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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 summarised 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 dataset of over 1700 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. Whilst 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]. Additionally, 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 parameterise 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 changed crop species or grazing integration, or more transformational options such as crop relocation or complete change in the farming system, such as moving from irrigated to dryland systems [10].

Meta-analyses that combine and compare results from multiple studies can be a useful way of summarising 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 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4), Easterling et al. 2007 [3, henceforth AR4] performed a meta-analysis of crop yield response to climate change, 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 for all crops, regions, and levels of warming. A subsequent analysis indicated that the benefit of adaptation to wheat yield plateaus at about 16% [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 dataset, with double the number of studies. This dataset is used to consider three questions: (1) What are the likely impacts of differing degrees of climate change on yields, by crop and by region?; (2) What is the quantitative effect of incremental adaptation as a function of temperature and rainfall?; and (3) 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 perform a simple analysis to summarise the dependence of yield changes on temperature, rainfall, crop photosynthetic pathway and adaptation. Some of the results of this meta-analysis, notably the data presented in the main figures in this paper, are also presented in the 5th Assessment Report of the Intergovernmental Panel on Climate Change.

The response of the three major crops to local mean temperature increases shows considerable spread, with the central tendencies being broadly similar to that 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 dataset 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 since AR4 associated with the use of global gridded crop models (see Supplementary Information). Without adaptation, the mean response of all three crops to climate change in both tropical and temperate regions is yield reductions. Further, 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: the majority of 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 US 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, over 30% of the datapoints (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 datapoints 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 at national [17] and global [3, 7] scales. Fig. 2 uses paired adaptation studies, whilst 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 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 at 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 multiple adaptations in a single study, makes conclusions regarding the most effective adaptation options difficult. Of the adaptation strategies distinguished in the study (planting date, fertiliser, irrigation, cultivar or “other agronomic”), cultivar adjustment was the most effective, with irrigation also showing benefit (see Supplementary Information).

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: 1) the lack of capacity to implement fully or other reasons for low adoption such as cultural inappropriateness [18]; 2) co-limitations such as increasingly restricted water resources limiting implementation of irrigation-based adaptations [19]; 3) the lack of inclusion of interactions with other factors such as pests and diseases [20], and 4) the lack of inclusion of altered climate variability and extremes in the analyses

[21]. On the other hand, the possible benefits of adaptation may be under-estimated, since 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 which 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 to 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 21st century can ameliorate some, but not all, risk of yield reductions. In the second half of the century more systemic or transformational adaptations may be needed in order to avoid the risk of significant reductions in mean yield.

The aggregation of data, whilst 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 yields 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 [e.g. 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 CV from six available studies (Fig. 4); the data, whilst 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 impacts 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 summary

The AR4 database (see Supplementary Information) was extended through a literature search to include publications from 2007-2012, thus increasing the number of studies from 42 to 91, and increasing the number of data points from 573 to 1722. 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 dataset represents current global coverage of the three crops, and found a reasonable match (see Supplementary Table 1). The literature search was broad and inclusive. We devised a quality control procedure in order to remove datapoints 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 performed 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 (OLS) 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 of 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 SI, 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 (ROBCOV) of parameter standard errors using study (S) as a cluster variable. For both the main and full models, we used normal Quantile-Quantile (QQ) and fitted values plots to confirm residuals were approximately Gaussian distributed and homogenous among fitted values (see SI). We also assessed co-linearity 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).

References

1. Beddington et al. 2012. What Next for Agriculture After Durban? Science VOL 335, 20 January 2012. DOI: 10.1126/science.1217941

2. Ericksen, P. J., John S.I. Ingram, Diana M. Liverman, Food security and global environmental change: emerging challenges, Environmental Science & Policy, Volume 12, Issue 4, June 2009, Pages 373-377, ISSN 1462-9011, 10.1016/j.envsci.2009.04.007.

3. Easterling, W., P. Aggarwal, P. Batima, K. Brander, L. Erda, M. Howden, A. Kirilenko, J. Morton, J.-F. Soussana, S. Schmidhuber, and F. Tubiello, 2007: Food, fibre and forest products. In Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, Eds. Cambridge University Press, pp. 273-313.

