Importance of considering technology growth in impact assessments of climate change on agriculture

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1. Introduction

Crop sensitivity to increasing temperature, precipitation, and CO₂ changes raise concern for the future food security of the world. Impact assessments of agriculture have been used to inform policymakers and the public on likely effects of climate change and potential of various technologies and adaptation options to reduce the same (Hoegh-Guldberg et al., 2018; Reidma et al., 2015; Challinor et al., 2014; IPCC, 2014; Rosenzweig et al., 2014; Rosenzweig and Parry, 1994). These assessments use biological process-based models, statistical techniques or a combination of these (Zhao et al., 2017) to project the likely impact of climate change on future crop yields in different time periods. All IPCC reports and numerous other studies have shown that climate change is expected to result in significant crop yield losses which are likely to increase with time (Challinor et al., 2014; Rosenzweig et al., 2014; Knox et al., 2012). In the short term, these studies project a loss of up to 25%, depending on the crop and the region. By 2080s, these losses are projected to be as high as 50% (Challinor et al., 2014; Knox et al., 2012). Similar loss trends are projected irrespective of the methods used (Lobell and Asseng, 2017; Liu et al., 2016). Management options such as change in planting dates, varieties or water and nutrient management practices and technologies are likely to help in moderating the negative impacts of climate change in many cases (Aggarwal et al., 2018; Campbell et al., 2016; Hertel and Lobell, 2014; Moore and Lobell, 2014; Liu et al., 2013; Howden et al., 2007). Research has also shown that climate change has indeed already started affecting crop production, with estimates of loss varying from 1 to 10%, compared with the situation of no climate change (Lobell et al., 2011; Lobell and Field, 2007).

Climate change impacts on crop yields are projected to be highly differentiated, with lower and middle-income tropical and developing countries being more affected (and hence vulnerable) than temperate and developed countries (IPCC, 2014). South Asia and Africa are projected to witness yield losses of up to 25% by the 2020s compared with
Europe and North America where there could be some yield gains (Knox et al., 2016, 2012).

The world has witnessed substantial increases in crop productivity over the last few decades due to increased diffusion of improved crop varieties and increased nutrient and water consumption across major crop-producing regions of the world. Crop (especially cereal) yield growth rates have remained between 1.5 to 2% per annum, from the time of green revolution up to the present (Crespo-Herrera et al., 2018; FAO, 2013; Evenson, 2003), although there are wide regional variations and evidence of yield plateaus in some countries (Grassini et al., 2013; Ray et al., 2012).

Given that impact assessments of climate change have been undertaken since the 1980s and we are now close to 2020, often the first time slice used in impact assessments, we have an opportunity to assess these projections by comparing them with observed yields for the same time period. The objective of this study is to review projected climate change impacts and compare them with recently observed national crop yields for the 2020s based on available global crop statistics. The results help in identifying hotspot regions and countries where technology trends and climate impacts pose a serious challenge in the short-term. To minimize individual study bias, we assembled a large database from a systematic review of studies published over the last three decades on the impact of climate change on rice, wheat and maize yields specifically for the period 2010–2039 and averaged them at the national level. A few such analyses have been carried out in the past but their focus has been more on analyzing the yield impacts of change with mean temperature change, different time slices, and quantifying adaptation benefits. None has undertaken country-level analysis, which provides greater scope for identifying hotspots for action.

2. Material and methods

2.1. Database of projected impacts on crop yields

We carried out a systematic literature review of major climate change impact studies for the 2020s (generally 2010–2039), a commonly-used time period in impact literature. Our review searched for all terms related to climate impact assessment on agriculture. We started by focusing on references in the five IPCC Assessment Reports, and the database was later expanded with other studies assembled from various sources: scientific databases (Scopus, Web of Science, CAB Direct, JSTOR, Agricola), journals and open-access repositories, and several institutional websites including FAO, AgMIP and the World Bank. The steps followed in the review process included initial identification of studies, screening, analyzing studies in relation to pre-determined eligibility criteria (required for this analysis) and final inclusion of studies for the review (refer Supplementary Information for more details). Although there are hundreds of studies dealing with climate change impacts on crops, not all of them deal with short-term country-level impacts. Therefore, several global studies, which provided average impacts for different countries, were used in the analysis. Only those regional studies, that provided dis-aggregated country-level impacts, were retained in the database. Point-based studies were omitted, because they could not be assumed to be representative of climate change impacts for the entire country, especially for large countries with diverse agro-ecological and climatic zones. Consequently, several point-based studies relating to large countries such as India, China and Australia; and studies for different time periods were not included in the final database. However, there were some studies where impacts were assessed for several points covering the majority of the crop growing region of a country. Such data were area-weighted and its average was included as country-level impact.

