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LETTER

Economic and biophysical impacts on agriculture under 1.5 °C and 2 °C warming

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Abstract

The goal of limiting global mean warming to well below 2 °C, and possibly to 1.5 °C, emerged in the Paris Agreement, motivated by the belief that achieving these targets 'would significantly reduce the risks and impacts of climate change'. Understanding the climate impacts of relatively low levels of warming, in particular whether there are substantial benefits to reducing emissions to limit warming to 1.5 °C rather than 2 °C, is important for informing climate policy, but such studies are scarce. Here we evaluate the difference in global biophysical and economic impacts related to agriculture between 1.5 °C–2 °C warming. Given the small difference in global average temperature, accounting for uncertainties is important, and we include key uncertainties in three main components of the analysis: climate system (regional climate variability), biophysical system (crop response to CO2 fertilization), and economic system (trade responsiveness). We are unable to meaningfully distinguish the regional agricultural impacts occurring with 1.5 °C warming from those occurring with 2 °C warming when accounting for these uncertainties. Under some assumptions 1.5 °C implies benefits relative to 2 °C, while under others it implies costs. Results are most sensitive to the uncertainty in the effect of CO2 fertilization on crop yield.

1. Introduction

Since the Paris agreement, studies have begun to compare agricultural impacts between 1.5 °C–2 °C warming. Schleussner et al (2016) assessed multiple biophysical impacts, including regional crop yields, concluding that while results vary between regions and crop types, both scenarios could result in significant yield reduction. Betts et al (2018) evaluated differences in vulnerability to food security, finding that although most countries would be less vulnerable in 1.5 °C scenario than with 2 °C, 24% of the countries would have the same or higher vulnerability at 1.5 °C. AgMIP (Agricultural Model Intercomparison and Improvement Project) has organized multi-model studies to assess impacts at these levels of warming in the context of climate, crop, and economic uncertainties (Rosenzweig et al 2018, Ruane et al 2018, Schleussner et al 2018). In all these studies, climate outcomes for 1.5 °C and 2 °C scenarios are approximated from existing higher climate scenarios (RCP8.5, RCP4.5 or RCP2.6) rather than using stabilized climate simulations at these levels.

These studies demonstrate that uncertainty is especially important to account for given the relatively small difference in global mean temperature between the two scenarios. It is possible that uncertainty in regional climate or biophysical or economic impact models could be large relative to the global mean climate difference (Betts et al 2018). Several previous studies have considered particular aspects of uncertainty in agricultural impacts, including uncertainty in climate projections (e.g. Burke et al 2011), crop models

4 It is possible that a 1.5 °C or 2 °C stabilized climate scenario could have different outcomes than a higher climate scenario at the time it reaches 1.5 °C or 2 °C. In the higher climate scenario, the 1.5 °C or 2 °C climate is a transient state. Tebaldi and Knutti (2018) showed that approximating annual mean temperature or precipitation in a low climate scenario from an existing high climate scenario is unlikely to be a substantial source of error. However, differences in other climate variables that influence agricultural yield, and at sub-annual timescales, might still be an issue.
(e.g. Asseng et al 2013), socioeconomic development pathways (e.g. Calzadilla et al 2013, Ren et al 2018), and combinations of climate and crop models (e.g. Lobell et al 2006, Nelson et al 2014, Rosenzweig et al 2014, Schleussner et al 2018). A recent AgMIP study (Ruane et al 2018) incorporates uncertainties in climate scenarios, climate models and economic models for the assessment of 1.5 °C and 2 °C scenarios, but does not decompose sources of uncertainty affecting the same outcome variable.

In this study, we evaluate differences in economic impacts between 1.5 °C and 2 °C warming driven by crop yield changes, with a focus on quantifying uncertainties from three sources: (1) climate system (regional climate variability); (2) biophysical system (crop response to CO₂ fertilization); and (3) economic system (trade responsiveness).

This study is part of a collection of papers constituting the BRACE1.5 project, which examines the Benefits of Reduced Anthropogenic Climate changE by evaluating differences between ranges of impacts at 1.5 °C and 2 °C warming. BRACE1.5 is a successor to the BRACE project, which examined impacts for higher forcing scenarios (O’Neill et al 2018). Section 2 outlines our methodology. Section 3 reports results, and section 4 summarizes conclusions.

