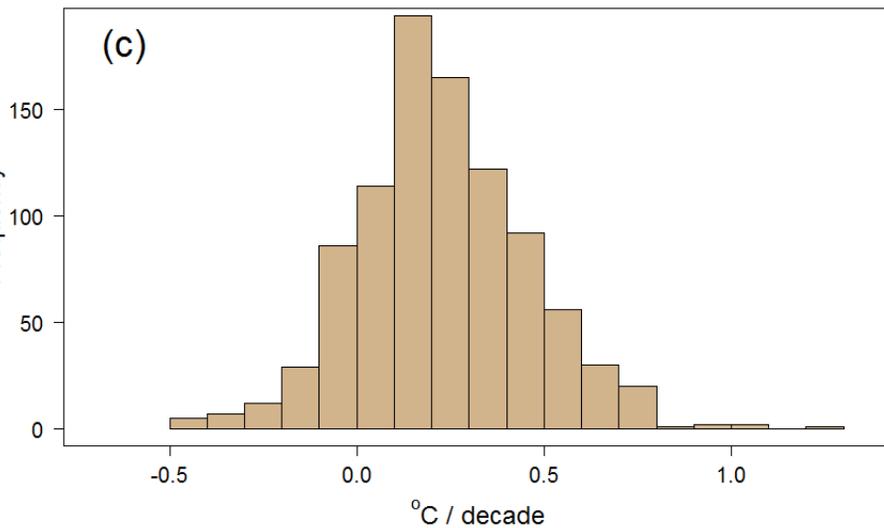
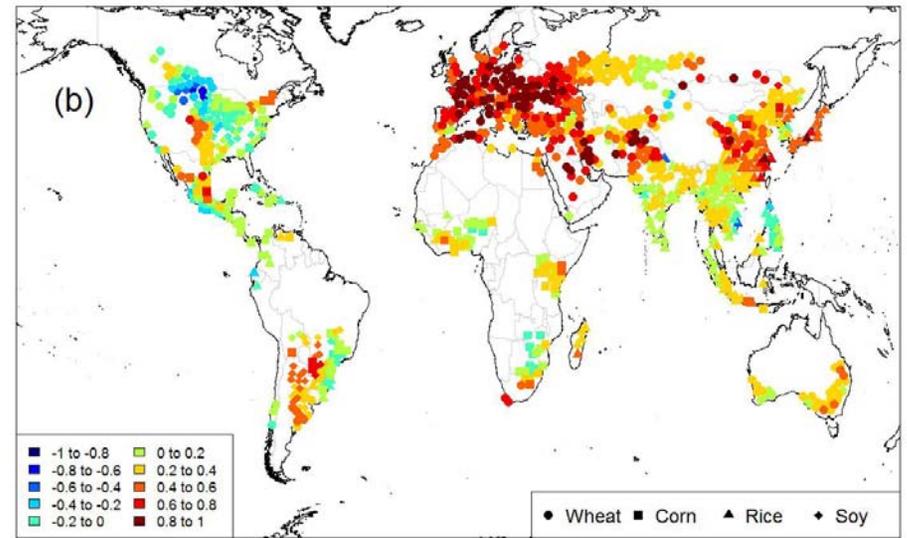
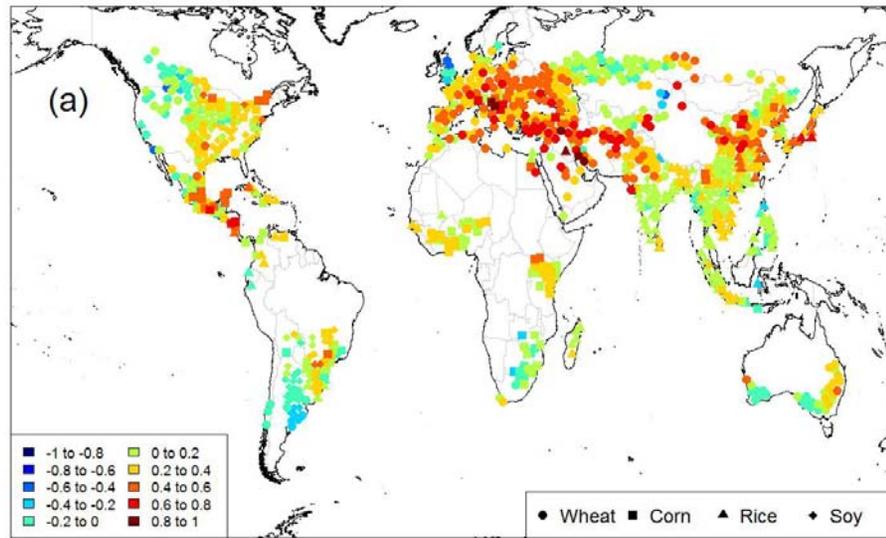
576 Figure Captions

- 577 1. Daily (a) calorie consumption and (b) protein supply from various food sources for the globe and
578 eight regions around the world. Data source: (FAO, 2012))
- 579 2. Decadal warming trends ($^{\circ}\text{C}/\text{decade}$) since 1980 in growing season daily minimum and maximum
580 temperatures in major global cereal cropping regions, displayed on maps (a & b), and as histograms (c &
581 d). Temperatures were averaged over the crop season (taken from Sacks et al., 2010) and points were
582 selected randomly from half-degree grid cells having at least 10% harvested area in one of the four
583 major cereal crops (wheat, corn, rice, soy) (based on Monfreda et al., 2008). Weather data were
