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A meta-analysis of crop yield under climate change and adaptation

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Feeding a growing global population in a changing climate presents a significant challenge to society[1,2]. The projected yields of crops under a range of agricultural and climatic scenarios are needed to assess food security prospects. Previous meta-analyses[3] have summarized climate change impacts and adaptive potential as a function of temperature, but have not examined uncertainty, the timing of impacts, or the quantitative effectiveness of adaptation. Here we develop a new data set of more than 1,700 published simulations to evaluate yield impacts of climate change and adaptation. Without adaptation, losses in aggregate production are expected for wheat, rice and maize in both temperate and tropical regions by 2 °C of local warming. Crop-level adaptations increase simulated yields by an average of 7–15%, with adaptations more effective for wheat and rice than maize. Yield losses are greater in magnitude for the second half of the century than for the first. Consensus on yield decreases in the second half of the century is stronger in tropical than temperate regions, yet even moderate warming may reduce temperate crop yields in many locations. Although less is known about interannual variability than mean yields, the available data indicate that increases in yield variability are likely.

Food security is influenced by many factors, including rising demand, higher input prices, soil degradation, the need to curb greenhouse gas emissions, and increasing competition for land and water from non-food uses[4–6]. Furthermore, climate change is expected to increasingly affect yields[7] and statistical analysis of crop yield data indicates it may already be doing so[8]. Process-based (or mechanistic) crop simulation models parameterize the daily dynamics of management, weather, soil and plant processes and can be used to project future yields. Statistical (or empirical) models, which summarize observed relationships between weather inputs and crop yield outputs, are increasingly used for the same purpose. Results from different studies can differ not only due to the scenarios used[3], but also due to differences in the analytical approaches[9].

Adaptations are expected to be helpful in dealing with climate change, but there remains considerable uncertainty about impacts and the effectiveness of adaptations. Adaptations explored using process-based models are typically incremental, crop-level adaptations of existing cropping systems, such as changes in varieties, planting times, irrigation and residue management. These relatively small adjustments contrast to more systemic changes such as crop species or grazing integration, or more transformational options such as crop relocation or a complete change in the farming system such as moving from irrigated to dryland systems[10].

Meta-analyses that combine and compare results from numerous studies can be a useful way of summarizing the range of projected outcomes in the literature and assessing consensus. Meta-analyses can also be useful for identifying causes of projection differences, although this is made difficult by a lack of model documentation and standardization of model experiments[11]. As part of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4)[3], a meta-analysis of crop yield response to climate change was carried out, using local mean temperature as metric of change, concluding that up to 2 °C of warming could result in increases in wheat, rice and maize yields, with yields subsequently declining with increased warming. AR4 also demonstrated that simulated crop-level adaptations had a significantly positive effect on all crops, regions and levels of warming. A subsequent analysis indicated that the benefit of adaptation to wheat yield plateaus at about 16% (ref. 12).

Many studies of crop yield projections have been published in the years since AR4, including some meta-analyses and summary studies for particular regions[13,14]. Here, we conduct a meta-analysis of impacts based on an update of the AR4 data set, with double the number of studies. This data set is used to consider three questions: what are the likely impacts of differing degrees of climate change on yields, by crop and by region; what is the quantitative effect of incremental adaptation as a function of temperature and rainfall; and what are the magnitudes and signs of yield changes for the remaining decades of this century? We also assess uncertainty bounds of the analyses using bootstrapping methods and carry out a simple analysis to summarize the dependence of yield changes on temperature, rainfall, crop photosynthetic pathway and adaptation. Some of the results from this meta-analysis, notably the data presented in the main figures here, are reproduced in the Fifth Assessment Report of the IPCC.

The response of the three main crops to local mean temperature increases shows considerable spread, with the central tendencies being broadly similar to those found in AR4 (Fig. 1). Temperate wheat differs from AR4 for the mid- to high latitudes for around 1–3 °C warming. The new data show both positive and negative yield responses, whereas AR4 had primarily positive responses at these temperature changes. For all three temperate crops the new data set shows a greater risk of yield reductions at moderate warming than AR4, which mostly projected yield increases at these temperatures. One of the reasons for this increase in spread since AR4 could be the increase in geographical sampling associated with the use of global gridded crop models (Supplementary Information). Without adaptation, the mean response of all three crops to climate

