# Economic impacts of climate-induced crop yield changes: Evidence from agri-food industries in six countries

Daoping Wang[1,+], Katie Jenkins[2,+], Nicole Forstenhäusler[2], Tianyang Lei[3], Jeff Price[2], Rachel Warren[2], Rhosanna Jenkins[2], Dabo Guan[3,*]

1. School of Urban and Regional Science, Shanghai University of Finance and Economics, Shanghai 200433, China
2. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK
3. Department of Earth System Science, Tsinghua University, Beijing 100084, China

+ both authors contributed equally to the work

* Corresponding Author: Dabo Guan. guandabo@tsinghua.edu.cn. Department of Earth System Science, Tsinghua University, Beijing 100084, China

## Abstract

The potential impact of climate change on agriculture has been one of the most discussed topics in the literature on climate change. Although the possible impacts of climate change on crop yields have been widely studied, there remains little quantitative understanding of the heterogeneous socioeconomic responses to climate-induced crop yield changes in different economies, particularly at higher levels of warming. This study assesses the socio-economic impacts of eight scenarios of warming, from 1.5° to 4°C, on rice and wheat yields in China, India, Brazil, Egypt, Ghana and Ethiopia. The role of both natural and social factors in crop production are considered by coupling a statistical crop model (ClimaCrop) and a global economic model (GTAP). Changes in economic outputs, consumer and producer prices, and national economic welfare are presented. The study shows marginal benefits of crop yield changes on GDP and welfare in China up to 3.5°C and 3.0°C respectively. This is due to projected increases in rice yields which lower domestic consumer rice prices. Although at higher warming levels these trends begin to reverse. The other countries are negatively impacted due to declining crop yields, with increasing consumer prices of domestic and imported rice and wheat. GDP and welfare declines, with more severe reductions associated with the higher warming levels, particularly in India and Ethiopia. The method is beneficial as the economic outputs reflect a more in-depth picture of the response of global markets and ultimately regional consequences of agricultural impacts that will be of importance to decision makers.

**Keywords:** Climate change; Crop yield; Economic effects; CGE modelling

## 1 Introduction

Climate change is already reducing crop yields in some parts of the world (IPCC 2014), whilst climate-change related extreme weather events, such as heat-waves, droughts and floods, have highlighted the major challenges such events pose to agricultural production. Later in the 21st century, the production of major cereal crops, such as wheat and rice is projected to decline in tropical and temperate regions due to the combination of changes in temperature, precipitation, extreme weather events, and increasing $CO_2$ concentrations (Hoegh-Guldberg et al. 2018). These impacts will be further exacerbated by rapidly rising crop demand and reduced food quality, with developing countries likely to bear the brunt of impacts (IPCC 2014).

At a global level, overall impacts are projected to be negative, but this masks variation in the magnitude and direction of change in crop yields at national or regional levels. Impacts can also vary depending on the type of crop/s modelled (see section 2). Studies can also be strongly influenced by the use of different regional climate change projections, the assumed strength of $CO_2$ fertilization effects, and uncertainties related to the choice of crop model (Rosenzweig et al. 2013; Hoegh-Guldberg et al. 2018). Progress in understanding the biophysical impacts of climate change on crops has been significant. However, whilst such studies provide important insights into understanding future changes in the growth and quality of major crops - the productive component of food security - how such agricultural impacts would affect the wider economy and socioeconomic structure of affected countries has, to date, received much less attention (Hertel et al. 2010; Bandara and Cai 2014).

Fujimori et al. (2018) review published estimates that report economic losses to agriculture in the range of 0–1% of global GDP but suggest that other metrics such as price changes may be more informative. A review of literature for the IPCC AR5 WG2 (Porter et al. 2014) concluded that it is very likely that changes in temperature and precipitation, without considering the effects of $CO_2$, will lead to increased global food prices ranging from 3 to 84% by 2050. This wide range reflects many differences in the studies reviewed, including: the level of regional aggregation; inclusion of different crop types and the aggregation of these; the use of different economic models and methods; and the assumed crop yield change, be it from different estimates from the literature or from different coupled crop yield models.

Global aggregate economic impacts also overlook substantial differences across countries and regions. Conversely, where individual countries or larger aggregate country regions are studied, they tend to be in isolation of others rather than being connected. This makes comparison of different studies difficult due to differing underlying data, risk assessment methodologies, and the scale of outputs (and hence the wide range in food prices above). This is problematic when considering the economic impacts of climate change on agriculture as direct crop impacts provide only a partial picture of the consequences for human livelihoods, as countries and production systems are interconnected through trade (Hertel et al. 2010). Trade has the potential to alleviate climate-induced scarcity by bridging the differences between demand and supply conditions globally. Conversely, it can also increase climate-induced vulnerability in regions which specialise in the production of certain products in which they have a comparative advantage, while relying on imports to meet demands for other commodities (Ouraich et al. 2019).

As well as the spatial scale of the study, economic estimates can also differ depending on the climate change projections used (Nelson et al. 2014). Since the publication of the IPCC Special Report on 1.5°C of warming (IPCC 2018) there has been an increased focus on the projections of climate change impacts under such ambitious targets, resulting in a relative dearth of projections relating to warming at higher levels such as 3°C or above. This is an important knowledge gap to fill, particularly for informing policy makers as the Nationally Determined Contributions (NDCs) under the UNFCCC Paris Agreement are estimated to result in global mean temperature rise in the range of 2.7°C to 3.5°C by 2100 (Gütschow et al. 2018).

Consequently, to examine the full range of climate change impacts on agriculture, a full range of climate scenarios need to be considered alongside coupled crop and economic models. This type of approach provides a flexible scenario-based framework which can provide a more complete understanding of the impacts of climate change on agriculture and the wider economy. This study provides fresh insights by focusing on a regional comparison of impacts, using a coherent set of climate simulations and crop yield changes estimated via a statistical crop model (ClimaCrop), coupled with a global economic general equilibrium model (Global Trade Analysis Project model, GTAP). Global outputs in terms of yield shocks are incorporated into the GTAP model via changes in land-use efficiency for the land used for agricultural production in each region. The framework is beneficial as it allows distinctions to be made between prices of domestically and internationally produced commodities, capturing the role of international trade when assessing the dynamics of economic impacts at the country level. This is important as trade can mitigate impacts of decreasing agricultural production at a country level, for example countries may increase imports to meet shortfalls in production, or net exporters may conserve domestic production by reducing net exports. In particular, this paper focuses on heterogeneities of the socio-economic impacts of climate-induced crop yield change on different regional economies, including on commodity prices and welfare. A second advantage of this study is that it evaluates these impacts under a wide range of global climate change scenarios. Warming levels range from 1.5° to 4°C, critical for national economies to choose appropriate strategies for climate change adaptation.