4. Pretty et al., “The top 100 questions of importance to the future of global agriculture”, International Journal of Agricultural Sustainability Vol. 8, No. 4, pp. 219–236, doi:10.3763/ijas.2010.0534, 2010.

5. Godfray, H. Charles, et al. (2010). Food Security: The Challenge of Feeding 9 Billion People. Science 327: 812-818.

6. Hertel, T.W. (2011). The global supply and demand for agricultural land in 2050: A perfect storm in the making? American Journal of Agricultural Economics, 93, 259-275

7. Tubiello, F.N., J.-F. Soussana, S.M. Howden, and W. Easterling, 2007: Crop and pasture response to climate change. Proc. Natl. Acad. Sci., 104, 19686-19690, doi:10.1073/pnas.0701728104.

8. Lobell, D.B., Schlenker, W., & Costa-Roberts, J. (2011). Climate Trends and Global Crop Production Since 1980. Science, 333, 616-620

9. Challinor, A. J., F. Ewert, S. Arnold, E. Simelton and E. Fraser (2009). Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. Journal of Experimental Botany 60 (10), 2775-2789. doi: 10.1093/jxb/erp062

10. Rickards, L., Howden, S.M. (2012) Transformational adaptation: agriculture and climate change. Crop and Pasture Science 63(3): 240-250.

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

12. Howden, S.M., J.-F. Soussana, F.N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke, 2007: Adapting agriculture to climate change. Proc. Natl. Acad. Sci., 104, 19691-19696, doi:10.1073/pnas.0701890104.

13. Knox, J, T. Hess, A. Daccache and T. Wheeler, 2012. Climate change impacts on crop productivity in Africa and South Asia. Environmental Research Letters 7 (3). Article Number 034032. DOI: 10.1088/1748-9326/7/3/034032

14. Müller C, Cramer W, Hare WL, Lotze-Campen H (2011): Climate change risks for African agriculture. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 108, 11, pp. 4313-4315, doi: 10.1073/pnas.1015078108

15. Thornton P K, Jones P G, Alagarswamy G, Andresen J, Herrero M (2010). Adapting to climate change: agricultural system and household impacts in East Africa. Agricultural Systems 103, 73-82.

16. Lobell, D and C. B. Field (2007). Global Scale Climate-Crop Yield Relationships and the Impacts of Recent Warming. Environmental Research Letters vol. 2 (2007)

17. Howden, S.M. & S. Crimp (2005) Assessing dangerous climate change impacts on Australia's wheat industry In: Zerger, A. and Argent, R.M. (eds) Advances and applications for management and decision making. Modelling and Simulation Society of Australia and New Zealand, pp. 170-176.

18. Adger et al. 2009. Are there social limits to adaptation to climate change? Climatic Change 93: 335-354.

19 Piao, S., P. Ciais, Y. Huang, Z. She, S. Peng, J. Li, L. Zhou, H. Liu, Y. Ma, Y., Ding, P. Friedlingstein, C. Liu, K. Tan, Y. Yu, T. Zhang and J. Fang. 2010. The impacts of climate change on water resources and agriculture in China. Nature, **467**, 43-51.

20 Soussana, J.F., A.I. Graux and F.N. Tubiello. 2010. Improving the use of modelling for projections of climate change impacts on crops and pastures. J. Ext. Bot. **61**, 2217-2228.

21 Challinor, A. J., E. S. Simelton, E. D. G. Fraser, D. Hemming and M. Collins(2010) Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. Environ. Res. Lett. 5 (2010) 034012

22 Gregory, P. J., Johnson, S. N., Newton, A. C. and Ingram, J. S. I. (2009) Integrating pests and pathogens into the climate change/food security debate. Journal of Experimental Botany, 60 (10). pp. 2827-2838. ISSN 0022-0957 doi: 10.1093/jxb/erp080

23 Garrett, K.A., Dobson, A.D.M., Kroschel, J., Natarajan, B., Orlandini, S., Tonnang, H.E.Z. and Valdivia, C. (2013). The effects of climate variability and the color of weather time series on agricultural diseases and pests, and on decisions for their management. Agric. Forest Meteorol. 170 216-227.

