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Crop productivity changes in 1.5 °C and 2 °C worlds under climate sensitivity uncertainty

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Abstract

Following the adoption of the Paris Agreement, there has been an increasing interest in quantifying impacts at discrete levels of global mean temperature (GMT) increase such as 1.5 °C and 2 °C above pre-industrial levels. Consequences of anthropogenic greenhouse gas emissions on agricultural productivity have direct and immediate relevance for human societies. Future crop yields will be affected by anthropogenic climate change as well as direct effects of emissions such as CO_2 fertilization. At the same time, the climate sensitivity to future emissions is uncertain. Here we investigate the sensitivity of future crop yield projections with a set of global gridded crop models for four major staple crops at 1.5 °C and 2 °C warming above pre-industrial levels, as well as at different CO_2 levels determined by similar probabilities to lead to 1.5 °C and 2 °C, using climate forcing data from the Half a degree Additional warming, Prognosis and Projected Impacts project. For the same CO_2 forcing, we find consistent negative effects of half a degree warming on productivity in most world regions. Increasing CO_2 concentrations consistent with these warming levels have potentially stronger but highly uncertain effects than 0.5 °C warming increments. Half a degree warming will also lead to more extreme low yields, in particular over tropical regions. Our results indicate that GMT change alone is insufficient to determine future impacts on crop productivity.

Introduction

Among the manifold impacts of anthropogenic climate change, its potential to threaten global food production has always been of particular concern (UNFCCC 1992). Observational evidence already indicates adverse impacts of climate change on crop productivity across the globe (Schlenker and Lobell 2010, Lobell *et al* 2011b, Moore and Lobell 2015) and underscores the risk posed by extreme weather events, in particular droughts and heat waves, on crop yield (Lesk *et al* 2016, Schauberger *et al* 2017, Ray *et al* 2015).

In addition to changes in climatic conditions, anthropogenic greenhouse gas emissions and associated rising atmospheric CO_2 concentrations could also play a direct role for crop growth and crop yield (Kimball 2016), also related to enhanced water use efficiency (Morgan *et al* 2011). CO_2 effects on crop performance are regionally different (McGrath and Lobell 2013, Deryng *et al* 2016), and remain a large source of uncertainty in climate impact assessment on agriculture (Asseng *et al* 2013, Rosenzweig *et al* 2014, Deryng *et al* 2016). Thus, despite the possible benefits of elevated CO_2 on crop yield, there is an emerging consensus that adopting a stringent mitigation pathway would reduce the risks of crop yield losses, and would especially benefit agriculture and food security in the tropics and sub-tropics (Müller *et al* 2015), which face a higher risk of heat-stress damage (Lobell *et al* 2011a, Deryng *et al* 2014).

The adoption of the Paris Agreement and the subsequent special report of the Intergovernmental Panel on Climate Change (IPCC) on 1.5 °C has led to an increasing interest in differentiation between impacts of climate change at 1.5 °C above pre-industrial levels in particular in comparison to 2.0 °C (Schleussner *et al* 2016b). This focus on impacts at specific warming levels calls for targeted modelling efforts (James *et al* 2017).

It also raises questions for which impacts of climate change a global mean temperature (GMT) level alone is sufficient to characterise impacts of climate change (Schleussner *et al* 2016b). In concentration scenarios such as the Representative Concentration Pathways (RCPs), CO_2 concentrations are prescribed. The climate sensitivity, however, is uncertain and differs substantially between climate models thereby leading to model-dependent warming trajectories (Stocker *et al* 2013). To account for uncertainty in the climate sensitivity, the link between CO_2 concentration pathways and GMT levels is generally explored in a probabilistic fashion (IPCC 2014). The probability for not exceeding 2 °C above pre-industrial levels in the lowest RCP2.6 scenario, for example, has been assessed to be more than 66% (IPCC 2014). In a concentration pathway approach, uncertainty in the climate sensitivity is thereby consistently dealt with. For GMT focussed studies, however, the corresponding CO_2 concentrations uncertainty range has to be explored systematically. This has profound consequences for the assessment of future crop yields at specific warming levels, and the biosphere response more generally, as it is responsive both to changes in CO_2 levels as well as climate.