The data were examined for outliers (impact values outside the 5th and 95th percentiles) for different projection periods, crops and countries. All outliers (34 points) were removed from the database. At the end of the review process, we thus had a dataset with 34 publications and 4491 data points at country-scale giving projected yield impacts of the major cereals (rice, wheat, and maize), with most of the data points emanating from global and national studies. Data were heterogeneous with diverse climate models, emission scenarios and crop models (refer to supplementary information for details).

2.1.1. Baseline Correction

A fixed baseline period (1960–1990), and modelled impacts for 2010–2039 (referred henceforth as the 2020s) was set as a reference for this analysis. A few impact assessment studies, however, used different baseline time-periods, which could result in bias. Such studies were corrected by normalizing the results to our reference time period. To illustrate, if the baseline was 1970–2000 and modelled impact was for 2015–2045, the difference between their mid-points was 45 years. This was corrected by normalizing the impacts for 50 years gap between our reference baseline of 1960–1990, and modelled impacts for 2010–2039.

2.1.2. Country-level impacts

These were estimated by pooling all the available data points for each country and calculating their simple average. Although effect size statistics were not calculated by fitting a meta-analytical model, our results were similar to a recent meta-analysis for a one degree increase in temperature-similar to 2020s climate scenario (Challinor et al., 2014).

2.1.3. Projected climate change impacts on yield

2.1.3.1. With adaptation. Most of the database dealt with impact assessments of climate change with adaptation. This included effects of changing planting dates, varieties, and moderate alterations in fertilizer and irrigation management on crop yields (generally referred to as autonomous adaptation in the literature; details are shown in the Supplementary Information). Recent studies have, however, rightly suggested that such options could be yield enhancing in the current climate but not necessarily ‘true’ adaptation in reducing the impact of future climate change (Lobell, 2014). However, the size of this effect is seldom quantified. Since quantification of adaptation benefits is not our objective here, we continue to refer our country averages as “impacts with adaptation”, in line with the common application of this term in the literature.

2.1.3.2. Without adaptation. Only a few studies presented climate change impacts on yields without adaptation. These were averaged and henceforth referred to as “impacts without adaptation”. Because the sample size is small, we include these data for reference only, and no direct comparison of impacts with and without adaptation is made here.

2.2. Database of observed changes in yield

All historical observed yields at country-level were obtained from the statistical databases of FAO (http://faostat3.fao.org). Baseline observed yields for the period 1960–1990, analogous to the modelled baseline of the same period, were calculated. To compare the changes in observed yields, we used two approaches: observed changes up until 2016, and forecasted changes to the 2020s.

2.2.1. Observed yield change-2016

To minimize the bias of specific years, we used the average of seven years’ data (2010–2016) to characterize observed yields till 2016 for each country. The percent change between this and the observed baseline is the observed yield change-2016.

2.2.2. Forecasted yield change-2020s

Because modelled impacts in our study relate to the 2010–2039 period, we wanted to compare them with likely yields for the same (future) time period. To do this, we forecasted yields for the same
period for each country using observed yield data of the last twenty years. We used an Autoregressive Integrated Moving Average (ARIMA) model, a frequently-used method to estimate future crop yields (Box et al., 1970). Derived models for each country and crop were checked individually for normality and goodness of fit. The forecasted yields were then averaged for the period 2010–2039 and percentage changes were computed from the observed baseline (1960–1990). Unless there are major yield collapses or substantial innovations in technology in the near future, these forecasted yield differences are likely to be reasonably realistic.