24 Angulo, C, R. Rötter, R. Lock, A. Enders, S. Fronzek and F. Ewert (2013). Implication of crop model calibration strategies for assessing regional impacts of climate change in Europe. Agric. Forest Meteorol. 170 Pages 32-46

25. Challinor, A. J., T. Osborne, A. Morse, L. Shaffrey, T. Wheeler, H. Weller (2009). Methods and resources for climate impacts research: achieving synergy. Bulletin of the American Meteorological Society, 90 (6), 825-835

26. Hawkins, E., Osborne, T.M., Kit Ho, C. and Challinor, A.J. (2013). Calibration and bias correction of climate projections for crop modelling: An idealised case study over Europe. Agric. Forest Meteorol. 170 32-46.

27. Rosenzweig, C, Jones, JW, Hatfield, JL et al (2013) The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agricultural and Forest Meteorology, http://dx.doi.org/10.1016/j.agrformet.2012.09.011.

28. Hansen, J., M. Satoa, and R. Ruedy (2012). Perception of climate change. PNAS 109 (37) 14720-14721

29. Benton, T. et al. (2012). Severe weather and UK food chain resilience. Detailed appendix to synthesis report. Available http://www.foodsecurity.ac.uk/assets/pdfs/frp-severe-weather-uk-food-chain-resilience.pdf

30. Hawkins, E., T. Fricker, A. J. Challinor, C. A. Ferro et al (2013), Increasing influence of heat stress on French maize yields from the 1960s to the 2030s. Global Change Biology Volume 19, Issue 3, pages 937–947. doi: 10.1111/gcb.12069

31 Berg, A., de Noblet-Ducoudré, N., Sultan, B., Lengaigne, M., Guimberteau, M., 2012. Projections of climate change impacts on potential C4 crop productivity over tropical regions. Agric. Forest Meteorol. 170 89-102 http://dx.doi.org/10.1016/j.agrformet.2011.12.003.

32 Tao, F., Zhang, Z., Liu, J., and Yokozawa, M. 2009. Modelling the impacts of weather and climate variability on crop productivity over a large area: A new super-ensemble-based probabilistic projection. Agricultural and Forest Meteorology 149(8): 1266-1278

33 Tao, Fulu, Zhao Zhang, 2013: Climate change, high-temperature stress, rice productivity, and water use in eastern china: a new superensemble-based probabilistic projection. J. Appl. Meteor. Climatol., 52, 531–551.

34 Urban, D., M. J. Roberts, W. Schlenker and D. B. Lobell, David (2012) Projected temperature changes indicate significant increase in interannual variability of U.S. maize yields. Climatic Change 112 (2) 525-533

Supplementary Information is linked to the online version of the paper at ww.nature.com/nature.

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Author contributions. All authors contributed to the dataset, discussed the results and commented on the manuscript. JW analysed the data. DS and DL performed the statistical analysis. AC, DL and MH designed the study and wrote the paper.

Author information. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to a.j.challinor@leeds.ac.uk

Term	Coefficient	S.E.	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= 'c3'=0; 'c4'=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	<0.0001 ***
ΔCO2	0.06	0.02	3.07	0.0022 **