In the following, we assess changes in crop productivity under 1.5 °C and 2 °C warmer climates provided by the model intercomparison project 'Half a degree Additional warming, Prognosis and Projected Impacts' (HAPPI, Mitchell *et al* 2017). Our analysis is based on modelled crop yield data from six models of the Global Gridded Crop Model Intercomparison (GGCMI, Elliott *et al* 2015, Müller *et al* 2017) as part of the Agricultural Model Intercomparison and Improvement Project (AgMIP, Rosenzweig *et al* 2014). We provide projections for the four major staple crops: wheat (*Triticum aestivum L.*), maize (*Zea mays L.*), rice (*Oryza sativa L.*), and soybean (*Glycine max L.*). Crop yield responses for varying CO_2 concentrations are analysed, which allows to disentangle the effect of CO_2 fertilization and 0.5 °C warming increments. Finally, we also assess changes in 10 year minimum productivity to understand implications for yield stability—a central aspect for food security.

Methods

The HAPPI modelling protocol includes three 10 year periods with prescribed atmospheric forcing as well as sea-surface temperatures and sea-ice forcing conditions (see Mitchell *et al* 2017 for further details on the HAPPI protocol). Participating general circulation models (GCMs) have provided multi-member realisations for each of the three periods. The reference period for the HAPPI experiment is the 'current decade' from 2006–2015 forced by observations including observed CO_2 concentrations that have increased from 380.9 parts per million (ppm) to 402.9 ppm over this decade. Mean warming over this period corresponds to about 0.9 °C above the 1860–1880 period in the Berkeley Earth GMT dataset. The Future 1.5 °C experiment is based on the RCP2.6 experiment and takes constant forcing for greenhouse gases and aerosols and sea-surface temperatures from the 2091–2100 decade. CO_2 concentrations in this experiment are constant at 423.4 ppm. The Future 2 °C experiment uses scaled atmospheric and sea-surface temperature forcing from RCP2.6 and RCP4.5 with CO_2 concentrations set to 486.6 ppm.

Multi-ensemble projections for four GCMs from the HAPPI intercomparison projected have been regridded to a 0.5×0.5 °C regular grid and bias corrected based on the EWEMBI dataset (Lange 2017) following the modelling protocol of the Intersectoral Impact Model Intercomparison Project (ISIMIP; Frieler *et al* 2017). Five bias-corrected ensemble members per GCM are used in this analysis. Harmonised agricultural management data for fertiliser application rates, irrigated and rainfed areas and crop calendar are applied according to the fully harmonized configuration (*fullharm*) as introduced in (Elliott *et al* 2015). An overview of GGCM model setups is provided in table S1 available at stacks.iop.org/ERL/13/064007/mmedia; an overview of available GCM simulations, model years and ensemble members in table S2. Crop producing regions are masked using rainfed and irrigated areas from the MIRCA 2000 dataset (Portmann *et al* 2010) that is also used for aggregation of crop yield over actual harvested areas (Porwollik *et al* 2017).