2. Methodology

We model the effect of climate and CO₂ changes on global and regional economies through their effects on crop yields. The overall methodology follows the approach taken in Ren et al (2018), and we therefore describe the process briefly; details are provided in the supporting material in Ren et al (2018). The integrated-Population-Economy-Technology-Science model (iPETS, Dalton et al 2008) is linked with the Community Land Model (CLM, Oleson et al 2013) to perform the analysis. A diagram of the workflow is shown in figure SM1 in the supporting material (SM). iPETS is a global integrated assessment model that has been used to examine the effects of demographic changes on emissions (O’Neill et al 2010, 2012) and climate change impacts on agriculture (Ren et al 2018). CLM is a global, spatially explicit land surface model with explicit representation of crops. It has been used to evaluate crop yields under climate change (e.g. Levis et al 2018) and its yield responses have been compared to observations and other crop and land surface models as part of AgMIP (Porwollik et al 2017). CLM reproduces spatial and temporal patterns of observed yields reasonably well (Müller et al 2017); further description and validation of CLM on yield responses to climate change are in SM1.

The climate impacts on yields from CLM are driven by simulations of the Community Earth System Model (CESM) from a set of initial condition ensembles of forcing scenarios designed to stabilize warming at 1.5 °C or 2 °C (Sanderson et al 2017). The analysis is global, with results in iPETS produced at the level of nine world regions (figure 1) and in CLM at a resolution of 2 degrees, and spans the period 2006–2100.

We carry out the analysis by first using iPETS to develop 1.5 °C and 2 °C scenarios of global and regional economies without climate change impacts. Next,
we use CLM to estimate the effect of climate and CO₂ changes on crop yields according to the two climate scenarios. Finally, we apply the CLM yield changes to iPETS to create 1.5 °C and 2 °C scenarios with climate change impacts on agriculture. The difference between the iPETS scenarios with and without yield impacts is our estimate of the economic impacts from climate change on agriculture. We describe each of these three steps in turn, with additional information in the SM.

To develop the iPETS no-climate impacts scenarios for 1.5 °C and 2 °C, we calibrate the model to match existing scenarios (Calvin et al 2016, Rogelj et al 2018) produced with the Global Change Assessment Model (GCAM, Brenkert et al 2003), a more comprehensive integrated assessment model with a long history of use in climate change analysis. The GCAM scenarios are based on one of the Shared Socioeconomic Pathways (SSPs; O’Neill et al 2014), the Middle of the Road pathway (SSP2) that assumes societal development follows moderate rates of change consistent with past experience. Mitigation is undertaken in these scenarios to limit warming to about 1.5 °C and 2 °C by 2100, respectively.

The iPETS calibration first reproduces GCAM outcomes for GDP, CO₂ emissions, energy demand, land use and crop yield (aggregated to iPETS regions) in an unmitigated SSP2 baseline scenario (see SM2 in Ren et al 2018). Next, we introduce a carbon tax such that the path of global CO₂ emissions from energy use matches the emissions pathway in the GCAM 1.5 °C and 2 °C scenarios through 2100 to produce a no-climate impact mitigation scenario. Both GCAM scenarios require negative emissions late in the century. We therefore introduced a carbon capturing technology in iPETS that is assumed to be available in unlimited supply at a specified cost in the future, an approach similar to the modeling of backstop technologies (Nordhaus 1979). Further details are in the SM2.