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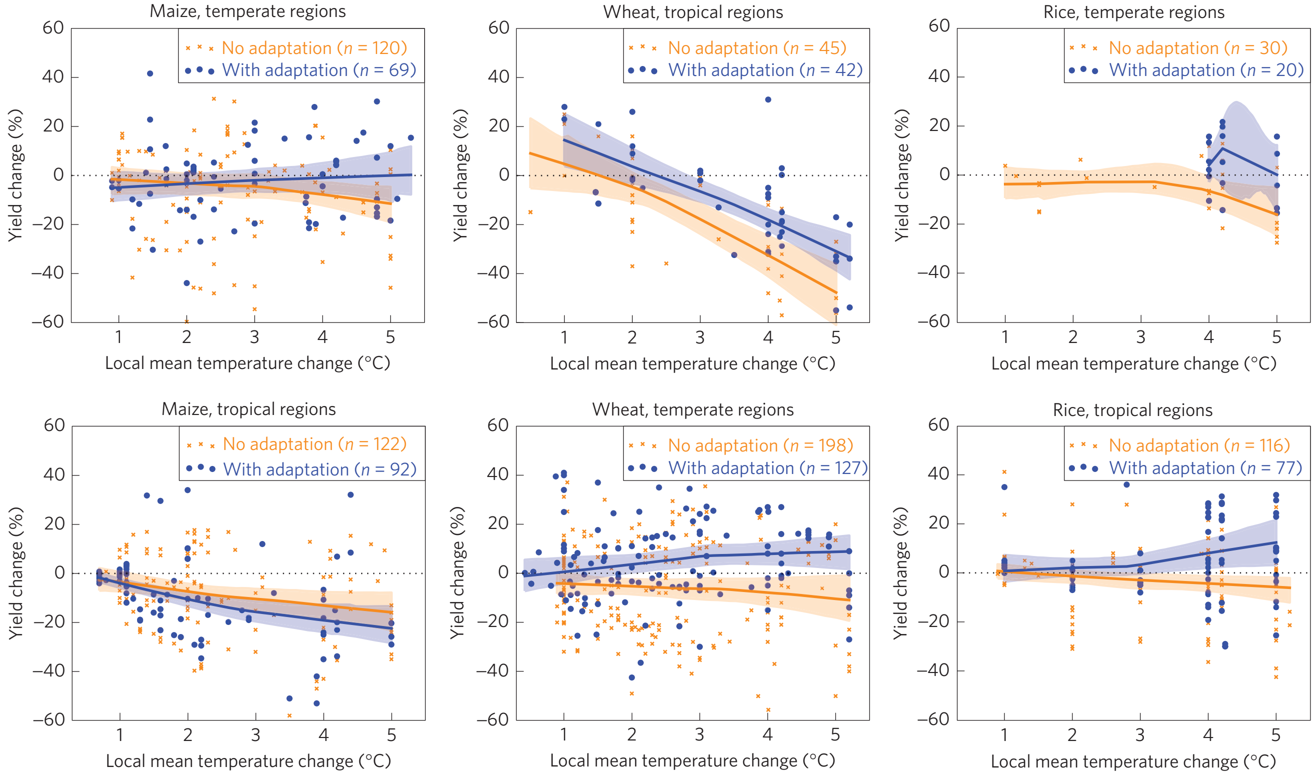

Figure 1 | Percentage yield change as a function of temperature for the three main crops and for temperate and tropical regions for local mean temperature changes up to 5 °C ($n = 1{,}048$ from 66 studies). Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, which are separated according to the presence (blue) or absence (orange) of adaptation. Note that four data points across all six panels are outside the yield change range shown. These were omitted for clarity. Supplementary Fig. 4 shows data from across all temperatures and yield ranges.

change in both tropical and temperate regions is yield reductions. Furthermore, the bootstrapped fits to no-adaptation studies in both regions indicate robust yield reductions for all crops over most of the temperature range, especially after 2 °C of local warming. The geographical distribution of rice, wheat and maize studies is reflected in the distribution of data points in Fig. 1: most wheat is grown in temperate regions, most rice is grown in the tropics and maize has a more even geographical spread with the leading producers being the USA and China.