This analysis focuses on the key crops of wheat and rice, two of the world's most widely cultivated crops, which alongside maize provide the current foundation for world food security (FAO 2016a, 2017). To demonstrate the capability of the method to multiple countries, and ability to facilitate a regional comparison China, India, Brazil, Egypt, Ghana and Ethiopia are included, although the method could be applied to other countries in a similar manner. These countries reflect a range of different climate impacts, geographies, levels of development, and a combination of major wheat and rice producers and major wheat and rice importers. The following section provides a review of current literature. Section 3 outlines the modelling framework, inputs and economic model. Section 4 presents the model results with the discussion and conclusions in section 5.

## 2 Literature Review

*2.1 Projected risks of climate change upon crop yields in our study countries*

The potential impacts of climate change on crop yields have been widely studied at global, national, and regional levels. Key methods include the use of statistical models and process-based dynamic crop models. In general, global studies show that Africa is particularly vulnerable to climate change, with agriculture being one of the more vulnerable sectors. Overall, negative impacts on yields are expected, but the extent of the loss is projected to vary between regions and crops (Porter et al. 2014). For example, West Africa is projected to see substantial reductions in wheat yield, of around 13% with 1.5°C and 19% with 2°C warming (Schleussner et al. 2016). Research conducted by AgMIP (Agricultural Model Intercomparison and Improvement Project) projected reductions in maize and wheat yields across much of Africa but increases in rice and soy yields for southern and eastern areas (e.g. Rosenzweig et al. 2013; Ostberg et al. 2018).

There has been a significant amount of research into changes in crop yield at the national scale for our study countries (see Table S1 for a full synthesis of studies). For India, most published studies used process-based models and projected lower overall crop yields in the future (e.g. Koehler et al. 2013). Challinor et al. (2006) modelled changes to groundnut in India and projected increases in yield in some northern and western areas but reductions in other areas under the SRES A2 scenario by the 2080s. For Brazil, a range of models have been used to project changes to crop yield (e.g. Costa et al. 2009; Margulis and Dubeux 2011). Most of these studies project a reduction in future yield, of around 30% for maize and beans. By contrast, studies focused on China largely project increases in yields in the future (e.g. Chen et al. 2013; Geng et al. 2019). However, some research projects lower crop yields in China as a result of climate change. Erda et al. (2005) suggest climate change will reduce the rice, maize and wheat yields in China by up to 37% in the next 20–80 years without $CO_2$ fertilisation. Disagreement over the sign in yield change comes, in part, from the model parameterisations. Likewise, Xiao et al. (2018) used the APSIM model with 28 GCMs, forced with the RCP4.5 and RCP8.5 scenarios to project changes in wheat yields in China by the 2080s. They reported an increase in yield when $CO_2$ fertilisation was included and reduction in yield when not.

National scale studies for India, China and Brazil generally agree with the results of global studies (Parry et al. 2004; Lobell et al. 2008). However, few national level studies exist for Egypt, Ghana and Ethiopia. Sagoe (2006) analysed changes to cassava and cocoyam in Ghana using a process-based model and projected a reduction in the yield of both crops. Araya et al. (2015) investigated changes to maize yields in Ethiopia under RCP 4.5 and RCP 8.5, projecting reductions in yield of up to 20% by the 2050s. Abera et al. (2018) projected reductions in maize yields at some sites in central Ethiopia (Bako and Melkassa) but increases at another site (Hawassa) under RCP 8.5 conditions by the end of the century. Projected increases in yields are linked to higher local rainfall whereas yield reductions are linked to greater rainfall variability and higher temperatures. Regional studies for Africa also project a general reduction in crop yields in Ghana (Jones and Thornton 2003; Parkes et al. 2018), Ethiopia (Jones and Thornton 2003; Liu et al. 2008) and Egypt (Jones and Thornton 2003; Liu et al. 2008).

*2.2. Economic implications of changing crop yields*

A few global studies have specifically addressed the changes in some of the six countries of interest to this study. Ren et al. (2018) examined the economic impact of climate change on seven crops globally using the iPETS model. For China, a 5-10% reduction in crop price was projected with $CO_2$ fertilisation and 10-20% increase in prices without $CO_2$ fertilisation. For India, crop price was projected to decline by 18% to 25% when the effects of $CO_2$ fertilisation were considered. Increasing by 20-50% when $CO_2$ effects were not included in the models. Similarly, Bandara and Cai (2014) projected increases in food prices of around 5% (wheat) and 9% (rice) in India by 2030. Calzadilla et al. (2013) used the GTAP-W model with the SRES B2 scenario and found a -0.01% (-667 million USD) change in GDP in China by 2050, which was associated with a 1.14% reduction in agricultural productivity.

Relatively few country-level studies of the economic impacts of climate change exist (see Table S2 for a full synthesis of studies). Mideksa (2010) investigated the economic impacts in Ethiopia using a CGE model and projected changes to agriculture would reduce GDP by about 10%. Similarly, Deressa and Hassan (2009) analysed crop net revenue in Ethiopia and projected a reduction per hectare by the end of the century. Arndt et al. (2015) found a similar situation is likely for Ghana, projecting declines in agricultural GDP and reductions in revenues from some major crops. Yates and Strzepek (1998) used two statically coupled economic models to project the economic impacts of climate change on Egypt by 2060 using a pessimistic and optimistic scenario, reporting changes in agricultural GDP of 96% (optimistic scenario) and 135% (pessimistic scenario). Some of these studies factor in trade linkages, including Arndt et al. (2015) which includes trade function elasticities in the model, and Mideksa (2010) who consider other countries as an agent which can demand exports and supply imported goods.

## 3 Methods

*3.1 Climate Scenarios*

This study projects the impacts of climate change on crop yields across a range of specific global warming levels from 1.5° to 4°C (Table 1). The scenarios represent a set of mitigation scenarios meeting various climate goals based on Shared Socioeconomic Pathways 2 (SSP2) (Kriegler et al. 2014). The SSPs narratives are characterised by assumptions on future economic growth, population change, and urbanization. SSP2 depicts the 'Middle of the Road' whereby social, economic, and technological trends do not shift markedly from historical patterns (Riahi et al. 2017).