3. Results and discussion

3.1. Analysis at country-level

Fig. 1 shows the comparison between the projected climate change impacts on crop yields and observed (2016) and forecasted (2020s) change in yields of maize, rice, and wheat globally (points represent the centroid of each country). For maize, the average loss after adaptation across all countries was 6% (average projected loss without adaptation was 9%, for reference). Some countries in temperate regions (Fig. 2) (Chile in South America and the Korean peninsula in Eastern Asia) showed positive impacts of climate change, because of increases in suitable cropping period due to warming, fertilization effects, and other factors, but such growth may stagnate by 2050s (Huang et al., 2017; Iizumi et al., 2017). Adaptation options also reduced differences across countries in net impacts (see Fig. 2).

Observed maize yield changes-2016 derived from national crop statistics, however, showed a completely different picture: an average of 106% growth in 2016 over the same baseline period. Forecasted maize crop yields for the 2020s are estimated to be 118% above the baseline. In the majority of the countries, particularly large maize producing countries such as China, India, Mexico, Russia, Poland, and Indonesia, substantial observed maize yield changes coupled with negative projected climate change impacts were found. Low-latitude and sub-tropical countries, which showed the largest projected decrease in crop yields due to climate change, indeed had the largest increase in observed and forecasted yields. In a few countries of sub-Saharan Africa, North Africa, and the Middle East, stagnation or even a decrease in productivity was noticed in observed maize yields (as also shown previously; Ray et al., 2012) (Fig. 2) because of stalled crop yield growth. Chad, Botswana, and Yemen were the only countries where both observed and projected maize yield changes were negative. Climate change impacts will pose a major threat to maize production in such countries even in the short term.

For rice, differences between changes in observed yields and projected changes in yields due to climate change were smaller as compared with maize but showed similar patterns (Fig. 1). Average yield loss was 3% with adaptation (6% without adaptation for reference). The average forecasted yield change in the same period was, however, 66%, with 56% increase already observed by 2016 (Fig. 2). These countries were scattered all over the world in tropic and sub-tropic regions, particularly in Latin America (Colombia, Venezuela, and Brazil), South Asia (India, Nepal, and Bangladesh) and South-east Asia (Indonesia, Philippines, and Malaysia). Most countries showed a substantial reduction in climate change impacts once adaptation was considered, with some temperate countries even showing positive climate impacts (China and the Korean peninsula, and in South America and Australia) (Fig. 2). Countries showing negative observed and projected yield changes were located in Sub-Saharan Africa (Cameroon, Mozambique) and central Asia (Kazakhstan).

Similar patterns were observed for wheat, with large differences in observed yield changes and projected changes in yield due to climate change over the same time period, although the observed yield growth was more equitable (between tropics and temperate) than maize and rice. Average projected impact of climate change on yields for the 2020s was -5.6%, with some positive impacts in many temperate countries (Fig. 2). Once adaptation was considered, the impact variability across countries irrespective of their latitude declined and net residual yield impacts were small (Figs. 1–2). The average forecasted yield change was 75% in the same period, with 2016 observed yields already showing a 66% increase. Like maize and rice, a few countries in sub-Saharan Africa and Central Asia showed observed productivity decline, along with substantial projected impacts of climate change. These countries (Nigeria, Tanzania, and Kazakhstan) showed similar patterns of negative growth in both observed and projected yields changes. Low-latitude countries (India, Mexico, and Brazil) and some temperate countries (Russia and northern European countries) showed the largest yield losses according to the climate change impact studies, but they exhibited the largest observed and forecasted growth in wheat.
3.2. Analysis by regional and economic groups

Results from a similar analysis by country income groups and region (area-weighted averages of maize, rice and wheat yield) showed that the maximum projected impact of climate change was in low-income, lower middle-income and tropical regions (Fig. 3). Median yield changes were close to zero in all crops across all income groups once adaptation options were considered. The results also highlighted the largest observed and forecasted yield increase in South Asia (75% and 82%, respectively) and the Middle East and North Africa (~90%), where assessments projected relatively larger negative impacts of climate change (-10% and -5% yield impacts, respectively) in the same