Adaptation provides clear benefits for wheat and rice: the central tendencies indicate that most yield loss in wheat may be avoided, or even reversed, in tropical regions up to 2–3 °C of local warming and in temperate regions across a broad range of warming. Tropical rice also shows potential for avoided loss for a large range of temperatures but there is a lack of data for temperate rice. In contrast, there is little evidence for the potential to avoid yield loss in maize, particularly in tropical regions, where there is even a negative—though not clearly separated—impact of adaptation. This counterintuitive result is due to the different modelling methods used by the studies with and without adaptation. For example, more than 30% of the data points (4/13) for adapted maize with yield reduction of more than 20%, at local mean temperature increases of greater than 3.5 °C, come from a single study[15], which has large negative impacts both with and without adaptation. Inferences regarding adaption made using Fig. 1 therefore have inherent limitations due to asymmetry in the number of data points with and without adaptation.

As a complement to the bivariate comparisons, a general linear model was fitted to all entries ($n = 882$) that had complete information on changes in yield (ΔY), temperature (ΔT), CO_2 (ΔCO_2) and precipitation (ΔP). The linear model should be interpreted with caution, because roughly half of the entries had incomplete information and were omitted from this analysis, and because no attempt was made to weight studies by their quality or representativeness of major production regions. Three categorical variables describing treatment of adaptation (A: yes or no), region (R: temperate or tropical) and crop metabolism (M: C_3 or C_4) were included in the model (we also included a cluster variable study, S, to control for non-independence, see Methods). The results indicate highly significant ($t = -3.92$; $P < 0.0001$) negative impacts of warming, with an average yield loss of 4.90% per °C (Table 1). The overall sensitivity of yields to ΔT is consistent with estimates of global mean sensitivity derived from statistical analyses of historical crop yields. For example, an analysis of global wheat yield and temperature time series resulted in an inferred sensitivity of 5.4% per °C, with larger sensitivities for maize, barley and sorghum, and smaller values for rice and soy[16]. The model also inferred significant positive effects of precipitation ($t = 3.0$; $P = 0.0031$) and CO_2 ($t = 3.1$; $P = 0.0022$) with average yield increases of 0.53% (per % ΔP), 0.06% (per ppm ΔCO_2), respectively (Table 1). Adaptation was also significant ($t = 2.3$; $P = 0.022$) with adapted crops yielding on average 7.16% greater than non-adapted (Table 1).

The impact of adaptation is also evident in Fig. 2, which plots projections from all studies that had paired yield values for both with and without adaptation, each derived for the same climate scenario and with the same crop model. The estimated gains of 7–15% from incremental crop-level adaptation in Table 1 and Fig. 2 are similar to previous assessments on national[17] and global[3,7] scales. Figure 2 uses paired adaptation studies, whereas the linear model, which produces adaptation gains of 7.15%, includes all data. Thus we expect the gains from adaptation to be at the upper end of the range shown in Table 1 and Fig. 2. The effectiveness