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

Figures

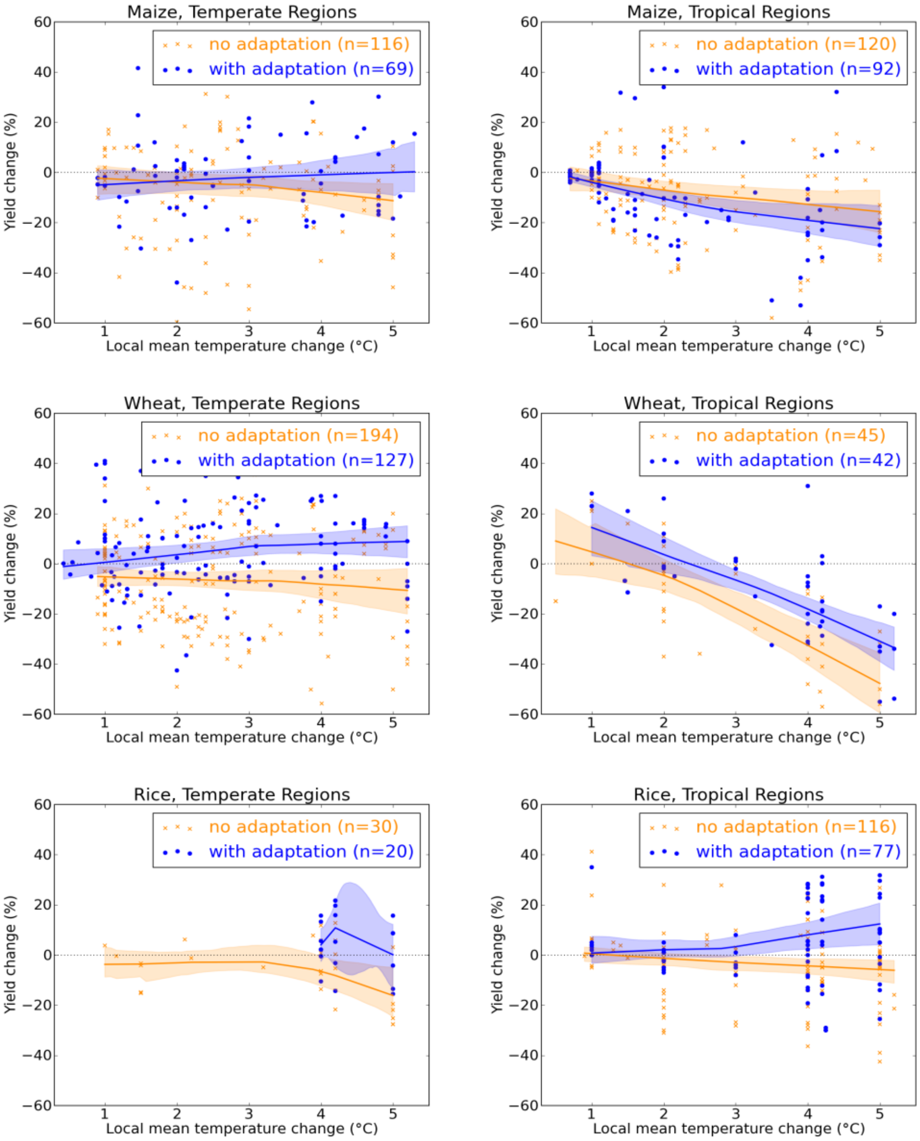

Figure 1. Percentage yield change as a function of temperature for the three major crops and for temperate and tropical regions for local mean temperature changes up to five degrees (n=1048 from 66 studies). Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, which are separated according to the presence (blue) or absence (red) of adaptation. Note that 4 datapoints 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.