Fig. 2. A comparison of global variation of projected impacts of climate change for the 2020s after adaptation vis-à-vis observed change in yields-2016 of rice, wheat, and maize relative to a baseline of 1960–90. Data shown for cereals are area-weighted yields of rice, wheat, and maize. Countries with very limited crop area (< 10,000 ha) are not shown.
period (Fig. 3). North America exhibited smaller impacts (approximately -3%) and large growth (62%) in crop yields whereas Europe and Central Asia exhibited moderate levels of impact of climate change (-7%) but high yield growth (~55%).

The above results show that grain yields have substantially increased over the last thirty years in most parts of the world. By comparison, review of climate change impacts for the same time period project low to moderate declines in the majority of the major food producing regions in the same time period. This discrepancy can be explained by inadequate consideration of technological growth in impact assessments, associated regional differences, and uncertainties in methodologies.

Globally cereal crops yields have an annual growth rate of almost 2% across the world (FAO, 2017a). These yield growth rates are differential, with low and mid-latitude, developing countries (particularly Asia and Latin America) having comparatively higher productivity growth rates (Grassini et al., 2013; Fuglie and Wang, 2012; Fischer et al., 2009; Evenson, 2003). The major reasons for such high-observed growth rates are existence of large yield gaps in these countries (van Oort et al., 2017) and technological changes like higher input use, better input efficiencies (Coomes et al., 2019) and the use of modern varieties (as a result of crop breeding). The annual growth rate of nitrogen fertilizers is almost 1% globally and up to 3.5% in developing countries (FAO, 2017b). Similarly, the contribution of modern varieties to potential yield (without nitrogen and water stress) (Rosenzweig and Iglesias, 1994) and the use of modern cultivars significantly increase the realism of country-level impact assessments (Rezaei et al., 2018). The inclusion of likely technological change thus significantly increases the realism of country-level impact assessments of climate change.

However, there are a few studies in which technology growth and socio-economic conditions are considered. These studies indeed show a large positive growth in yield in low-latitude countries, at least in the short term, despite climate change (Huang et al., 2017; Iizumi et al., 2017; Liu et al., 2013; Nelson et al., 2010). To illustrate, we reanalyzed data from a global study by Nelson et al. (2010), which included the effects of likely future technology and socio-economic scenarios in projecting crop yields. The results show that in general, observed yields, as well as projected climate impacts for maize, rice, and wheat, are in a similar range (Fig. 4). This is particularly true for low-latitude tropical countries, which show a large growth in yields related to technology use. The global mean of projected impacts from the study was found to be 87.6% for maize, 77% in rice and 66% in wheat; compared with observed change (from FAO statistics) of 106% in maize, 56% in rice and 66% in wheat. Another recent study has shown that the choice of cultivars significantly affect the impact results and assuming a single/fixed management input may over-estimate crop yield sensitivities (Rezaei et al., 2018). The inclusion of likely technological change thus significantly increases the realism of country-level impact assessments of climate change.

![Comparison of box-plots of projected changes in cereal yields due to climate change for the 2020s with the observed yield change for 2016 and forecasted yield change for 2020s for regional grouping on world Bank Classification.](https://example.com/fig3.png)
Uncertainty also plays an important part in any assessment of future impacts of climate change (Beck and Krueger, 2016). Most simulation and statistical models of agricultural systems generally have an error of ~10% (Liu et al., 2016). Added to this are uncertainties in climate and emission scenarios, crop models (Asseng et al., 2013) and input data (Cheng et al., 2017) (Folberth et al., 2016). This highlights the importance of careful uncertainty analysis in interpreting the results of any impact assessment where impacts are small. In recent years ensemble scenarios, dynamic modelling and meta-analyses have helped improve the global assessment of impacts, although some modelling uncertainty still remains (Asseng et al., 2013). We are aware that in our review there could be uncertainties in projected impacts of climate change arising from the pooling of multiple heterogeneous studies having different model parametrizations. Additionally, there are also uncertainties in our forecasted yields due to constraints in ARIMA methodology such as structural breaks in the time-series of data. Nevertheless, these uncertainties are, unlikely to affect the large gaps reported above between projected impacts and observed yield changes. Even when we reduce the modelling uncertainties by using a single harmonized dataset that gap and its magnitude persist (refer to supplementary information).