The crop model was driven by monthly climate change variables on a spatial grid of resolution 0.5 x 0.5 degrees, obtained by pattern-scaling Global Circulation Model (GCM) projections. To sample uncertainty in regional climate change projections, patterns of change simulated by twenty-three CMIP5 GCMs were used. The pattern-scaling technique assumes there is an approximately linear relationship between the change in a climate variable in a grid cell and the change in the global-mean surface temperature, and that this relationship is invariant under the range of climate changes being considered here (Osborn et al. 2016). This is a commonly used method with Osborn et al. (2018) showing it emulates the underlying GCM projections well with errors that are small relative to the climate change signal. Tebaldi and Arblaster (2014) show that errors are small relative to the spread in results between different GCMs.

To obtain monthly time-series we combined the observational mean climate, the pattern-scaled change in mean climate, and observed monthly anomalies superimposed to provide realistic climate variability. Observed mean and anomalies were taken from the CRU TS3.00 dataset, for the years 1961-1990, on a 0.5° latitude by 0.5° longitude grid (Harris et al. 2014). For future precipitation, the observed monthly anomalies were first transformed so that their probability distribution is consistent with the changes in monthly precipitation variability projected by each GCM (Osborn et al. 2016). Monthly evapotranspiration (ET) was calculated using the Penman–Monteith formula from ClimGen data for minimum, maximum and mean temperature, vapour pressure, cloud cover, and the CRU CL 2.0 wind speed climatology.

[Table 1 here]

*3.2 Crop yield data and method*

Impacts of climate change on crop yields of wheat and rice are modelled using the statistical crop yield model, ClimaCrop, underpinned by 23 GCMs, for each of the eight climate scenarios (Warren et al. 2017). National annual yields were obtained from the FAO (2016b) for the years 1961-2012 and matched with CRU TS 3.22 climate data (Harris et al. 2014) for the same period. The annual average temperature and precipitation in a country were calculated as the mean across all 0.5 x 0.5 degree grid cells and months in which the respective crop is grown under rain fed conditions as given in the MIRCA2000 data set, a global data set of monthly irrigated and rainfed crop areas around the year 2000 with a spatial resolution of 5 arcmin (about 9.2 km at the equator) (Portmann et al. 2010). It was assumed that optimal weather conditions exist for each crop resulting in maximum obtainable yield and that any deviation from this optimum will result in reduced crop yield. Following Schlenker and Lobell (2010), the natural logarithm of crop yield was regressed with quadratic specifications in temperature and precipitation (see SM table S3) and a quadratic time trend was used to account for technological process over the time period (Equation 1):

$$log(Y_{c,t}) = (\alpha + \alpha_c) + \beta_1 T_{c,t} + \beta_2 T_{c,t}^2 + \beta_3 P_{c,t} + \beta_4 P^2 c,t + (\beta_5 + u_{5,c})t + (\beta_6 + u_{6,c})t^2 + \epsilon_{c,t}$$

Eq. 1

For country $c$ and time $t$ where $\alpha$ is a global intercept, $\beta$ represents estimated coefficients, *T* and *P* are the average temperature and precipitation during growing season, and $\epsilon$ is an error term. In all cases, the country specific intercepts $\alpha_c$, error term $\epsilon_{c,t}$ and the coefficients were assumed to be normally distributed. To create spatially explicit projections of future crop yield changes for each country the equation is then applied at the grid cell level. To quantify the impacts of climate change on crop yields, we limited the crop growing area to locations given in Monfreda et al. (2008), keeping both the area and the crops grown constant over time. In each grid cell, we calculated predicted yield for all warming levels as

$$Yield_{c,t} = e^{log\left(Y_{c,t}\right)+\frac{\sigma^2}{2}}$$

Eq. 2

where we included the variance of the error term, $\sigma^2$, of each model to account for Jensen's inequality (Schlenker and Lobell 2010). All yields were then transformed to country totals by calculating an area-weighted sum and a 30-year average was determined to represent production under long-term conditions. To enable coupling with the economic model these country totals were provided for the 140 countries and aggregated country regions of the GTAP database version 9 (see section 3.3 below). Finally, predicted changes in crop production (and thus crop yield) were estimated using equation 3 where $p_0$ represents production under baseline conditions and $p_1$ represents production for any other warming level.

$$\Delta p = \frac{p_1}{p_0}$$

Eq. 3

### *3.3. Economic Modelling*

GTAP is a well-known multi-region and multi-sector global general equilibrium economic model (Hertel and Tsigas 1997; Corong et al. 2017). It tracks bilateral trade flows between countries and models the consumption and production of commodities of national or aggregated regional economies. Producers are assumed to maximise profits and consumers are assumed to maximise utility. Product and factor market clearing requires that supply equals demand in each market (Xie et al. 2018). The standard GTAP model has been widely used for policy analysis and due to its generic, modularised framework has also been modified and extended for use in specific research areas, including climate change and food security policy (Corong et al. 2017). It is beneficial here given countries may be directly affected by climate change impacting on domestic crop yields, as well as indirectly through trade and changing commodity prices. In assessing the potential socio-economic impacts of crop yield change on the six countries it is important to capture both direct and indirect components to provide a robust estimate. As such, the study uses the standard GTAP version 7 and associated GTAP database 9, which includes 140 regions and 57 sectors, aggregated into eleven sector groups for the analysis (Table 2). The model is run for all 140 regions so that both domestic impacts on the six countries and global implications are captured simultaneously.

[Table 2 here]

Yield shocks for rice and wheat are incorporated into the GTAP model via changes in land-use efficiency for the land used by rice and wheat production in each GTAP region (parameter *afe* in equation 4). This is the conventional method for translating yield perturbations into economic models (e.g., Iglesias et al. 2012; Xie et al. 2018). Changes in crop productivity are interpreted in the model as affecting both price and demand for land, as expressed as a percentage in equations (4) and (5). This causes a price increase in agricultural goods causing higher costs in the sector and affecting input markets. The reallocation of resources due to these direct effects will indirectly affect other sectors of the economy and can affect household decisions on consumption (Iglesias et al. 2012). The composite price of primary factors (i.e. land, labour, enterprise and capital goods) in each sector and region is calculated following Corong et al. (2017):

$$pva_{j,r} = \sum_{k=1}^{n} (SVA_{k,j,r} \times (pfe_{k,j,r} - afe_{k,j,r}))$$

Eq. 4

where *j* is the production commodity (industry), *r* is the region, *k* is the endowment commodity, *pva* is the firm's price of value added, *pfe* is the firm's price for endowment commodity *k*, *SVA* is the share of endowment commodity *k* in total value added and *afe* is the primary factor augmenting technology change, specific to each sector of each region. The input of the endowment commodities to each region/industry is calculated by:

$$qfe_{k,j,r} = -afe_{k,j,r} + qva_{j,r} - ESUBVA_j(pfe_{k,j,r} - afe_{k,j,r} - pva_{j,r})$$

Eq. 5

where *qfe* is the demand, *qva* is the value added and *ESUBVA* is the elasticity of substitution between capital, labour and land in industry *j*. To reflect the difficulty of substitution between land and other key inputs such as labour and capital in the context of global warming the elasticity of substitution between endowments (*ESUBVA*) of crop production sectors is changed to 10% of the original value. This is in line with guidance from previous literature (e.g., Rose and Liao 2005).