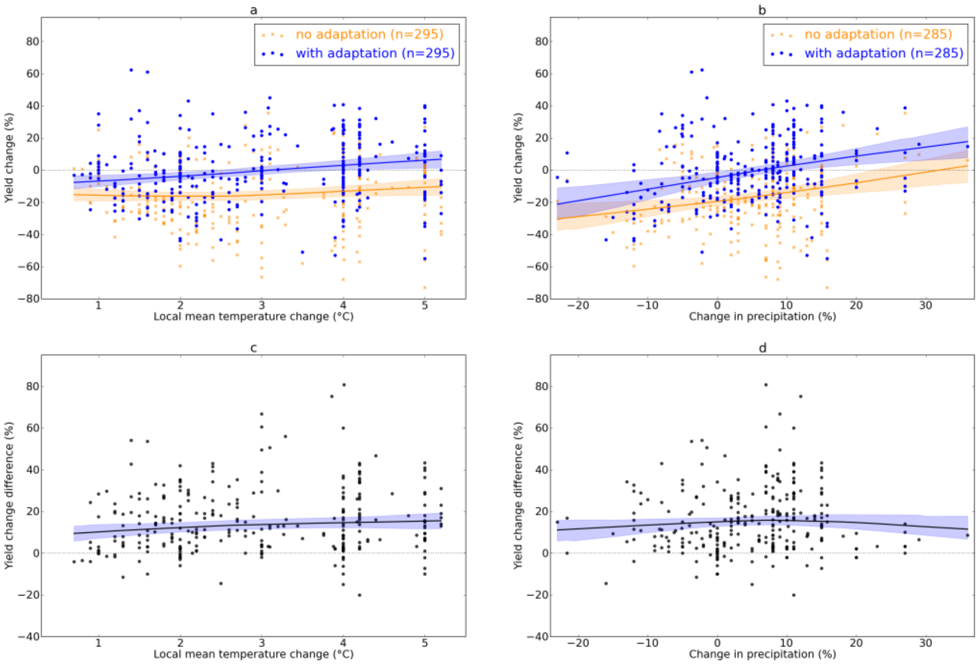

Figure 2. Percentage yield change as a function of (a) temperature and (b) precipitation, for the 33 paired adaptation studies, across all regions and crops. Shaded bands indicate the 95% confidence interval of regressions consistent with the data based on 500 bootstrap samples, with blue and red bands in top panels corresponding to with and without adaptation. The difference between simulations with and without adaptation for **(c)** temperature and **(d)** precipitation are shown in bottom panels, 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^{o}C and yield change >0), which shows less sensitivity to high localtemperature change than other crops.