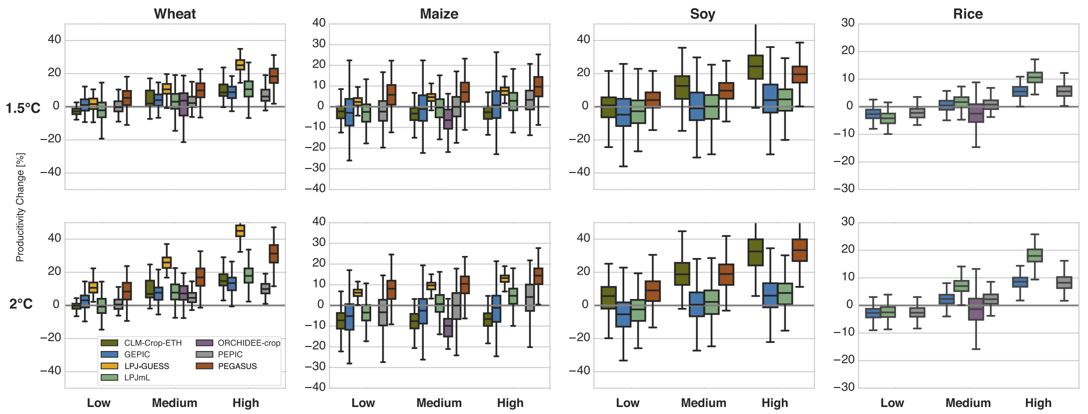

Figure 1. Changes in global crop productivity under 1.5 °C warming (upper panel) and 2 °C (lower panel) for four major staple crops (wheat, maize, soybean and rice from left to right, note that *y*-axis scaling is different). Projections for 7 crop models from the global gridded crop model intercomparison (GGCMI) project are shown for a set of warming level specific CO_2 concentrations (see table 1). The levels of CO_2 concentrations for Low, Medium and High (1.5 °C: 390 ppm, 423 ppm, 486 ppm; 2 °C: 423 ppm, 486 ppm, 590 ppm) are chosen so that they resemble similar climate response probability levels for 1.5 °C and 2 °C (see Methods). Changes are derived relative to the 2006–2015 median for each GGCM-GCM combination before aggregation. Boxes indicate the interquartile range across climate-crop model multi-realisation ensembles and years (see table S2, $n = 135–200$), whiskers extend to at most 1.5 of the interquartile range. Outliers are not shown.

Table 1. Applied CO_2 concentrations for the three model periods and corresponding classifications in terms of exceedance probability for the respective warming levels according to a TCR-based estimate (see Methods). Medium values correspond to standard HAPPI CO_2 concentrations.

	CO_2 concentrations associated with different climate responses		
	Low	Medium	High
2006–2015	Observed [~390 ppm]		
1.5 °C	390 ppm	423.4 ppm	486.6 ppm
2 °C	423.4 ppm	486.6 ppm	590 ppm

In addition to the core set of HAPPI experiments, the sensitivity to different CO_2 levels linked to uncertainty in the climate sensitivity is explored. A useful metric to assess the climate sensitivity to increase in CO_2 concentrations is the 'transient climate response' (TCR) that is defined as the annual mean GMT change at the time of CO_2 doubling following a linear increase in CO_2 forcing over a period of 70 years (Stocker *et al* 2013). The AR5 provides an estimate for a likely range for the TCR between 1 °C to 2.5 °C (Stocker *et al* 2013). Here we are approximating probabilities for end of century warming by this TCR estimate assuming a normal distribution with mean at 1.75 °C and a standard deviation of 0.75 °C. Based on this distribution, TCR probability levels for not exceeding 1.5 °C and 2 °C at different CO_2 concentrations are derived (see figure S1). Radiative forcing from non-CO_2 greenhouse gases and aerosols are based on RCP2.6 (1.5 °C, 0.45 W m^{-2}) or scaled RCP2.6 and RCP4.5 (2 °C, 0.63 W m^{-2}) end of century conditions, respectively (Mitchell *et al* 2017).

Following this TCR-based approach, the 1.5 °C, non-exceedance probabilities for 390.0 ppm, 423.4 ppm and 483.0 ppm are 84%, 67% and 44%, respectively. Probabilities for 2 °C and 423.4 ppm (87%) and 483.0 ppm (67%) yield quite consistent values, thereby allowing for comparing consistent GMT—CO_2 combinations. For the 2 °C experiments an additional CO_2 concentration of 590.0 ppm (42%) is chosen that is in line with the high ppm-probability of the 1.5 °C set. These GMT-CO_2 combinations thereby establish a consistent scenario set that in the following will be called 'low', 'medium' and 'high' following the respective CO_2 concentrations (see table 1).

Results

The choice of CO_2 mixing ratio sets with very similar climate sensitivity probabilities for the 1.5 °C and 2 °C simulations allow for directly assessing the effects of climate sensitivity uncertainty on global crop productivity. Results for wheat, maize, soybean and rice are depicted in figure 1. The response in globally aggregated crop productivity to changing CO_2 concentrations is found to be strongly model and crop dependent. For maize, which is least responsive to elevated CO_2 concentrations, most models do not indicate a substantial effect of different CO_2 levels. On the contrary, for rice as well as wheat for some models, the CO_2 level largely determines the sign of the warming effect. GGCM projections for rice indicate a change in direction of the warming impact from negative at low CO_2 level to (moderately) positive under (medium) high CO_2 levels. This dominant CO_2 effect is independent of the warming level. Results for soybean follow a similar pattern. Projections for wheat indicate generally beneficial effects of rising CO_2 levels and typically a moderately positive response to rising temperatures in most models even at the lowest CO_2 levels considered (compare figure 1, panel 1.5 °C–Low CO_2).