In the model, capital and labour can move freely between production activities, while for land and natural resources movement is largely restricted (equations 6 and 7). Following Corong et al. (2017) the allocation of the sluggish endowments across sectors is:

$$qoes_{k,j,r} = qo_{k,r} + ETRAE_k(pm_{k,r} - pmes_{k,j,r})$$

Eq. 6

whereby *qoes* is the supply of sluggish endowment, *qo* is the industry output of endowment, *ETRAE* is the elasticity of transformation for sluggish primary factor endowments, *pm* is the market price of endowment and *pmes* is the market price of sluggish endowment. By default, different crops can adjust their demand for land within some margin (transformation elasticity *ETRAE* = –1). However, in the context of global warming the growth of other competing crops, e.g., grains and pastures, can also be negatively affected leading to an increase in land demand in these sectors. Given this study does not consider changes in yields of other cereals and pastures, nor alternative demands for land (e.g. for BECCS), the transformation elasticity is reduced to 10% of the default value, to increase the difficulty of land transfer between different sectors.

The composite price for sluggish endowments is shown in equation 7, where *REVSHR* is the share of endowment used by different industries.

$$pm_{k,r} = \sum_{j=1}^{n} (REVSHR_{k,j,r} - pmes_{k,j,r})$$

Eq. 7

Allocation of mobile endowments across sectors is shown in equation 8, where *SHREM* is the share of mobile endowments at market prices.

$$qo_{k,r} = \sum_{j=1}^{n} (SHREM_{k,j,r} \times qfe_{k,j,r})$$

Eq. 8

The composite price for mobile endowments is:

$$pm_{k,r} = VFM_{k,j,r}/qfe_{k,j,r}$$

Eq. 9

where *VFM* is the producer expenditure on endowment valued at market prices. This study has further included changes in crop foreign trade to production for each country, thereby simulating the changes in crop supply. For other modules, we use the default GTAP model settings (Corong et al. 2017).

As GTAP is a comparative static model each simulation represents the variance between different possible states of the global economy with respect to two points in time, the base period vs. the future projection period. It is assumed that climate change only affects land productivity, ignoring other potential impacts of climate change such as on human health, which can affect labour productivity, and capital productivity. Productivity changes in agriculture in other sectors are not considered. Global population and socio-economic conditions are held constant in the model, focusing results on the influences of climate change (e.g., Xie et al. 2018).

## 4. Results

### *4.1 Crop yield change*

The impact of the climate scenarios on rice and wheat yields were modelled for each of the 140 GTAP regions. There is large regional variation in the direction and magnitude of changes, however, at a global level mean rice yields are projected to decrease marginally under the future scenarios, reaching ~4% under scenario 6. Implications for wheat are more significant, with average global yield reductions of ~2.5 to 12.5% for scenarios 1 to 6 (full results are displayed in Supplementary Material (SM) figures S1 and S2).

At a country level, except for China, rice yields generally decrease under the future scenarios, with more severe reductions associated with higher warming levels (figure 1). Changes in rice yields are initially slightly positive for Ethiopia (0.5%) and Egypt (0.1%) with little change between scenarios 1 to 4. However, at higher warming levels, crop yield changes become negative, reducing by 2.75% and 1.5% under scenario 6 for Egypt and Ethiopia respectively. India and Ghana are projected to suffer more severe reductions, with an average reduction of ~14% under scenario 6 in Ghana. In contrast, an increase in rice yield is projected for China, ranging from 2.2% to 5.25% for scenario 1 and 6 respectively, although incremental benefits become more marginal at the higher levels of warming.

[Figure 1 here]

Figure 2 highlights that for all countries wheat yields decrease from the baseline under the future scenarios, with more severe reductions associated with the higher warming levels, and particularly for India and Egypt. Average reductions range from 2.5% to 5% across the countries under scenario 1, increasing to 12.5% to 20% under scenario 6.

[Figure 2 here]

The results for wheat and rice reflect projections of declining crop yields due to climate change reported in the literature for India, Brazil, Egypt, Ghana and Ethiopia (section 2). For China the direction and magnitude of change differs for wheat and rice but given the larger scale of rice production would result in an overall yield increase.

*4.2 Production and price changes*

The yield changes for the 140 regions provide input to the GTAP model facilitating an investigation of how global changes in rice and wheat yields will translate into economic impacts. The most immediate impacts are on the value added and production of the rice and wheat sectors. Figure 3 highlights that the modelled changes in regional rice yields corresponds to a decrease in global production ranging from 1.5 to 8.5Mt, with a decline in sectoral value added of 0.25% to 1.4%. For wheat, the change in modelled yields corresponds to a decrease in global production of 1.25 to 5.5Mt, with a decline in sectoral value added of 0.2% to 0.95%. Impacts are also shown to increase non-linearly under scenarios 1 to 6.

[Figure 3 here]

At the country level production and value added generally reflect the trends seen in crop yields, declining or increasing alike. All countries see an increasing decline in wheat production and value added under scenarios 1 to 6. For rice, China is shown to benefit from increased yields, with an increase in production and value added, although reflecting the trend in figure 1 the additional benefits become more marginal for scenarios 5 and 6, and do not reflect the expected decline in rice nutrient content that occurs concurrently with climate change responses (Myers et al 2017). Production and value added in India, Egypt and Ghana are negatively affected. Brazil also suffers negative impacts, however, these begin to reduce in severity at higher levels of warming, whilst Ethiopia shows a significant increase in production and value added with up to an 18% increase in value added under scenario 6. Ethiopia's rice relies heavily on imports, i.e., domestic production only accounts for about 20% of consumption of rice. When the price of imported rice increases significantly (see Fig. 4), the compensation of input factors in domestic rice production also increases.