In the second step of our analysis, climate impacts on exogenous yields are obtained using a version of CLM4.5 (Levis et al 2018) in which seven explicit crop types were modeled (temperate corn, soybean, wheat, sugarcane, cotton, tropical corn, and tropical soybean). Exogenous yield impacts (Nelson et al 2014) are defined as climate effects on yield evaluated in CLM, used as exogenous input to iPETS; within iPETS, economic adjustments determine actual yield changes. We use a version of CLM4.5 that allows for the use of monthly mean values of atmospheric forcing (the only outcomes available from the CESM initial condition ensembles) rather than the typical 6 hourly forcing (see SM3 for description and validation of this ‘anomaly forcing’ version). Yield impacts were estimated from a database of pre-computed offline CLM simulations that includes annual yield information for all CLM crop types at every grid cell under both the 1.5 °C and 2 °C climate scenarios, with a variety of management assumptions, as discussed in SM8 in Ren et al (2018). CLM4.5 only allows for crop location and management assumptions (fertilizer, irrigation) that are fixed over time. With the offline database, we can estimate yield impacts in scenarios in which crop location and management are changing over time, by estimating yield impacts in each year and location based on simulations in the database with time-invariant assumptions (SM1). We make use of the offline database approach to incorporate the effects of changing fertilizer assumption according to an FAO projection. Regional exogenous yield changes for use as input to the iPETS model are calculated by aggregating the spatial, crop-specific yields into one average crop type for each iPETS region. For this study, we assume a constant spatial distribution of cropland at the 2005 pattern. The implication of aggregation over crop types within iPETS regions and constant spatial distribution of cropland over time are discussed in SM4 and SM5. The yield estimation process is repeated both with and without climate change, and the difference between the two gives the climate effect on regional yields. We do not model climate effects on pasture yield; we assume that this effect is equal in percentage terms to the impact on crop yield, simply to avoid artificial distortions to crop impacts (SM6).

The climate-driven exogenous yield changes are applied in iPETS by modifying the total factor productivity (TFP) of crop production and partial factor productivity (PFP) of animal product production. This approach best corresponds to the nature of the information from CLM (SM6). Each of the iPETS scenarios is run with these yield impacts included, producing a new set of results, including GDP, food prices and demand, and land use demand. The difference between this set of results (with climate effects on exogenous yield) and results for the no-climate impact scenarios gives the climate impact on the economy.

There are three models involved in this study: the climate model, the crop model and the economic model. In this study, we evaluate the main uncertainties from the three models that have major impacts on the agricultural system: climate variability in the climate model, CO₂ fertilization in the crop model and the trade system in the economic model.

3. Results

We first present the impact results assuming that our three uncertain factors (climate variability, CO₂ fertilization, trade) are at their default values and then discuss the effect of uncertainty by changing one factor at a time.

3.1. Results with default parameters

The default cases for both the 1.5 °C and 2 °C scenarios use a single CESM ensemble member (#9), include the CO₂ fertilization effect with increasing atmospheric CO₂ concentration (the average atmospheric CO₂ concentrations in 2081–2100 are 380.8 ppm and 443.3 ppm in the 1.5 °C and 2 °C scenarios, respectively), and the trade parameter in the iPETS model, known as the Armington elasticity of
substitution (Armington 1969), is set at the default iPETS value of 2. Figure 2 shows the effect of climate and CO2 on exogenous CLM yield changes and on several economic outcomes for the 1.5 °C and 2 °C scenarios for 2081–2100. Negative values indicate outcomes are lower with climate change (and CO2) impacts than without them, in the same time period (and vice-versa for positive values). The differences in results between these two scenarios are shown in figure 3. Negative values here indicate outcomes are lower in the 1.5 °C scenario than in the 2 °C scenario.

While results vary by region, when the effects of climate change itself and CO2 fertilization are considered, generally (1) the 1.5 °C scenario (figure 2(a)) produces a mix of negative and positive effects on the agriculture sector across regions, (2) the 2 °C scenario (figure 2(b)) produces more positive outcomes than negative, and therefore (3) the sector is generally worse off in the 1.5 °C scenario than in the 2 °C scenario (figure 3).

These general results can be understood by first looking at CLM results for exogenous yield changes. The effects of 1.5 °C warming on crop yield, with default CO2 fertilization included, are mixed and small (<±8%). Two tropical regions, India and Sub-Saharan Africa, experience the largest negative effects. In contrast, two higher-latitude regions (China and Transition Countries) see large positive effects on yield. With 2 °C warming, more regions have yield increases. The results from these scenarios are consistent with those from previous work on higher scenarios (about 2.5 °C and 3.7 °C warming) with the same modeling system (Ren et al 2018). Taken together, they indicate that in CLM, the net effect of climate change and CO2 fertilization on crop yields is more positive at higher levels of warming and CO2.6

Figure 2. Climate impacts on exogenous yield and economic outcomes with default parameters (average 2081–2100), expressed relative to outcomes in SSP2 no-climate impact mitigation scenarios. See figure 1 for region definitions.