Regrouping of the combined GMT-CO_2 sensitivity runs allows for directly assessing the effect of ~0.5 °C

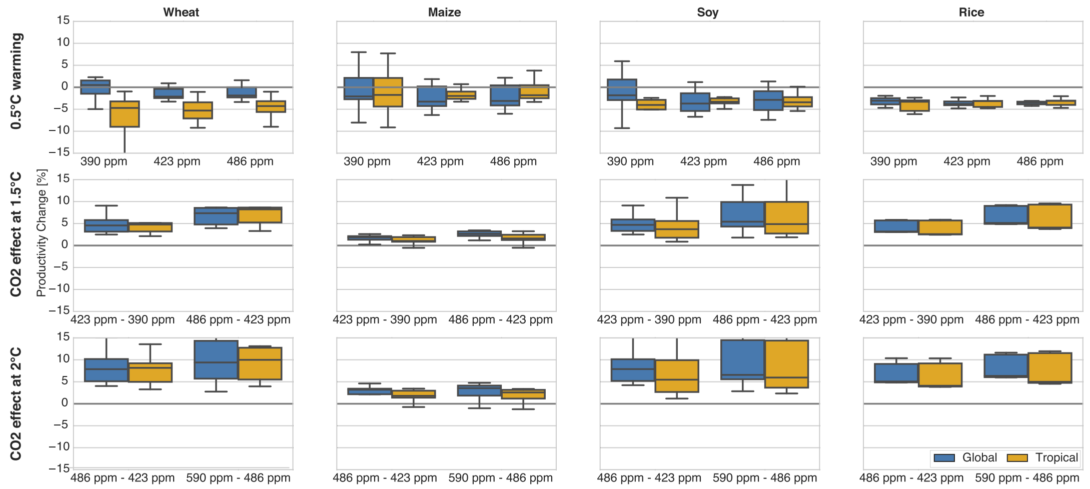

Figure 2. Projected changes in global (blue) and tropical (yellow) crop productivity relative to the 2006–2015 period for ~0.5 °C GMT increases at different levels of CO_2 concentrations (top panel) as well as for the same warming but different CO_2 concentrations (middle and bottom panel). Top panel: For 390 ppm, the difference is derived based on the 1.5 °C and the 2006–2015 periods (i.e. an GMT increase of 0.7 °C), for 423 ppm and 486 ppm between 2 °C and 1.5 °C. Changes in crop productivity are aggregated over present day crop producing regions following MIRCA-2000; tropics only consider these areas between 23.5°S and 23.5°N. The box-whiskers comprise the spread of mean changes for the individual GCM-GGCMs pairs (temporal and multi-realisation ensemble mean, $n = 9$–21, see table S2 for an overview of the GCM-GGCM simulations). Boxes indicate the interquartile range. Note that the number of GGCMs differs betweens crops. Whiskers extend to at most 1.5 of the interquartile range. Outliers are not shown.

warming increments at different CO_2 concentrations. For the GCM ensemble used, the warming difference between the recent past (2006–2015) and the 1.5 °C period is about 0.67 °C, between the 1.5 °C and 2 °C periods around 0.45 °C (see table S3 for the GCM specific warming differences). From our set of GMT-CO_2 experiments we can thereby form three pairs to investigate the impact of ~0.5 °C warming increments: 1.5 °C minus recent past at 390 ppm, 2 °C minus 1.5 °C at 423 ppm and 2 °C minus 1.5 °C at 486 ppm. The resulting global as well as tropical (between 23.5°S/°N) crop productivity changes are displayed in figure 2 (top panel). Apart from a slight positive response of global productivity up to 1.5 °C warming for wheat and maize, median global crop productivity is consistently negatively affected by 0.5 °C warming increments. Differences between global and tropical yields are particularly pronounced for wheat, whereas median crop productivity is projected to decrease by 2.5% as a result of additional 0.5 °C warming (see also table S4). As shown in figure 2 (middle and bottom panel), the effect of uncertainty in climate sensitivity is comparable and for wheat, soy and rice more pronounced than the effect of a 0.5 °C temperature increase.