4. Conclusion

Our results show the importance of understanding and making explicit the assumptions made about technology and technological change in impact assessments of climate change. If the widespread growth in technological change, as observed in parts of Latin America and Asia over the last few decades, is not considered (as is the case with most of the impact assessments considered here), the analysis may give the impression that the climate signal in the short term is large. There is no doubt that climate change in isolation will increase food insecurity in many regions of the world, but technology growth, policy support, and strengthening the enabling environment will have a significant role in combating these effects and helping to achieve food security for all. A major conclusion of our study is that there are different country "hot-spots" that may need substantial priority action (Fig. 2). Most of the impact assessments carried out to date have highlighted regions such as South Asia and Latin America as being particularly vulnerable to the effects of climate change on agriculture. Results here suggest that, in view of observed yield trends, there are several countries in Central Asia, sub-Saharan Africa, and the Middle East and North Africa where technological growth is stagnating or collapsing, and climate change has indeed affected food production even over the short term. Accordingly, a focus on impact projections based on observed yield growth rates (dependent on both technology and climate, among other things) rather than just crop yields may be able to provide more realistic insights for decision-makers for prioritization of investments.

Whether the recent growth of observed cereal yields is likely to continue in the longer term is a question that warrants more investigation (Mauser et al., 2015; Ray et al., 2013). Food demand in many countries is rapidly increasing (Valin et al., 2014). Technological growth in some parts of the world could undoubtedly help other countries to increase their harvests but this consideration needs to be tempered by the magnitude of the sustainable increase in agricultural production needed and the associated environmental costs, if food and nutritional security is to be ensured for all (Chen et al., 2014; West et al., 2014). The current pattern of growth in many countries is likely to slow as yields approach their maximum attainable levels (Grassini et al., 2013). Additionally, many countries having considerable potential for production growth, are constrained by access to technology, water resources and capital (van Ittersum et al., 2016); and anticipated decline in suitable areas for cultivation due to warming (Huang et al., 2016). On the other hand, new agricultural technologies such as efficient irrigation systems and better adapted crop varieties (Bevan et al., 2017), together with increased investments in agricultural infrastructure, can accelerate productivity growth in many lower-income countries (Rippke et al., 2016). The modelling of relatively complex future scenarios of agricultural production for different regions is undoubtedly challenging, but omitting considerations of technology and technological change from impact assessments runs the risk of seriously diminishing the realism and utility of the results.

Global assessments of the impact of climate change have been of critical importance in the past as a “call to arms” for action on both adaptation and mitigation in agriculture. It is difficult to trace a direct impact pathway stretching from the IPCC’s First Assessment Report published in 1990 to decisions taken at COP 21 in Paris in late 2015 concerning agriculture as a key sector in which effective action on adaptation and mitigation needs to be taken. Nevertheless, we would contend that crop yield impact assessments have played a vital role in
spurring action at the global level, as well as in promoting considerable investment by organizations such as the World Bank, IFAD and FAO in climate-smart agriculture (Donner et al., 2011). For the future, we believe their usefulness as a tool for intervention targeting and prioritization will only grow. At national and regional scales, a greater focus is needed on climatic variability and on the potential impacts of extreme events such as drought and flood, which may seriously disrupt food systems for hundreds of millions of people. At the same time, the spatial and temporal resolutions of the models and data used in impact studies are slowly improving, and it will increasingly be possible to evaluate impacts at local scales to help define at high levels of detail who is vulnerable, why, and to what. As we have demonstrated here, linking such assessments to an improved understanding of likely future technological change and its enablers has a crucial role to play in the search for adaptation actions that are both feasible and profitable.

5. Author information

The data generated and analyzed for this research are available along with the codes used from the corresponding author upon request. The authors declare no competing interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to the corresponding author.

6. Conflicts of interest

The authors declare no competing interests.

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