These trends occur as productive output is affected by both natural factors (e.g. change in yields) and social factors (e.g. commodity prices). In general, the more land efficiency declines due to reduced crop yields the more crop production will decrease. For example, if rice production declines (both domestically and internationally) consumption of domestically produced rice can increase significantly, alongside a rise in the price of rice produced abroad. Distinguishing between domestically and internationally produced commodities such as rice and wheat for each region in the model is important when estimating price changes. For instance, rice produced in India and China have very different tastes with Indian consumers preferring to buy Indian-produced rice at higher prices than imported Chinese-produced rice at relatively low prices. By capturing this imperfect substitution in the model prices of rice and wheat can vary greatly across different regions.  Consequently, even with inefficient land for production, producers are still profitable when product prices are high, and in this case can rent more land for production. As such international trade plays an important role in determining supply and price changes for countries. Rice or wheat exporting countries may conserve domestic production by reducing net exports, or profit from increasing net exports to meet demands of other countries whose domestic production has declined. Consequently, changes in regional export prices (shown in SM figure S) will have consequences on importing countries.

Figure 4 shows the percentage change in the price of both domestic and imported rice and wheat for the six countries under scenarios 1 and 6. In China the price of domestic rice declines by up to 10% under scenario 6, in line with increased crop yields, whilst import prices increase. The increase in import prices reflects an increase in export prices of China's major import partners for rice (Vietnam, Thailand and Pakistan, see SM figure S4). In the case of Ethiopia, the natural effects on rice yields are small (figure 1), but price effects are large (figure 4) driving the increase in production of rice highlighted in figure 3 above. For India domestic prices of rice and wheat increase significantly from scenario 1 to scenario 6, with domestic prices far exceeding imported prices.

[Fig 4 here]

The consequences of changing rice and wheat yields on both domestic and imported consumer prices can also propagate to other economic sectors, particularly related sectors such as other crops and food manufacturing. Whilst not shown here (see SM tables S4 and S5) the model highlights increasing prices for domestic and imported food manufacturing commodities across the countries, with the largest increases seen in India and Egypt under scenario 6. The exception is China, where domestic prices for food manufacturing commodities decline.

As well as impacts on consumers, producers will also be affected by price changes to primary factors such as land and labour, determined by supply and demand. In countries with declining crop yields the subsequent changes in land efficiency drive additional demand for more land to produce food, which leads to higher land prices. For all countries except China, the price of land rents increase (see SM table S6). In China land rents fall under scenario 1 due to the projected increase in rice yields which offset the impact of declining wheat yields. However, marginal increases are seen under scenario 6. The price change of other primary factors such as labour and capital are less significant, and generally opposite to the land price changes. There are two opposing channels through which price changes can occur here. One, where land efficiency declines more labour or capital can be required to enhance productive output, increasing the demand for these factors. Two, declines in land efficiency can also make such factors surplus, such as labour, which can cause the price to fall.

Figure 5 encapsulates the above information, presenting the impacts at a macroeconomic level in terms of the percentage change in real GDP. GDP is marginally higher in China under scenarios 1 to 5, however begins to transition from scenario 3 onwards (2.5°C) becoming negative under scenario 6 (4.0°C). For the remaining countries changing rice and wheat yields have a negative impact, with losses increasing with warming levels. The most serious consequences are reported for India, with a decline in GDP of 0.015 and 0.75% for scenarios 1 and 6 respectively.

[Fig 5 here]

*4.3 Welfare change*

In this study, equivalent variation, EV, is used as a proxy for welfare change of regional households. EV compares the cost of pre and post-shock levels of consumer utility, both valued at base year prices (Huff and Hertel 2000). It can be affected by changes in production of rice and wheat and subsequently consumer prices (as in section 4.2). Figure 6 shows that for China benefits to welfare are initially projected to be positive, increasing by up to $400 million US dollars. However, as above a transition begins from scenario 3 onwards with reductions in welfare estimated under scenarios 5 and 6. Despite negative impacts on real GDP welfare changes are also positive for Brazil, increasing between $41 million to $488 million US dollars under the six scenarios. This reflects the focus of the metric on price changes. In Brazil rice and wheat production are less significant compared to other agricultural products it produces (FAO 2019). It is therefore less vulnerable overall to increasing prices of domestic and imported rice and increasing prices of exports of rice and wheat. In parallel, Brazil imports many other manufacturing products where prices are declining (SM Table 4) whilst also exporting large quantities of legumes and food manufacturing products where prices increase under the scenarios.

[Fig 6 here]

India, Egypt, Ghana and Ethiopia are projected to suffer negative impacts on welfare due to effects of climate change on rice and wheat yields. India is particularly affected with losses ranging from $606 million to $2,523 million under the six scenarios. These trends reflect the impacts of changes in land efficiency on factors such as labour and commodity prices which can affect the income of residents and in turn welfare. Secondly, if the country is a rice or wheat importer then higher export prices from major import partners will raise prices for consumers and reduce welfare. Thirdly, if the country is a rice exporter then benefits to welfare can reflect the decline in global supply and rising demand and prices for their exports.

## 5. Discussion and conclusions

The above analysis examines the direct impacts of climate change on global yields of rice and wheat, and economic consequences in terms of changes in production, commodity prices and welfare. The climate scenarios represent both ambitious targets as well as the potential for higher levels of warming, ranging from 1.5 to 4°C. This allows a comparison of economic impacts, highlighting the potential benefits in terms of avoided damages for more stringent climate change goals, and can also indicate potential tipping points as in the case of GDP and welfare in China (figures 5 and 6). Yields of wheat were projected to decrease in China, Brazil, India, Ethiopia, Ghana and Egypt under all scenarios, with more severe reductions associated with the higher warming levels. Reductions in wheat yields are notably larger than for rice, with India and Egypt projected to suffer the largest consequences. Similar trends were seen for rice, with the exception that yields increase in China, with greater benefits associated with the higher warming.

At the macroeconomic level changes to GDP in China, although minimal, are initially positive but begin to transition from scenario 3 onwards becoming negative under scenario 6. For the remaining countries GDP is projected to decline with the largest impacts reported for India. Consumer prices for both domestic and imported rice and wheat were projected to increase under scenarios 1 to 6 for all countries except China. In the case of China there was a decline in the price of domestic rice, in line with increased crop yields and production. Indirect price effects were also reported for related sectors such as food manufacturing. The results also illustrated the potential impact on producers of price changes to primary factors such as land and labour. These combined factors will be important when considering the impacts on welfare of households. The study suggests that the impact of rising temperatures on crop yields could reduce overall welfare levels in some countries, such as India and Ethiopia, even under more stringent climate change goals, whilst benefits were projected for Brazil.

The paper highlights how trade can mitigate impacts of decreasing agricultural production at a country level. Conversely, it may act as less of a buffer for major food importing countries such as Egypt or Ethiopia, who will face the impacts of declines in domestic production alongside increasing global food prices. These types of market effects can be hidden in more aggregated multi-region or global analyses or underrepresented in studies that focus on countries independently (Islam et al. 2016).