Changes in crop productivity are further regionalised using the climatological regions from the IPCC SREX report (IPCC 2012). Figure 3 depicts the regionally resolved changes (see also table S4). While some high latitude regions like North Asia or Northern Europe see some benefits under future warming up to 1.5 °C (blue bars in figure 3), warming benefits beyond 1.5 °C remain limited. Tropical and subtropical regions are affected most strongly, with median reductions in total crop productivity of 3%–5% projected for regions such as Central America and the Caribbean, the Sahel or East Africa. Rice productivity is particularly affected in water-scarce regions such as the Mediterranean or West Asia (projected median productivity reductions of about 5%). Future drought during summer is projected to increase (Greve and Seneviratne 2015) for these regions, the period where irrigation demand is highest (Thiery *et al* 2017). This renders the projected changes for these regions conservative, as no water limitations are considered for irrigated crops in our simulations. Finally, the multi-ensemble nature of the HAPPI modelling protocol also allows for assessing changes in the 1-in-10 year low global crop productivity as shown in figure 4. The changes in 10 yr extreme lows follow the trend for the median projections displayed in figure 2. For rice, the impact of warming from current GMT to 1.5 °C is more pronounced for the 1-in-10 year low harvests than the warming from 1.5 °C–2.0 °C at any CO_2 level (Wang *et al* 2015).

Discussion

Our findings of consistently reduced productivity under scenarios of increased warming align well with existing literature estimating the impacts of warming on crop productivity using either process-based (Rosenzweig *et al* 2014, Zhao *et al* 2017, Liu *et al* 2016) or statistical estimates (Lobell and Asseng 2017). Not considering uncertain effects of CO_2 fertilisation, median changes in local yields over the tropical crop producing regions for the four major staple crops wheat, maize, soybean and rice have been found to be negatively affected under a 1.5 °C GMT increase relative