584 generated by interpolating anomalies of surface weather station data (from www.ncdc.noaa.gov)
585 relative to climate normals in the WorldClim database (www.worldclim.org). Different symbols indicate
586 the predominant crop for each grid cell.
- 587 3. Model projected differences between 2040-2060 and 1990-2010 in June-August temperature and
588 precipitation for cropland areas by continent. Each point represents projections from a single model for
589 each region, while hatches indicate model-average for each region. Values are a weighted area average,
590 with weights equal to the fraction of each grid cell with agriculture based on (Ramankutty et al., 2008).
591 (Data source for climate projections: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/)
- 592 4. Average yields for six major crops plotted against average growing season temperatures as computed
593 in (Lobell et al., 2011). Each dot represents a single country, with size of dot proportional to total
594 national production for that crop. Gray vertical lines indicate optimal temperature for yields based on
595 experiments, as reported in (Hatfield et al., 2011). The highest national yields are typically observed
596 close to the optimum temperature, with lower average yields for warmer countries. Also apparent is
597 that many countries that are major producers are currently above optimal temperature.
- 598 5. (a) Observed global average yields since 1961 for six major crops. (b) Linear rates of yield change per
599 decade for each decade (based on slope of regression line fit to 10-years of data (e.g., 1971-1980). (c)