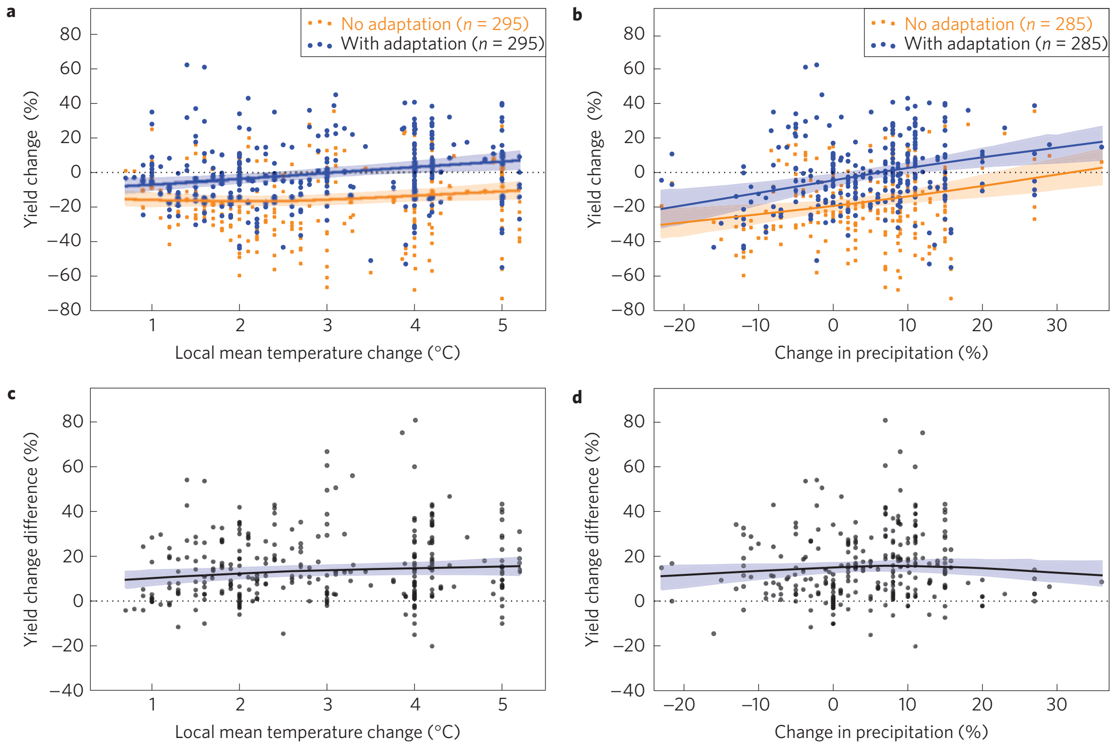

Figure 2 | Quantification of the benefits of adaptation. Percentage yield change as a function of temperature (**a**) and precipitation (**b**), for the 33 paired adaptation studies, across all regions and crops. Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, with blue and orange bands corresponding to with and without adaptation. **c**,**d**, The difference between simulations with and without adaptation for temperature (**c**) and precipitation (**d**) are shown, using the same bootstrapping technique. Note that part of the lack of decline at high temperatures in the non-adaptation curve in **a** is due to high representation of rice (23 of 28 no-adaptation studies with $T > 4\,°C$ and yield change >0), which shows less sensitivity to high local temperature change than other crops.

of adaptation is relatively consistent across different temperature increases and rainfall changes (Fig. 2c,d). However, there is a large scatter of possible results, indicating the need for a more contextual approach on regional and local scales and reinforcing that central tendencies are not an indication of expected adaptation in any one location or situation. This scatter, and the difficulty of separating the impact of numerous adaptations in a single study, makes conclusions regarding the most effective adaptation options difficult. Of the adaptation strategies distinguished in the study (planting date, fertilizer, irrigation, cultivar or other agronomic), cultivar adjustment was the most effective, with irrigation also showing benefit (Supplementary Information).

Table 1 | Summary of crop yield responses to climate change and adaptation.

Term	Coefficient	s.e.m.	t	P
Intercept	−5.40	6.78	−0.80	0.44
A (no = 0; yes = 1)	7.16	3.11	2.30	0.022*
R (temperate = 0; tropical = 1)	−2.83	3.89	−0.73	0.47
M = C_3 = 0; C_4 = 1	−0.003	3.04	−0.00	0.99
ΔP	0.53	0.18	2.97	0.0031**
ΔT	−4.90	1.25	−3.92	<0.001***
ΔCO_2	0.06	0.02	3.07	0.0022**

Results of a general linear model applied to all studies with reported values for changes in yield (ΔY), temperature (ΔT), CO_2 (ΔCO_2) and precipitation (ΔP), as well as three categorical variables describing treatment of adaptation (A: yes or no), region (R: temperate or tropical) and crop metabolism (M: C_3 or C_4). $n = 882$. Significance levels: $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

In practice there could be reasons why adaptation benefits could be either larger or smaller than those calculated here. They could be overstated because of *inter alia*: the lack of capacity to implement fully or other reasons for low adoption such as cultural inappropriateness[18]; co-limitations such as increasingly restricted water resources limiting implementation of irrigation-based adaptations[19]; the lack of inclusion of interactions with other factors such as pests and diseases[20]; and the lack of inclusion of altered climate variability and extremes in the analyses[21]. Yet the possible benefits of adaptation may be underestimated, as the array of adaptations typically investigated is often limited by the assessment tools available. Assessed options are therefore a subset of even the incremental adaptations that may be feasible, as well as omitting possible systemic or transformational adaptations[12].

Adaptation involves planning across a range of timescales. It is therefore important to know the magnitude of expected impacts on mean yield as a function of time. Despite uncertainty in global and regional patterns of climate change and in the emissions scenarios used, some time dependency is seen in the data when the yields of all crops are analysed by decade and for 20-year periods (Fig. 3). There is a majority consensus that yield changes will be negative from the 2030s onwards. More than 70% of projections indicate yield decreases for the 2040s and 2050s, and more than 45% of all projections for the second half of the century indicate yield decreases greater than 10%. The magnitude of the yield impact generally increases with time: 67% of yield decreases in the second half of the century are greater than 10% and 26% are greater than 25%, compared with 33.2% and 10.4%, respectively, for the first half of the century. These projections include simulations with adaptation, suggesting that farmer adaptation earlier in the twenty-first century can ameliorate some, but not all, risk of yield reductions. In the