The findings of the study are generally in line with the direction of trends reported in the literature (section 2). However, none of these studies include the potential for climate change to reduce the nutrient content of crops (Myers et al 2017) so in terms of food security, effects might be underestimated. Furthermore, for several of the countries analysed here there are relatively few country-level studies on the economic consequences of climate change on agriculture, with this paper contributing to evidence in this area. However, as with other economic impact studies of climate change it is difficult to capture all aspects of the subject within a single, concise framework. Other agricultural risks from climate change include changes in the intensity and frequency of extreme weather events, and altered weather patterns can also increase the vulnerability of crops to disease and pest infestation (Rosenzweig et al. 2001). The focus here is on changes in mean temperature and precipitation in line with other modelling studies, allowing some comparison, and providing a useful output in terms of how the agricultural system may change over the longer-term to 2100. Whilst extremes are not directly modelled, extreme climate conditions are partially considered given that as the extremes over the growing period increase the mean conditions also increase. By creating annual yield projections prior to taking the 30-year average these annual changes in extreme conditions are captured.

The study excludes the possibility of adaptation under future warming scenarios, such as increased farm productivity due to the new use of technology or different or more heat-tolerant cultivars, a potential area of future research. While some studies do aim to gauge the potential effects of adaptations, such as crop cultivars and sowing dates, on crop yields under scenarios of climate change (e.g. Xiong et al 2014), these tend to be more detailed, farm level studies, and there has been much less uptake in how this would translate into economic impacts. Rosenzweig and Tubiello (2007) note that at the national level economic based studies focus on benefits of higher adaptation potential, albeit with less agronomic detail. These studies tend to suggest small overall benefits at the global scale, for climate change up to 2050 of about 3°C. Howden et al (2007) also note that implementation of various adaptation options is likely to have benefits under moderate climate change for some cropping systems. However, there are limits to their effectiveness under more severe climate changes.

The study also relies on outputs from a single crop model, which does not consider $CO_2$ fertilization effects, which can have implications for crop yield estimates and subsequent economic estimates. The literature review (see also Table SM-1) illustrates that there is no current consistency in the incorporation of $CO_2$ fertilisation, although it can affect the magnitude and potentially direction of change in crop yields. Studies that exclude $CO_2$ fertilization effects may overestimate negative impacts of reduced yields. This conservative approach, owing to the wide range of issues surrounding $CO_2$ fertilisation effects, can be interpreted as focusing on direct impacts of climate change only, and justified by the fact that $CO_2$ fertilisation may be countered by other factors such as pest and diseases, or the role of $O_3$ and nitrogen use efficiency excluded from studies (Vanuytrecht and Thorburn, 2017). In contrast, studies that do include $CO_2$ fertilization may have a positive bias as plants grown in experimental settings, on which model parameterisation is based, are not fully representative of farmers fields (Rosenzweig and Parry 1994), adding uncertainty to impact assessments (Vanuytrecht and Thorburn, 2017).

Output is also provided for two crops only and does not consider changes in yields of other cereals and pastures, nor alternative demands for land (e.g., for BECCS). In the case of Brazil if the model were also to consider changes in soybean yield then given projections from other studies (e.g. Margulis and Dubeux 2011) benefits to welfare may weaken or potentially become negative. There is also the issue of scalability in terms of how crop yield data is integrated with the GTAP model. Gridded data has been aggregated to the 140 GTAP regions, however this means that regional differences can be averaged out (e.g. SM figures 1 and 2). This will be important given potential distributional differences in the direction and magnitude of crop yield change across countries such as China. Consideration of these issues will be important in future research agendas.

However, the method presented here is beneficial as it heeds calls to consider the role of both natural and social factors in crop production when estimating the impact of climate-induced crop yield changes in different economies under a wide range of warming scenarios. It contributes to current country specific case studies and could be applied to other regions in the future. As noted by Challinor et al., (2010) such an approach will provide a deeper and broader understanding of future climate change impacts, provides a more realistic picture of the response of global markets and ultimately regional consequences. This information will be key to decision makers. For example, by providing more information on the potential economic risks of agricultural impacts, or benefits of avoided damages, of different climate change goals; to help inform government or industry investment decisions such as purchasing or selling land; or in weighing potential costs against benefits of adaptive policy responses.

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## References

Abera K, Crespo O, Seid J, Mequanent F (2018) Simulating the impact of climate change on maize production in Ethiopia, East Africa. Environ Syst Res. https://doi.org/10.1186/s40068-018-0107-z

Aguiar A, Narayanan B, McDougall R (2016) An Overview of the GTAP 9 Data Base. J Glob Econ Anal 1:181–208. https://doi.org/10.21642/JGEA.010103AF

Araya A, Hoogenboom G, Luedeling E et al (2015) Assessment of maize growth and yield using crop models under present and future climate in southwestern Ethiopia. Agric For Meteorol 214–215:252–265. https://doi.org/10.1016/j.agrformet.2015.08.259

Arndt C, Asante F, Thurlow J (2015) Implications of Climate Change for Ghana’s Economy. Sustainability 7:7214–7231. https://doi.org/10.3390/su7067214