600 Percentage yield changes per decade for each decade. Data source: (FAO, 2012)
- 601 6. Trend yields in 1980 and 2008 (based on regression line fit to annual data for 1980-2008), along with
602 estimated yields for counterfactual scenarios of no climate trends since 1980 or no climate or CO_2 trends
603 since 1980. Based on results from (Lobell et al., 2011).

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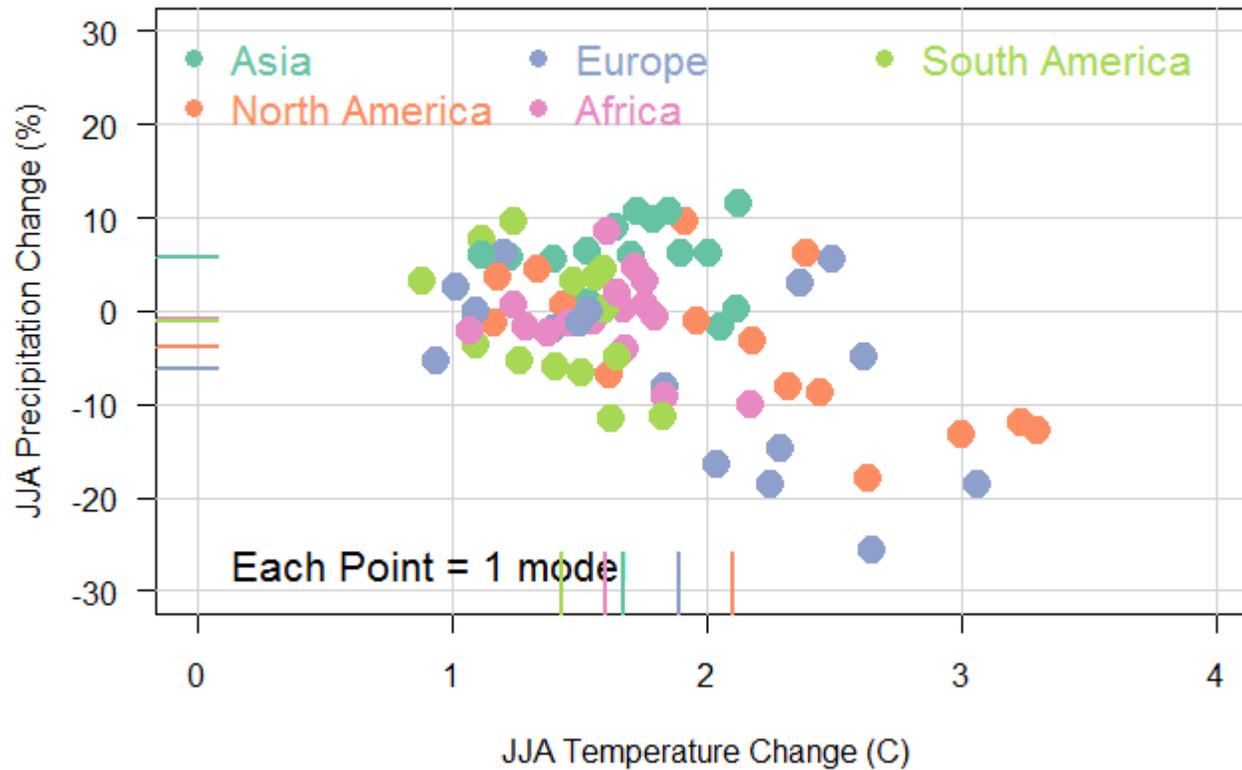


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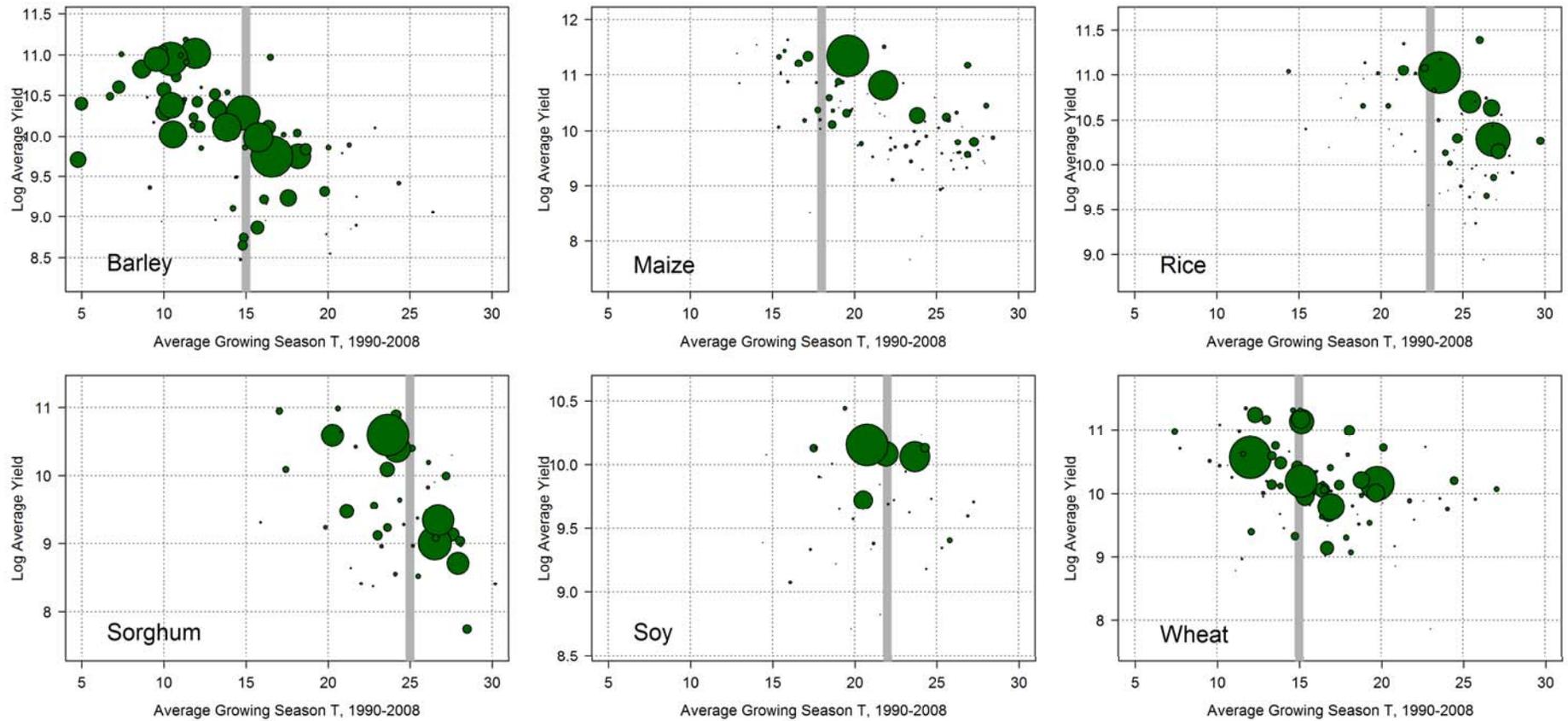


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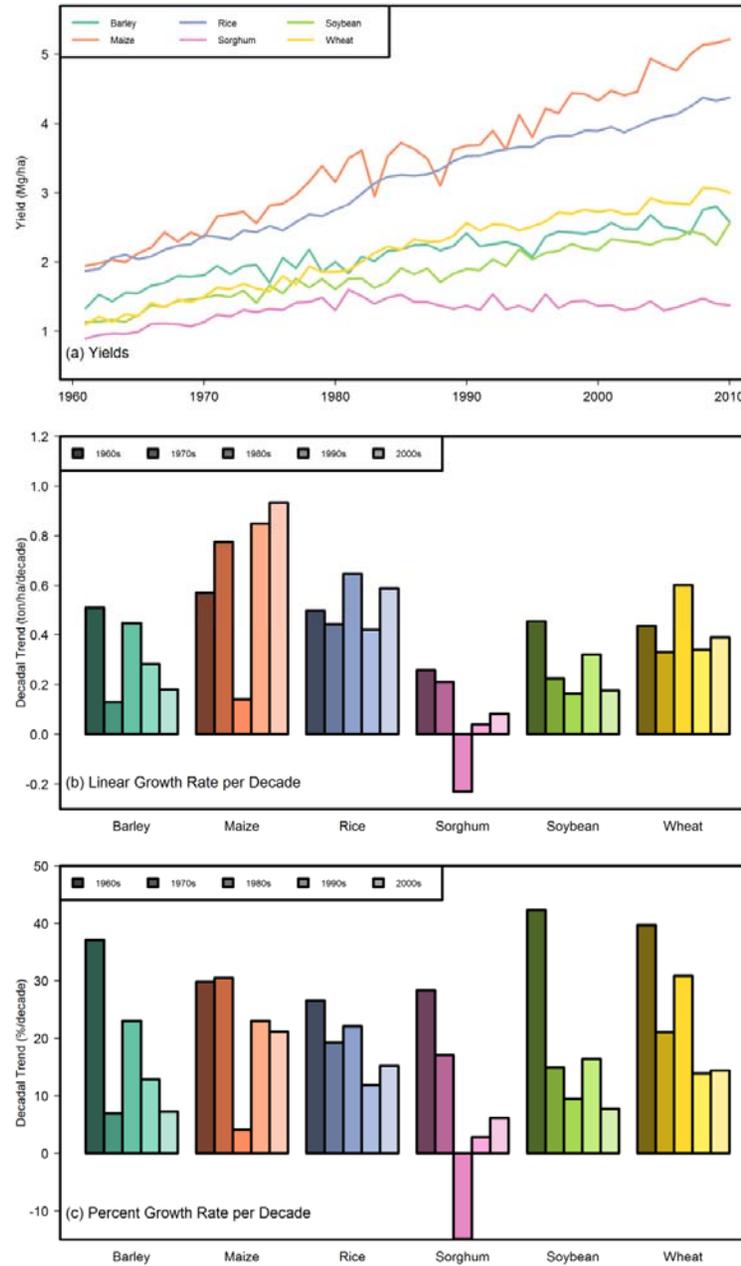
T and P Changes (2050 minus 2000) for 16 Climate Models Averaged over Crop Area by Continent