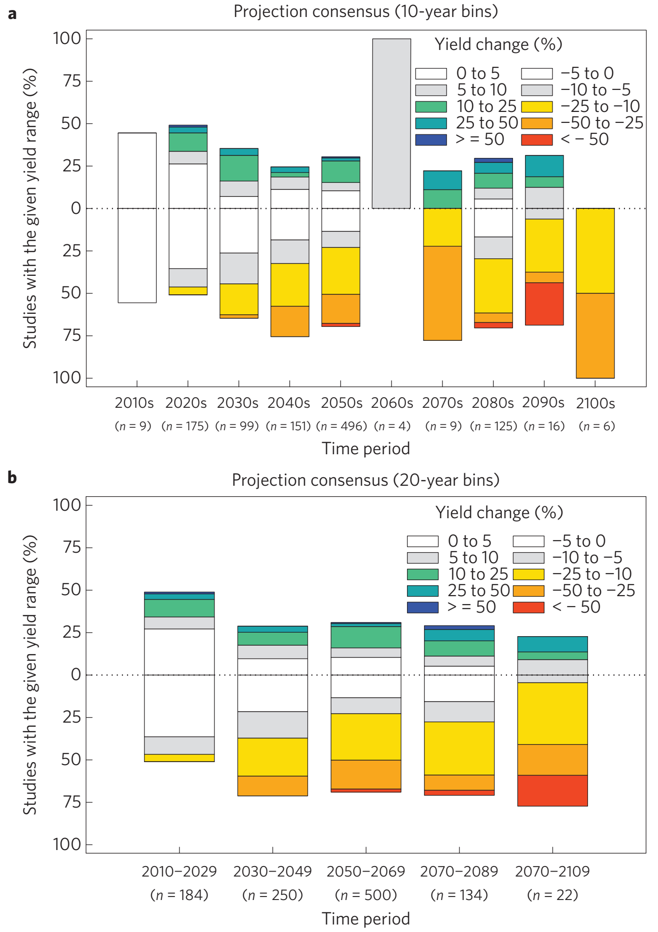

Figure 3 | Projected changes in crop yield as a function of time for all crops and regions (*n* = 1,090 from 42 studies). a,b, The vertical axis indicates degree of consensus and the colours denote percentage change in crop yield. Data are plotted according to decade (**a**) or 20-year periods (**b**) in which the centre point of a study's projection period falls. The decadal analysis has positive yield change for the 2060s, which has the fewest data points of all decades (Supplementary Fig. 1), with all of the data being for temperate maize. The scenarios used include A1B, A1F1, A2, B1, B2 and IS92a.

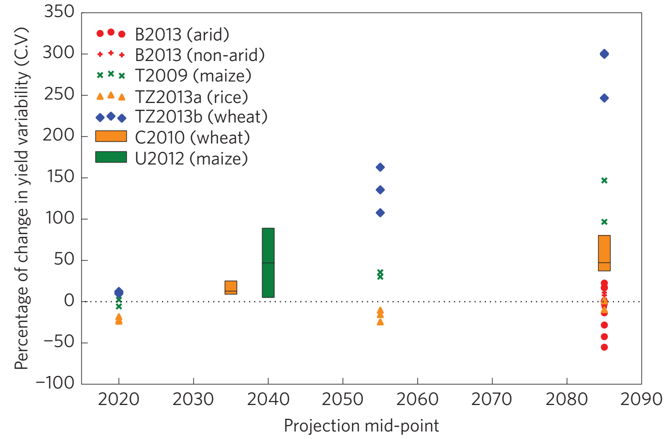

Figure 4 | Projected percentage change in yield coefficient of variation for wheat, maize, rice and C4 crops taken from C2010 (ref. 21), B2012 (ref. 31), T2009 (ref. 32), TZ2013a (ref. 33), TZ2013b (ref. 34) and U2012 (ref. 35). U2012 and C2012 plot numerous data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in coefficient of variation. For C2012, paired coefficient of variation changes were not available, so the rectangle shows changes in the mean coefficient of variation, the mean coefficient of variation plus one standard deviation and the mean coefficient of variation minus one standard deviation. The studies used a range of scenarios (IPCC Special Report on Emissions Scenarios A1B, A2, A1F1 and B1). B2012 is a global study, U2012 is for the USA and the remaining studies are for China.

second half of the century more systemic or transformational adaptations may be needed to avoid the risk of significant reductions in mean yield.