5 The Armington elasticity of substitution represents the degree to which domestic and imported goods can be substituted. It can range from zero–infinity. The higher its value, the more willing the consumer is to substitute between domestic and imported goods in response to price changes.

6 Note that our conclusion is drawn from CLM which is not accounting for effects of other factors on yield, including extreme heat, flood events, pests and disease, and ozone damages, which would be increasingly important at higher levels of climate change.
Over this full range, a lower level of climate and CO$_2$ (compared to a higher one) therefore implies a dis-benefit in the agricultural sector.

The effects on exogenous yield in the 1.5 °C and 2 °C scenarios produce changes in crop production in the iPETs model that generally reflect this same pattern across regions (figure 2). Changes in the production of animal products are generally positive and much smaller in magnitude. There are differences between the response of production of crops and animal products, even though we assume the same percentage change in exogenous yield of cropland and pasture, because the exogenous yield impacts from CLM are best represented as TFP change in the crop sector but PFP changes (of pasture) in the animal products sector. This different implementation dampens the response of animal products production to the climate impact (SM6).

Changes in food prices and consumption are in line with the regional pattern of crop production change (as opposed to animal products, since crop production changes are larger) but with a smaller magnitude. When there is a yield reduction, *ceteris paribus*, crop production costs increase, leading to higher prices and therefore decreased food demand, to which industries respond with decreased production. The effects of yield increases are opposite. These effects on the agriculture sector lead to small GDP changes (<±0.6% for 1.5 °C and <±0.8% for 2 °C).

The effect of exogenous yield changes on land use depends on the changes in both yield and production. The change in production itself depends on a number of factors, including how large the exogenous yield change is, how easily producers can shift inputs toward or away from land use, changes in input prices, and the demand response to lower prices. For both 1.5 °C and 2 °C scenarios, the changes in regional cropland are of the same sign as the exogenous yield changes and are <±10% in magnitude. For pasture, changes in land use are generally of opposite sign to the exogenous yield change and of somewhat larger magnitude than cropland changes.

Comparing outcomes in the 1.5 °C and 2 °C scenarios, with default model assumptions the 1.5 °C scenario results in exogenous regional yields that are up to 6% lower than in the 2 °C scenario, in all regions (figure 3). The lower yields induce decreased crop production, small increases in animal product production in most regions, small decreases in food consumption (up to −4%), slightly higher food prices (<6%), a land use shift from cropland to pasture, and reductions in GDP (up to −0.4%). The fact that economic impacts are generally worse in the 1.5 °C scenario than they are in the 2 °C scenario is primarily a consequence, as we will see below, of CO$_2$ fertilization effects on crop yield.

In this study we are examining only the difference in the effects of climate change and CO$_2$ on outcomes between the two scenarios. There will also be effects on the economy of the costs of different levels of mitigation in the two scenarios, a potentially large effect (Hasegawa *et al* 2015). We have removed those effects here in order to focus on impact outcomes.

### 3.2. Uncertainty analyses

To examine the sensitivity of results to our three sources of uncertainty, we compare outcomes with two alternative assumptions about each uncertain factor that span a wide but plausible range. The rationale for selecting the alternative parameter values is discussed in SM7. Here we report results in terms of the difference in impacts between 1.5 °C and 2 °C warming, averaged for 2081–2100, as in figure 3. The corresponding absolute impacts in each of the two 7 Crop production in other industrialized countries increases slightly due to trade effects since its yield reduction is the least among all regions. More discussion can be found in section 3.2.3. 8 Specifically, outcomes in figure 3 are calculated as (1.5 °C yield change with 2 °C mitigation scenario − 2 °C yield change with 2 °C mitigation scenario)/(2 °C yield change with 2 °C mitigation scenario).
3.2.1. Climate variability
To test the uncertainty in regional climate outcomes due to inherent climate variability, we compare the outcomes from our default cases, as described in section 3.1, to scenarios driven by a different CESM ensemble member (#5) from the 1.5 °C and 2 °C ensembles. These ensemble members were chosen in order to represent a wide range of temperature and precipitation changes across regions, evaluated as differences in future (2090–2100) outcomes relative to the present (2006–2015) (figure SM7).