Bandara JS, Cai Y (2014) The impact of climate change on food crop productivity, food prices and food security in South Asia. Econ Anal Policy 44:451–465. https://doi.org/10.1016/j.eap.2014.09.005
Calzadilla A, Zhu T, Rehdanz K, et al (2013) Economywide impacts of climate change on agriculture in Sub-Saharan Africa. Ecol Econ 93:150–165. https://doi.org/10.1016/j.ecolecon.2013.05.006
Challinor AJ, Simelton ES, Fraser EDG et al (2010) Increased crop failure due to climate change: assessing adaptation options using models and socio-economic data for wheat in China. Environ Res Lett 5:034012. https://doi.org/10.1088/1748-9326/5/3/034012
Challinor AJ, Wheeler TR, Osborne TM, Slingo JM (2006) Assessing the vulnerability of crop productivity to climate change thresholds using an integrated crop-climate model. In: Avoiding Dangerous Climate Change. Cambridge University Press, Cambridge, pp 187–194
Chen Y, Wu Z, Okamoto K et al (2013) The impacts of climate change on crops in China: A Ricardian analysis. Glob Planet Change 104:61–74.
Corong EL, Hertel TW, McDougall R, et al (2017) The Standard GTAP Model, Version 7. 2:119. https://doi.org/10.21642/jgea.020101af
Costa LC, Justino F, Oliveira LJC et al (2009) Potential forcing of CO2, technology and climate changes in maize (Zea mays) and bean (Phaseolus vulgaris) yield in southeast Brazil. Environ Res Lett 4:014013. https://doi.org/10.1088/1748-9326/4/1/014013
Deressa TT, Hassan RM (2009) Economic Impact of Climate Change on Crop Production in Ethiopia: Evidence from Cross-section Measures. J Afr Econ 18:529–554. https://doi.org/10.1093/jae/ejp002
Erda L, Wei X, Hui J et al (2005) Climate change impacts on crop yield and quality with CO2 fertilization in China. Philos Trans R Soc B Biol Sci 360:2149–2154. https://doi.org/10.1098/rstb.2005.1743
FAO (2016a) Save and Grow - in practice maize, rice, wheat. Food and Agriculture Organisation of the United Nations, Rome
FAO (2017) FAOSTAT. Online statistical database: Production. Available at http://faostat3.fao.org/download/Q/QC/E. Accessed 17 January 2020
FAO (2016b) FAOSTAT Crops database. Available at: http://www.fao.org/faostat/en/#data/QC. Accessed 20 January 2020.
FAO (2019) FAOSTAT commodities by country. Available at: http://www.fao.org/faostat/en/#rankings/commodities_by_country. Accessed 20 January 2020.
Fujimori S, Iizumi T, Hasegawa T et al (2018) Macroeconomic Impacts of Climate Change Driven by Changes in Crop Yields. Sustainability 10:3673
Geng X, Wang F, Ren W, Hao Z (2019) Climate Change Impacts on Winter Wheat Yield in Northern China. Adv Meteorol 2019:2767018. https://doi.org/10.1155/2019/2767018
Gütschow J, Jeffery ML, Schaeffer M, Hare B (2018) Extending Near-Term Emissions Scenarios to Assess Warming Implications of Paris Agreement NDCs. Earths Future 6:1242–1259. https://doi.org/10.1002/2017EF000781
Harris I, Jones PD, Osborn TJ, Lister DH (2014) Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. Int J Climatol 34:623–642. https://doi.org/10.1002/joc.3711
Hertel TW, Tsigas ME (1997) Structure of GTAP. In: Hertel TW (ed) Global Trade Analysis: Modeling and Applications. Cambridge University Press, Cambridge, pp 9–71
Hertel TW, Burke MB, Lobell DB (2010) The poverty implications of climate-induced crop yield changes by 2030. Glob Environ Change 20:577–585. https://doi.org/10.1016/j.gloenvcha.2010.07.001
Hoegh-Guldberg O, Jacob D, Taylor M et al (2018) Impacts of 1.5°C Global Warming on Natural

and Human Systems. In: Masson-Delmotte V P Zhai, HO Pörtner, D et al (ed) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.
Howden SM, Soussana J-F, Tubiello FN et al (2007) Adapting agriculture to climate change. Proc. Natl. Acad. Sci. 104:19691-19696. https://doi.org/10.1073/pnas.0701890104
Huff KM, Hertel TW (2000) Decomposing Welfare Changes in the GTAP Model. GTAP Technical Paper No 5. Purdue University, West Lafayette
Iglesias A, Garrote L, Quiroga S, Moneo M (2012) A regional comparison of the effects of climate change on agricultural crops in Europe. Clim Change 112:29–46. https://doi.org/10.1007/s10584-011-0338-8
IPCC (2014) Summary for policymakers. In: Field CB VR Barros, DJ Dokken et al (ed) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1–32
IPCC (2018) Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press, Cambridge.
Islam S, Cenacchi N, Sulser TB, et al (2016) Structural approaches to modelling the impact of climate change and adaptation technologies on crop yields and food security. Glob Food Secur 10:63–70. https://doi.org/10.1016/j.gfs.2016.08.003
Jones PG, Thornton PK (2003) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob Environ Change 13:51–59. https://doi.org/10.1016/S0959-3780(02)00090-0
Koehler A-K, Challinor AJ, Hawkins E, Asseng S (2013) Influences of increasing temperature on Indian wheat: quantifying limits to predictability. Environ Res Lett 8:034016.
Kriegler E, Edmonds J, Hallegatte S, et al (2014) A New Scenario Framework for Climate Change Research: The Concept of Shared Climate Policy Assumptions. Climatic Change 122:401–414. https://doi.org/10.1007/s10584-013-0971-5
Liu J, Fritz S, van Wesenbeeck CFA, et al (2008) A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. Clim Change Desertification 64:222–235. https://doi.org/10.1016/j.gloplacha.2008.09.007
Lobell DB, Burke MB, Tebaldi C, et al (2008) Prioritizing Climate Change Adaptation Needs for Food Security in 2030. Science 319:607. https://doi.org/10.1126/science.1152339
Margulis S, Dubeux C, Marcovitch J (2011) Economia da mudança do clima no Brasil. Synergia Editora, Brazil
Mideksa TK (2010) Economic and distributional impacts of climate change: The case of Ethiopia. Glob Environ Change 20:278–286.
Monfreda C, Ramankutty N, Foley JA (2008) Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob Biogeochem Cycles 22:1-19. https://doi.org/10.1029/2007gb002947
Myers, S.S. et al (2017) Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. Annual Review of Public Health, 38(1), 259 – 277, doi:10.1146/annurev-publhealth-031816-044356.
Nelson GC, Valin H, Sands RD et al (2014) Climate change effects on agriculture: Economic responses to biophysical shocks. Proc Natl Acad Sci 111:3274–3279. https://doi.org/10.1073/pnas.1222465110

