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**PREFACE**

Focus on agriculture and forestry benefits of reducing climate change impacts

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1. Introduction

Agriculture and forestry are important economic sectors that are vulnerable to changes in the climate system. Climate change both positively and negatively affects the distribution and productivity of these sectors, as production is sensitive to changes in temperature and precipitation, carbon dioxide fertilization effects, availability of water for irrigation, increasingly frequent and severe extreme weather, and stress from diseases and pests (Porter et al 2014, Hatfield et al 2014, Joyce et al 2014). A large number of recent efforts have investigated the impacts of climate change on agriculture, including those based on meta-analyses (e.g. Hatfield et al 2011, Porter et al 2014, Knox et al 2016), statistical modeling (e.g. Schlenker and Roberts 2009, Lobell and Burke 2010, Lobell et al 2013, Burke and Emerick 2016, Zhang et al 2017), process-based crop models (e.g. Challinor et al 2009), integrated assessment modeling (e.g. Thomson et al 2005, Nelson et al 2014a, Ren et al 2016), and model inter-comparison exercises (e.g. Asseng et al 2013, Nelson et al 2014b, Rosenzweig et al 2014). Looking across this rich literature, several common themes emerge: (a) projected effects of climate change on crop yields tend to be more negative than positive, especially as the magnitude of climate change increases, but can vary considerably across regions and under different modelling approaches; (b) inter-annual variability of crop yields will likely increase in many regions, which will pose new challenges for landowners and potentially create increased volatility in commodity markets; (c) water shortages inhibit yields while carbon dioxide (CO₂) enrichment generally has a stimulatory effect; (d) adaptation (e.g. switching crops or practices) improves yields but is highly variable depending upon location and crop type; and (e) climate change is expected to have generally negative effects on food markets and food security (Porter et al 2014).

Climate change impacts on natural vegetation and forests have also been well-studied, at global scales (e.g. Bowman et al 2009, Gonzalez et al 2010, Settele et al 2014, Sohngen and Tian 2016) and for large regions (e.g. Malhi et al 2008, Lindner et al 2010, Vose et al 2012, Joyce et al 2014, Reyer et al 2017). General findings from this literature include: (a) projected effects of climate change leading to large-scale shifts in the distribution and productivity of all forest types, with some of the largest changes occurring in boreal forests; (b) observed adverse effects of temperature stress and drought on tree mortality and forest dieback, likely resulting in forests becoming a weaker carbon sink globally before the end of the century; (c) projected increases in the extent of wildfire activity under higher emission scenarios, with climate-driven disease and pest outbreaks increasing overall risk; and (d) uncertain effects of climate change on global timber and pulp production due to high variability across regions.

With good reason, much focus has been placed recently on model inter-comparison (e.g. Rosenzweig et al 2014, Elliott et al 2015), efforts to better understand the effects of CO₂ enrichment (Leakey 2009), and broader considerations of the nexus between land, water, and energy (Hibbard et al 2014). But amid active climate and energy policy debates at local, domestic, and international scales, information describing the risks of inaction on climate change, and how these risks may change with greenhouse gas (GHG) reductions has never been more critical. Though less well studied, understanding the importance of climate forcing, relative to other uncertainties, is particularly important for assessing the influence of GHG mitigation on the agriculture and forestry sectors.

The papers published in this issue investigate agriculture and forestry impacts across multiple climate forcing scenarios at national, multi-national,
and global scales. In addition, a number of the papers in this focus issue (Monier et al 2016, Sue Wing et al 2015, Beach et al 2015, Kim et al 2017, and Tian et al 2016) represent modeling contributions to the Climate Change Impacts and Risk Analysis (CIRA) project (Martinich et al 2015), which utilizes a consistent analytic framework to estimate climate change impacts across sectors and regions.

The following section provides a brief overview of the contents of this focus issue, organized into agricultural impacts in the United States (US), European Union (EU), and globally (section 2.1); global forestry impacts (section 2.2); and an integrated agriculture and forestry analysis (section 2.3). A brief synopsis of key themes that emerged from the focus issue is provided in section 3.