Results with the alternative ensemble member (figure 4(a)) show exogenous yield reductions in the 1.5 °C versus 2 °C scenario (up to −10%) are generally larger than those in the default case (figure 4(b), up to −6%) with the exception of India, Sub-Saharan Africa and USA. These larger yield changes result in somewhat stronger economic responses, causing larger reductions in food consumption (up to −8%), food price increases (up to 12%) and GDP reductions (up to −0.8%) in the 1.5 versus 2 °C scenario. In all regions, uncertainty in climate variability does not change the sign of outcomes; impacts are worse in the 1.5 °C scenario than they are in the 2 °C scenario with default CO2 fertilization effects.

3.2.2. CO2 fertilization
There is little agreement on the magnitude of the CO2 fertilization effects on yields (Schleussner et al. 2018). Since CLM yield response to CO2 appears to be strong relative to many other crop models (Ren et al. 2018), we consider our default case to represent one end of our uncertainty range. For the lower end of the range, we assume no further increase in the CO2-driven yield response, by carrying out a simulation assuming that CO2 is constant at current levels (359.8 ppm), while climate changes according to the 1.5 °C or 2 °C scenarios. A comparison between CLM yield change with no additional CO2 fertilization effects and AgMIP outcomes shows that this assumption represents a reasonable lower bound for the strength of the fertilization effect (figure SM8).

When additional CO2 fertilization effects are excluded (figure 5(a)), reducing warming from 2 °C to 1.5 °C implies an increase in exogenous yields across all regions (up to 11%), while in our default case with CO2 fertilization, yields generally declined by up to −6%. The increased exogenous yields result in increased crop production and food consumption, lower food prices (<−9%), and increases in GDP (<0.6%). In this case, all regions are better off in the 1.5 °C scenario compared to 2 °C. Thus with CO2 fertilization uncertainty considered, we cannot tell if impacts in the 1.5 °C scenario are better or worse than in the 2 °C scenario.

3.2.3. Trade
Trade is a common adaptation strategy when there are impacts on a region’s economy. When the magnitude of exogenous yield changes differ across regions, regions will adjust their trade activity accordingly and assumptions on the trade parameter (Armington elasticity) can strongly affect regional economic outcomes, particularly production, land use, and prices.

There are a wide range of Armington elasticity values for food (mostly for specific food types) used in different models and different regions in the literature. To be conservative, we adopt the highest (4.5, GTAP7.0, Narayanan and Walmsley 2008) and lowest (0.45, Shiells and Kenneth 1993) we found (recall the default parameter value is 2). We apply the same Armington elasticity values to both crop and animal products goods to avoid artificial shifts between the production (and consumption) of crops and animal products in the model (SM6).

The effect of uncertainty about trade is clearest when considering impacts within a given climate change scenario. For example, in the 2 °C scenario, the high elasticity case leads to larger changes in regional crop production in response to climate impacts on yield, compared to the response in the low elasticity case (compare figures SM11(b) to SM12(b)). The amplification of production responses occurs because with a higher elasticity value, relative differences in exogenous yield impacts across regions will lead to larger increases in exports (in less negatively affected regions) or imports (in more negatively affected regions), which will in turn affect regional production. The larger production differences generate larger differences in GDP and land use, as well.