Osborn TJ, Wallace CJ, Harris IC, Melvin TM (2016) Pattern scaling using ClimGen: monthly-resolution future climate scenarios including changes in the variability of precipitation. Clim Change 134:353–369. https://doi.org/10.1007/s10584-015-1509-9
Osborn TJ, Wallace CJ, Lowe JA, Bernie D (2018) Performance of Pattern-Scaled Climate Projections under High-End Warming. Part I: Surface Air Temperature over Land. J Clim 31:5667–5680. https://doi.org/10.1175/JCLI-D-17-0780.1
Ostberg S, Schewe J, Childers K, Frieler K (2018) Changes in crop yields and their variability at different levels of global warming. Earth Syst Dynam 9:479–496. https://doi.org/10.5194/esd-9-479-2018
Ouraich I, Dudu H, Tyner WE, Cakmak EH (2019) Agriculture, trade, and climate change adaptation: a global CGE analysis for Morocco and Turkey. J North Afr Stud 24:961–991. https://doi.org/10.1080/13629387.2018.1463847
Parkes B, Defrance D, Sultan B, et al (2018) Projected changes in crop yield mean and variability over West Africa in a world 1.5 K warmer than the pre-industrial era. Earth Syst Dyn 9:119–134
Parry ML, Rosenzweig C, Iglesias A, et al (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Clim Change 14:53–67. https://doi.org/10.1016/j.gloenvcha.2003.10.008
Porter JR, Xie L, Challinor AJ, et al (2014) Food security and food production systems. In: Field CB, Barros VR, Dokken DJ, et al (eds) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK
Portmann FT, Siebert S, Döll P (2010) MIRCA2000—Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. Glob Biogeochem Cycles 24: GB1011. https://doi.org/10.1029/2008gb003435
Ren X, Weitzel M, O'Neill BC, et al (2018) Avoided economic impacts of climate change on agriculture: integrating a land surface model (CLM) with a global economic model (iPETS). Clim Change 146:517–531. https://doi.org/10.1007/s10584-016-1791-1
Riahi K, van Vuuren DP, Kriegler E, et al (2017) The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob Environ Change 42:153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009
Rose A, Liao S-Y (2005) Modelling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions. J Reg Sci 45:75–112. https://doi.org/10.1111/j.0022-4146.2005.00365.x
Rosenzweig C, Iglesius A, Yang XB, et al (2001) Climate change and extreme weather events - Implications for food production, plant diseases, and pests. Glob Chang Hum Health 2:90–104
Rosenzweig C, Tubiello FN (2007) Adaptation and mitigation strategies in agriculture: an analysis of potential synergies. Mitig. Adapt. Strategies Glob. Change 12: 855-873.
Rosenzweig C, Jones JW, Hatfield JL, et al (2013) The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agric For Meteorol 170:166–182. https://doi.org/10.1016/j.agrformet.2012.09.011
Rosenzweig C, Parry ML (1994) Potential impact of climate change on world food supply. Nature 367:133–138. https://doi.org/10.1038/367133a0
Sagoe R (2006) Climate change and root crop production in Ghana. Crops Research Institute, Kumasi
Schlenker W, Lobell DB (2010) Robust negative impacts of climate change on African agriculture. Environ Res Lett 5:014010. https://doi.org/10.1088/1748-9326/5/1/014010
Schleussner C-F, Lissner TK, Fischer EM, et al (2016) Differential climate impacts for policy-

relevant limits to global warming: the case of 1.5°C and 2°C. Earth Syst Dynam 7:327–351. https://doi.org/10.5194/esd-7-327-2016
Tebaldi C, Arblaster JM (2014) Pattern scaling: Its strengths and limitations, and an update on the latest model simulations. Climatic Change 122:459–471. https://doi.org/10.1007/s10584-013-1032-9
Vanuytrecht, E, Thorburn, P.J (2017) Responses to atmospheric CO2 concentrations in crop simulation models: a review of current simple and semicomplex representations and options for model development. Glob Change Biol 23: 1806-1820.
Warren R, Alfieri L, Burke S, et al (2017) Report on different degrees of adaptation measures applied in the impact models. Deliverable 4.4, High End Climate Impacts and Extremes (HELIX). European Commission
Xiao D, Bai H, Liu LD (2018) Impact of Future Climate Change on Wheat Production: A Simulated Case for China's Wheat System. Sustainability 10:1277. https://doi.org/10.3390/su10041277
Xiong W, van der Velde M, Holman IP, et al (2014), Can climate-smart agriculture reverse the recent slowing of rice yield growth in China? Agric Ecosyst Environ 196:125-136. doi.org/10.1016/j.agee.2014.06.014.
Xie W, Xiong W, Pan J, et al (2018) Decreases in global beer supply due to extreme drought and heat. Nat Plants 4:964–973. https://doi.org/10.1038/s41477-018-0263-1
Yates DN, Strzepek KM (1998) An Assessment of Integrated Climate Change Impacts on the Agricultural Economy of Egypt. Clim Change 38:261–287.

**Tables:**

| **Scenario** | **Description** |
|---|---|
| Scenario 1 (S1) | <1.5°C (aiming to stay below 1.5°C in 2100 with 66% probability) |
| Scenario 1E (S1E) | 1.5°C |
| Scenario 2 (S2) | <2.0°C (aiming to stay below 2.0°C in 2100 with 66% probability) |
| Scenario 2E (S2E) | 2.0°C |
| Scenario 3 (S3) | 2.5°C |

| | |
|---|---|
| Scenario 4 (S4) | 3.0°C |
| Scenario 5 (S5) | 3.5°C |
| Scenario 6 (S6) | 4.0°C |

Table 1: Climate change scenarios

| **Sector Code** | **Description** | **GTAP sectors** |
|---|---|---|
| pdr | Paddy rice | pdr |
| wht | Wheat | wht |
| ocr | Crops not elsewhere classified (n.e.c) | gro, v_f, osd, c_b, pfb, ocr |
| lsf | Livestock | ctl, oap, rmk, wol, frs, fsh |
| mng | Mining | coa, oil, gas, omn |
| fdm | Food manufacturing | cmt, omt, vol, mil, pcr, sgr, ofd, b_t |
| omf | Other manufacturing | tex, wap, lea, lum, ppp, p_c, crp, nmm, i_s, nfm, fmp, mvh, otn, ele, ome, omf, ely, gdt, wtr |
| cns | Construction | cns |
| trd | Trade | trd |
| tps | Transportation | otp, wtp, atp |
| sev | Services | cmn, ofi, isr, obs, ros, osg, dwe |

Table 2: Sector aggregation scheme. For the full list of 140 regions and 57 sectors and abbreviations in GTAP see Aguiar et al. (2016).

**Figure Captions:**

Figure 1: Change in rice yield under eight climate scenarios. (Box and whisker plots illustrate climate model uncertainty. Insets provide data relative to the last ten years, 2008-2017, on the yield, area and production of rice in each country).

Figure 2: Change in wheat yield under eight climate scenarios (There is no cultivation of wheat in Ghana). (Box and whisker plots illustrate climate model uncertainty. Insets provide data relative to the last ten years, 2008-2017, on the yield, area and production of wheat in each country).

Figure 3: Production change of rice and wheat globally and in the six study countries under the different warming scenarios *(CoVA denotes percentage change in value-added; CoP denotes change in production in Million tonnes)*

Figure 4: Comparison in the change in price (%) to households of domestic and imported rice and wheat commodities in the six selected countries. Results are shown for scenario 1 and scenario 6.

Figure 5: Percentage change in real GDP under the eight warming scenarios

Figure 6: Change in welfare of households under the eight warming scenarios