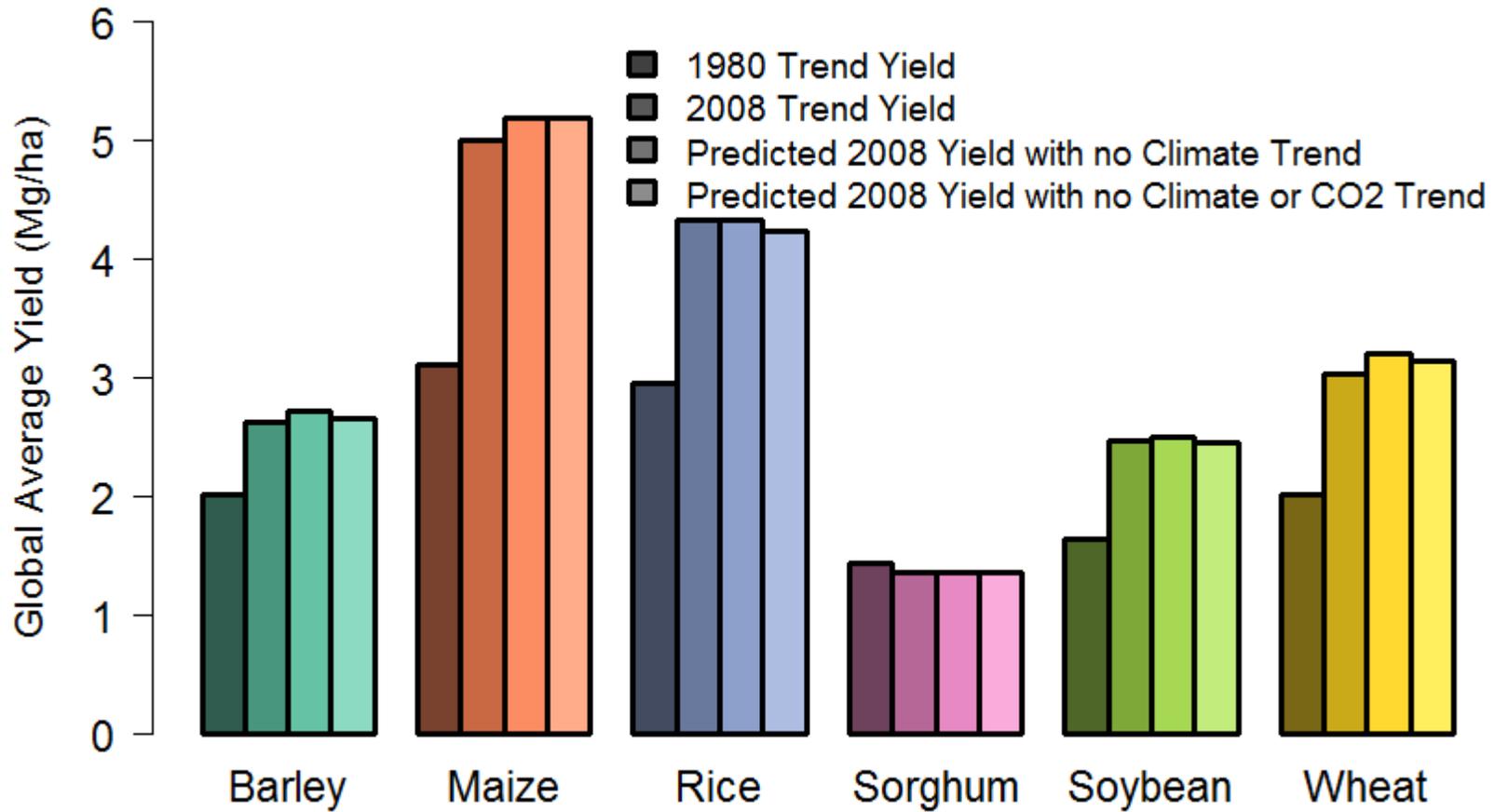
3. Model projected differences between 2040-2060 and 1990-2010 in June-August temperature and precipitation for cropland areas by continent. Each point represents projections from a single model for each region, while hatches indicate model-average for each region. Values are a weighted area average, with weights equal to the fraction of each grid cell with agriculture based on ([Ramankutty et al., 2008](http://www.pnas.org/content/105/11/4131)). (Data source for climate projections: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/)



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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. 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 CO₂ trends since 1980. Based on results from [\(Lobell et al., 2011\)](#).