In terms of the difference in impacts between the 1.5 °C–2 °C scenarios, although the higher elasticity case does yield larger differences in most outcomes than the low elasticity case (figure 6), the differences are not as pronounced as the absolute impacts within each climate scenario (figures SM11 and SM12). The most sensitive outcome is regional production. In particular, in Other Industrialized Countries and Sub-Saharan Africa, the 1.5 °C scenario can lead to more or less production depending on the elasticity values, compared to the 2 °C scenario, despite the fact that exogenous yield declines by the same amount in each case. The increase in production in the high elasticity case occurs because compared to other regions, OIC and SSA have the smallest yield reduction, and therefore exports (and production) increase. A more flexible trade system allows these two regions to benefit more from the higher negative yield changes of other regions; in this scenario their GDPs increase by up to 0.4%, while in the low elasticity case, their GDPs change −0.3%. Thus when uncertainty in the trade system is considered, for some regions we cannot tell whether
impacts in the 1.5 °C scenario are better or worse than 2 °C.

3.2.4. Sensitivity analysis comparison
Among the three uncertainties we analyzed, climate variability and CO₂ fertilization affect economic responses through their effects on exogenous yield changes, while the trade elasticity affects the economic response to a given set of exogenous yield changes. Figure 7 summarizes the results of the individual uncertainty analyses in terms of ranges of possible outcomes for the difference in impacts between the 1.5 °C–2 °C scenarios.

Uncertainties in the impact differences between scenarios are large compared to the absolute impact in a given scenario. With all three uncertainties included, the difference in climate impacts between the two scenarios can be positive or negative in all regions and for all variables. Thus we cannot conclude that 1.5 °C is better or worse than 2 °C warming in terms of agricultural impacts.

Considering individual uncertainties, CO₂ fertilization has the largest effect on outcomes in most regions and it is the key factor determining whether the agriculture sector is better off in the 1.5 °C (rather than 2 °C) scenario. Climate variability has a substantial effect in some regions, but generally does not change the sign of the outcome. Uncertainty in the trade elasticity mainly affects crop production and its effect is most pronounced in a few regions, particularly Sub-Saharan Africa where it is the largest of the three sources of uncertainty.

4. Discussion and conclusion
This study evaluates the differences in exogenous yield and economic outcomes between scenarios with 1.5 °C and 2 °C warming, with a focus on the effect of uncertainties from three sources: climate variability, CO₂ fertilization and trade-related assumptions in the economic model. Our results imply that given these uncertainties, the change in agricultural impacts in the
1.5 °C scenario compared to 2 °C at the end of the century can be either positive or negative.

The climate impact results are important for informing discussions of the relative risks associated with limiting warming to either 1.5 °C or 2 °C, both of which are included in the Paris Agreement as long-term temperature targets. This analysis contributes only to the evaluation of a single type of climate change impact (on agriculture); a comprehensive assessment of relative risks would need to include a much wider range of impacts, including sea level rise consequences, human health, and ecosystems.

In our analysis, the strength of CO2 fertilization effect on yield is the largest uncertainty and is the key determinant of the sign of the difference in impacts between scenarios. When we assume the strength of the CO2 fertilization effect is at the lower end of its uncertainty range, the 1.5 °C scenario produces net benefits to the agriculture sector (and to the whole economy) relative to 2 °C. In addition, uncertainties from climate variability are also substantial, particularly at the regional level. Uncertainty in the responsiveness of the trade system to price changes has a substantial effect on where production takes place in a given scenario. When trade is relatively flexible, differences in climate change impacts across regions induces substantial changes in regional production, ameliorating food price increases.

Caveats to this study (SM10) include additional sources of uncertainty not represented, including structural uncertainty in the climate, crop, and economic models employed here; possible effects of climate variability that are not captured in the anomaly forcing approach to crop modeling; alternative socioeconomic scenarios; and interactions with the energy system.

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Figure 6. Differences of climate impacts on the economy (average 2081–2100) between 1.5 °C–2 °C warming, expressed relative to outcomes in the 2 °C case. See region definitions in figure 1.

(a) Armington elasticity = 4.5

(b) Armington elasticity = 0.45

Figure 7. Ranges of differences in climate impacts on exogenous yield and economic outcomes (average 2081–2100) between the 1.5 °C–2 °C scenarios, expressed relative to outcomes in the 2 °C scenario, for different sources of uncertainties. See region definitions in figure 1. Each sub-section of the vertical bars represents the range of uncertainty due to one of the three sources, while the full length of the vertical bar represents the uncertainty range covered by all three sources.
as stating an official position of the European
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