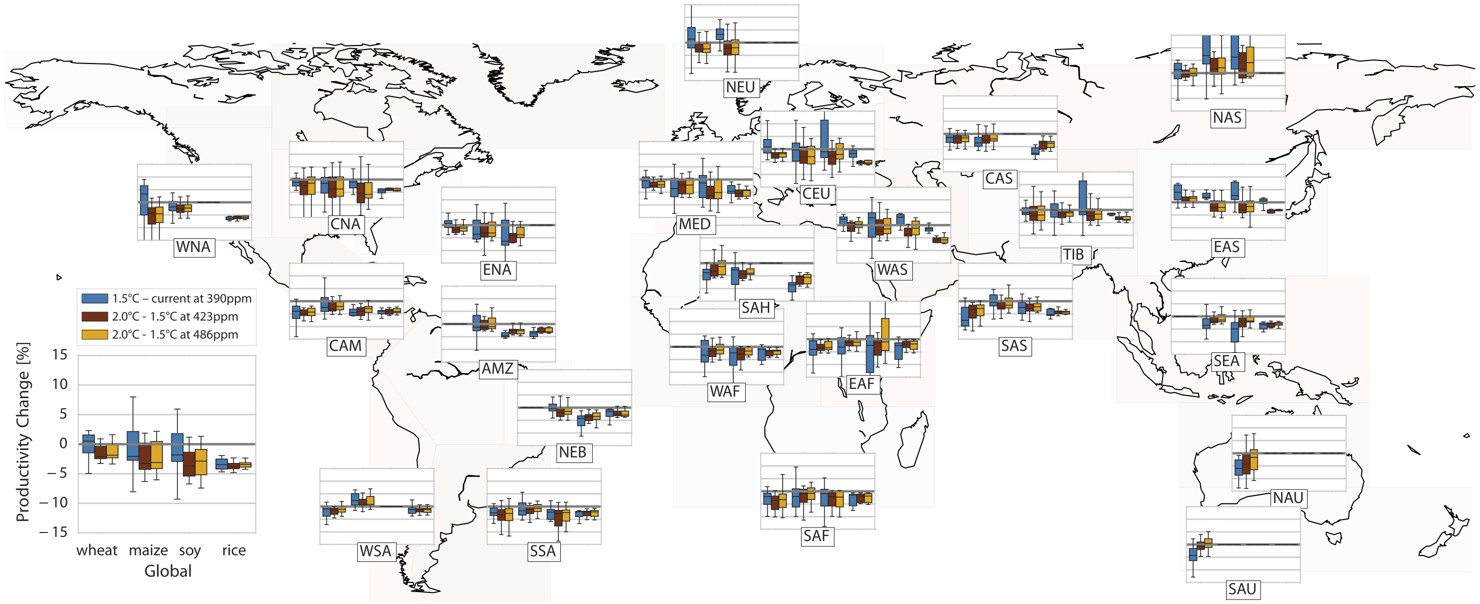

Figure 3. As figure 2, but aggregated over the SREX world regions. Projections are only given for regions that include at least 0.1% of global production in MIRCA-2000. Results for individual regions are also given in table S4. Note that agricultural areas for the different regions vary substantially (see table S5 for the regional share of grid cells with agricultural activity per crop and region).

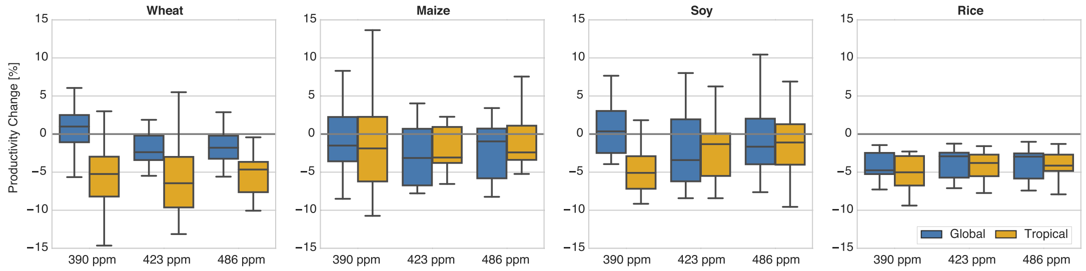

Figure 4. As figure 2 top panel, but for extreme low yields with a return period of 10 years or higher. Extreme low yields are derived as mean over the <10% quantile per warming level and GCM-GGCM pair (45–50 years, see table S2). Relative changes are derived relative to the extreme low yields of the reference period.

to pre-industrial levels and even more so under 2 °C (Schleussner *et al* 2016a). Even when accounting for the full effects of CO_2 fertilisation in crop models, median local tropical yields for wheat and maize are still found to be negatively affected and reductions to double between 1.5 °C and 2 °C. Our findings confirm the assessment of increasing risk for local crop productivity between 1.5 °C and 2 °C based on 20 year time slices at mean warming levels of 1.5 °C and 2 °C from RCP8.5 simulations from the ISIMIP Fast Track experiment (Warszawski *et al* 2013). If at all, our reported reductions are on the low end. For wheat, we find a reduction for global productivity of about 2% per 0.5 °C warming (likely range −2.7 to −0.1%) compared to 4%–6% per degree of warming reported in other studies combining observational and model evidence (Asseng *et al* 2014, Liu *et al* 2016). Zhao *et al* (2017) have investigated impacts of GMT increase for all four major staple crops at 380 ppm. They find warming to reduce global yields of wheat by 6.0 ± 2.9%, rice by 3.2 ± 3.7%, maize by 7.4 ± 4.5% and soybean by 3.1% ± 5% per °C GMT increase. Our findings for soybean and rice are at the upper end of the confidence range of Zhao *et al* (2017), but our median projections for maize are again slightly more conservative.

One possible origin for our lower estimate is the limited capability of most models in our ensemble to represent the effects of heat stress on wheat that is found to play a dominant role in productivity losses in field studies (Asseng *et al* 2014) and observations (Liu *et al* 2016), and different temperature response mechanisms in models are a major source of uncertainty in wheat (Wang *et al* 2017). Similar effects of extreme heat on crop productivity are documented for maize and soybean, which these models were able to capture in a recent study for the USA (Schauberger *et al* 2017, Anderson *et al* 2015). Another key uncertainty relates to the CO_2 fertilization effect that may lead to enhanced photosynthesis rates and increased crop water productivity, and thereby increased crop productivity under elevated CO_2 concentrations. The strength of this effect is not at all well-constrained by observations and very differently represented in different crop models (Deryng *et al* 2016, see also figure 1). Hasegawa *et al* (2017) suggest that this uncertainty could be reduced for rice, if the reduced effect of CO_2 fertilization on morphological development, in particular leaf area, would be accounted for. This is, however not yet included for in the models used here.