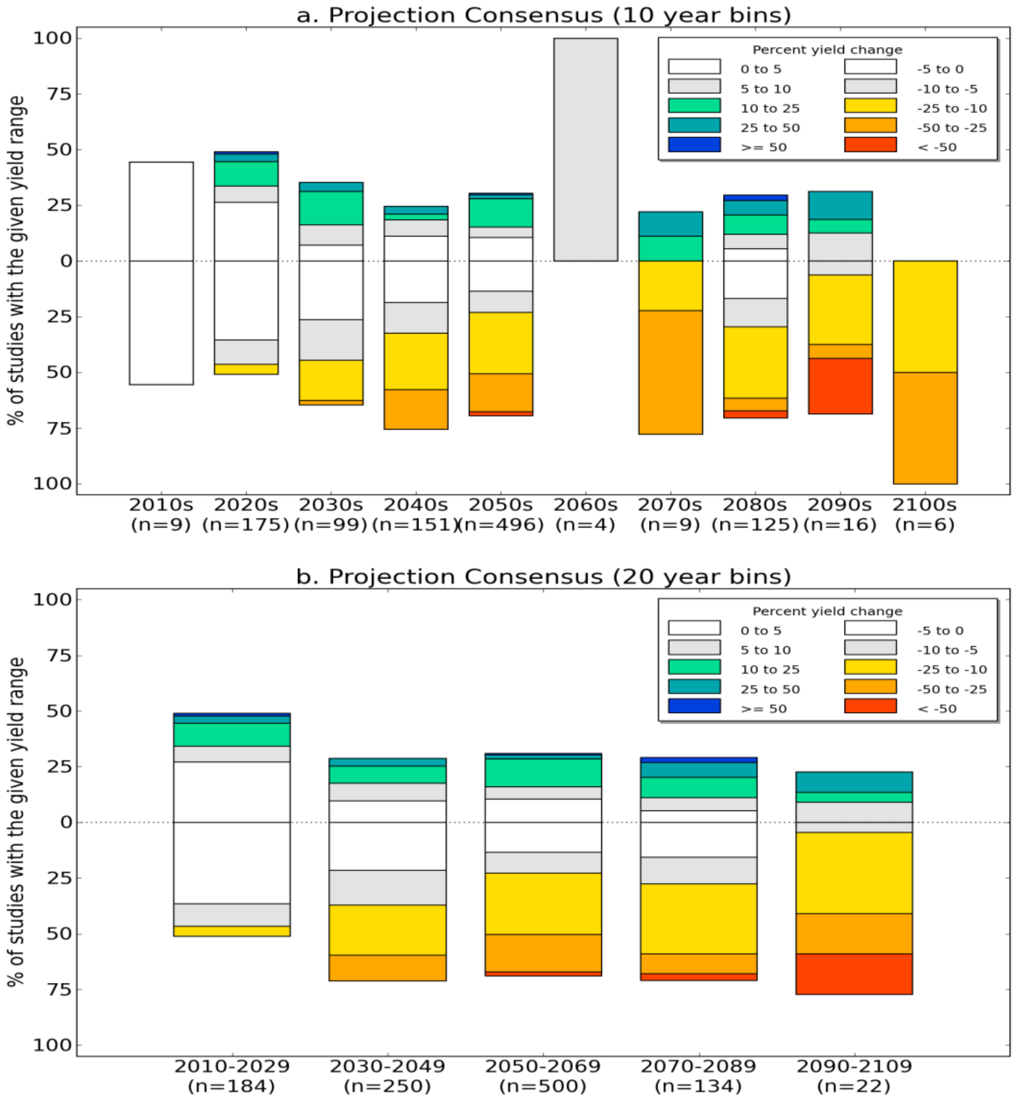

Figure 3. Projected changes in crop yield as a function of time for all crops and regions (n= 1090 from 42 studies). The vertical axis indicates degree of consensus and the colours denote percentage change in crop yield. Data are plotted according to **(a)** decade or **(b)** 20-year periods in which the centre point of a study's projection period falls. The decadal analysis has positive yield change for the 2060s, which has the fewest datapoints 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.

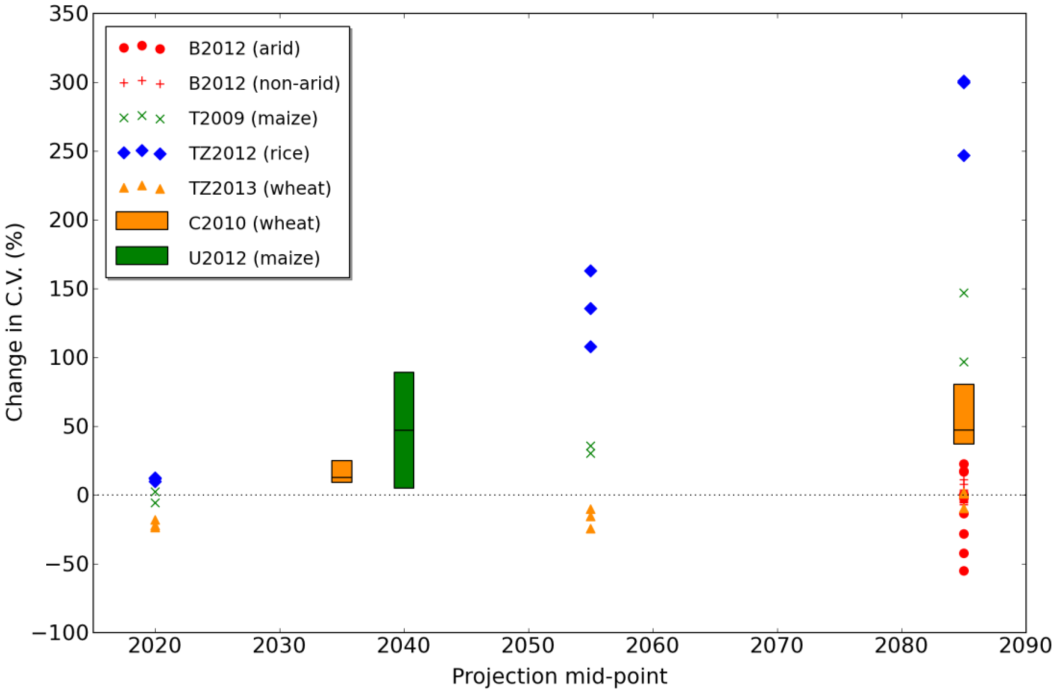

Figure 4. Projected percentage change in yield coefficient of variation (CV) for wheat (gold), maize (green), rice (blue) and C4 crops (red) taken from C2010 (ref. 21), B2012 (ref. 31), T2009 (ref. 32), TZ2013 (ref. 30), TZ2012 (ref. 33) and U2012 (ref. 34). U2012 and C2012 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in CV. For C2012 paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. The studies used a range of scenarios (SRES A1B, A2, A1F1 and B1). B2012 is a global study, U2012 is for the US, and the remaining studies are for China