The aggregation of data, although valuable in assessing consensus, masks some important differences. First, all of the positive yield changes in the 2070s and 2090s come from temperate regions, suggesting a strong consensus that the yields of tropical crops will decrease in the second half of the century. This is consistent with a meta-analysis of yield impact studies in sub-Saharan Africa and south Asia[13], which showed significant yield reductions for the second half of the century. Second, analysis of the effect of adaptation as a function of time revealed that, for all temperate crops taken together, there is a difference of 14 percentage points between mean adapted and non-adapted yield changes for the period 2040–2059. For all tropical crops, no significant adaptation effect is seen (Supplementary Fig. 2).

The meta-analysis is subject to limitations from both the experimental design and from the methods used in the modelling studies themselves. Of particular concern are deficiencies that are common to many of the studies, such as the lack of simulation of pests, weeds and diseases[20,22,23]; the frequent assumption of water availability into the future despite ongoing changes in many regions[19]; inaccuracies in representing adaptations[12]; and structural, parameter and bias correction uncertainty in both crop and climate models[9,24–26]. Some of these issues are being addressed by model intercomparison projects (for example, ref. 27).

A key concern is that most analyses focus on changes in mean yields and thus cannot be used to assess the future year-to-year stability of food crop supplies. Contemporary occurrence of extreme climate anomalies is increasingly accepted as a consequence of climate change[28] and is known to have significant impact on food chain resilience[29]. Increases in yield variability due to extremes of temperature have been observed[30] and future increases are expected[21] that will increase adaptation challenges, yet variability remains unassessed or unreported in most yield impact studies. We collated projections of yield coefficient of variation from six available studies (Fig. 4); the data, although relatively sparse, indicate that increases in yield variability become increasingly likely as the century progresses. A clear recommendation emerging from this study is that yield variability be reported in all climate impact studies, along with the underlying assumptions regarding climate variability. Such reporting would allow assessment of the additional challenges for adaptation posed by increases in variability and extreme events.

Methods

The AR4 database (Supplementary Information) was extended through a literature search to include publications from 2007 to 2012, thus increasing the number of studies from 42 to 91 and increasing the number of data points from 573 to 1,722. Our rationale for examining central tendencies is similar to that of AR4: we interpret averages over all sites as being the expected response of aggregate production. Accordingly, we assessed the extent to which the data set represents current global coverage of the three crops and found a reasonable match (Supplementary Table 1). The literature search was broad and inclusive. We devised a quality control procedure to remove data points that are not representative of global production. Maize, wheat and rice are the most common crops in the database, with 488, 454 and 295 entries, respectively. Best-fit lines on all plots were derived from local polynomial fits (loess) using a span of 1. Five hundred bootstrap replicates were carried out to derive a 95% confidence interval shown in shading. The analysis focuses on simulated responses of crop yields to climate change—with no consideration of systemic or transformational adaptation, market response to the projected changes, or the impact of the technology trend. Further details of the database, assessment of spatial coverage quality control and limitations of the study can be found in the Supplementary Information.

We fitted two ordinary least squares models to assess for significant influences on ΔY from three continuous (ΔT, ΔCO_2 and ΔP) and three categorical (A, R and M) explanatory variables. The latter each comprised two factor levels: A: yes/no; R: temperate/tropical; M: C_3/C_4. The first model (as presented in the main paper, hereafter main) fitted the explanatory variables as main effects. The second model (presented in Supplementary Information, hereafter full) fitted main effects as well as all first-order interactions between explanatory variables. To control for non-independence we calculated robust covariance matrix estimates of parameter s.e.m. using study as a cluster variable. For both the main and full models, we used normal quantile–quantile and fitted values plots to confirm residuals were approximately Gaussian distributed and homogenous among fitted values (Supplementary Information). We also assessed colinearity between temperature, precipitation and CO_2, finding it to be low enough not to cause difficulty in interpreting overall trends (see Methods and Supplementary Fig. 5).

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Author contributions

All authors contributed to the data set, discussed the results and commented on the manuscript. J.W. analysed the data. D.R.S. and D.B.L. carried out the statistical analysis. A.C., D.L. and M.H. designed the study and wrote the paper.

Additional information

The data for the study will be made available at http://www.ag-impacts.org. Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.J.C.

Competing financial interests

The authors declare no competing financial interests.