In spite of substantial uncertainties in model response, our analysis of crop yield changes at 1.5 °C and 2 °C for different warming and concentration levels indicates that the warming level alone is insufficient to characterise projected impacts of crop productivity. The responsiveness to geophysically plausible CO_2 concentrations at 1.5 °C and 2 °C is large for most models and crop species and generally outweighs the difference introduced by a half a degree warming increment (figure 2). This sensitivity remains even for maize, which has no direct CO_2 fertilisation of photosynthesis and only experiences increased water use efficiency under elevated CO_2 (figure 1). However, the crop response to elevated CO_2 response in GGCMs has been shown to be a large source of uncertainty (Deryng *et al* 2016) and provides rather optimistic results as models have yet to represent CO_2 interaction processes with, for example, ozone. Another uncertainty dimension relates to the effects of elevated CO_2 on crop quality (Taub *et al* 2008, Myers *et al* 2014), which is a key dimension of food security. Assessments of climate impacts on crop productivity overlooking the nutrition dimension may easily be misleading with regard to the effect of climate change on future food security (Gustafson *et al* 2016, Müller *et al* 2014). Thus, the medium and high CO_2 level scenarios as shown in our study are associated with greater level of uncertainty than our low CO_2 level scenario and should be interpreted with caution.

Our analysis highlights consistent negative effects of 0.5 °C warming on global and most regional crop productivity for all crops and CO_2 levels investigated. As the climate sensitivity, and thereby the CO_2 concentrations at which warming levels of 1.5 °C and 2 °C may be reached, are inherently uncertain, this has important implications for our understanding of future climate impacts on crop productivity in light of climate sensitivity uncertainty. If TCR turns out to be towards the high end (meaning stronger warming at the same CO_2 concentration level), the negative effects of additional warming may subsequently dominate over small (and uncertain) effects of CO_2 fertilization. In the opposite case, stronger CO_2 fertilization, if fully materialized, may dominate, but temperature increase between 1.5 °C and 2 °C will still lead to adverse impacts (figure 2). At the same time, a low TCR would allow for a bigger carbon budget to reach warming targets (Rogelj *et al* 2016). Since it is currently not possible to further constrain estimates of TCR, the uncertainty in future impacts on crop productivity under different warming levels is inherently coupled to the geophysical uncertainty of the climate sensitivity (Knutti *et al* 2017).

Finally, additional 0.5 °C warming increments will consistently lead to more extreme low yields, in particular in tropical regions (figure 4). Together with a steep rise in world population and food demand over the next decades (Kc and Lutz 2017), this will greatly increase the risk of future food shortages already as early as the 2030s when 1.5 °C warming could be reached (Lobell and Tebaldi 2014). In a globally connected food system, such production shortages would not only affect the producing regions, but will potentially have strong effects in remote but food importing regions and especially on vulnerable populations that spend large shares of their available income on food. Studies on observed food price shocks linked to extreme weather have indicated that poor, food importing countries—most often least developed countries and small island states—are particularly vulnerable to external production shocks (Bren d'Amour *et al* 2016).

Conclusion

Using multi-model multi-ensemble projections for future 1.5 °C and 2 °C worlds, we have analyzed changes in crop productivity at these warming levels. We have found consistent negative imprints of 0.5 °C warming increments for median as well as low productivity extremes alike for global food productivity with tropical regions being affected more strongly. Despite uncertainties in potential positive effects of elevated CO_2 concentrations for crop productivity, we have found that warming levels alone are insufficient to assess future impacts of climate change on future crop productivity. By linking this back to the uncertainty in the geophysical climate response to increased CO_2 emission, our analysis provides a novel viewpoint on the nested geo- and biophysical uncertainties linked to assessments of climate impacts at discrete warming levels. Our findings indicate that impacts of warming on crop production will be consistently lower at 1.5 °C compared to 2 °C. However, uncertainties related to potentially positive effects of increasing CO_2 fertilization on crop productivity are found to dominate over warming increments. Thereby, our results underscore that GMT levels alone are insufficient to characterise impacts of anthropogenic greenhouse gas emissions on crop productivity.

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