2. Perspectives on the state of agriculture and forestry impacts modelling

2.1. Impacts on agriculture and markets

2.1.1. US-focused studies

Using a large ensemble of integrated economic and climate simulations to investigate the role of multiple sources of uncertainty (emissions scenarios, climate sensitivities, and natural variability), Monier et al (2016) analysed projected changes in five climate indices relevant to agriculture and forestry. The authors found that the US is projected to experience fewer frosts, a longer growing season, more heat stress, an earlier start of field operations, and no significant change in dry days by the end of the century. However, there is considerable variability in magnitude, spatial patterns, and even the direction of the projected changes across regions. Natural variability plays an important role, in particular for changes in dry days (a precipitation-related index) and heat stress (a threshold index). Global GHG mitigation has the potential to significantly reduce the projected adverse effects (heat stress, risks of pest and disease) of climate change on agriculture, while also curtail ing potentially beneficial impacts (earlier planting, possibility for multiple cropping). Overall, the authors find that the mitigation scenarios reduce climate impacts by approximately half compared to those projected under the unconstrained emissions case. In addition, they conclude that mitigation can delay the point at which mean changes in climate indices are projected to fall outside the historical range of natural variability, potentially beyond 2100 for some indices.

Sue Wing et al (2015) use an econometric approach to characterize the county-level yield response of five major crops (soybeans, wheat, cotton, corn, sorghum) to climatic variability in the contiguous US. While substantial geographic variability was observed, the authors project that unmitigated climate change will adversely affect soybean and wheat yields by mid-century, and cotton yields by 2100, but generally result in positive effects on the more heat-tolerant corn and sorghum yields. Accounting for future expansion of the agricultural sector, Sue Wing and collaborators find a modest net annual benefit of these climate-driven changes, however, global GHG mitigation can boost these benefits by $7–17 billion yr$^{-1}$, depending upon mitigation stringency. These results were highly dependent on assumptions regarding the yield response to increasing CO$_2$; when this effect is excluded, climate change results in negative impacts on the agriculture sector, and annual mitigation benefits increase to as much as $26 billion per year.

Urban et al (2015) evaluate the combined effects of moisture and heat on maize yields in Iowa, Indiana, and Illinois to assess future impacts under two emissions scenarios. They find that explicitly accounting for interactions between heat and moisture lead to significantly higher projected yield variability under warming and drying trends than when accounting for each factor independently. Including the benefits of elevated CO$_2$ significantly reduces impacts, particularly for yield variability, but net damages from rising CO$_2$ and climate change become larger in the latter half of the 21st century, and significantly so by the end of century, under a high emissions scenario. This methodology represents an improvement over previous studies that are based on indirect measures of soil moisture, fail to explicitly capture potential interactions between temperature and soil moisture availability, or omit beneficial effects of elevated CO$_2$ on transpiration efficiency.

2.1.2. EU-focused analysis

Using scenarios of near term future climate change projected in 2030, simulations by Donatelli et al (2015) investigate crop responses (wheat, rapeseed and sunflower) in EU27 member states. They demonstrate a negative net impact of the combined effects of projected changes in climate variables and CO$_2$ in most areas, but with a high degree of variability. The combination of greater precipitation and increased photosynthesis efficiency in some regions, particularly Southern Europe, was shown to potentially result in increasing yields in those areas. Simple adaptation techniques, such as changing sowing dates and the use of different varieties, may be effective in alleviating adverse effects of climate change in most areas, although optimal response differed across crops.

2.1.3. Global analyses

Comparing data from archived crop yield projections, Müller et al (2015) find that climate mitigation leads to overall benefits from avoided damages at the global scale and especially in many regions that are already at risk of food insecurity. In simulations that do not include the potential benefits of CO$_2$ fertilization on crop productivity, the authors find that aggressive mitigation could eliminate ∼81% of the negative
impacts of climate change on biophysical agricultural productivity globally by the end of the century. In this case, benefits of mitigation typically extend well into temperate regions, but vary by crop and underlying climate model projections. Should large benefits to crop yields from CO₂ fertilization be realized, the effects of mitigation become much more mixed, though still positive globally and beneficial in many food insecure countries.

A model inter-comparison analysis by Wiebe et al (2015) examines the global and regional impacts of a range of plausible socioeconomic scenarios along with emission pathways on agricultural yields, area, production, consumption, prices and trade for coarse grains, rice, wheat, oilseeds and sugar crops to 2050. Climate impacts for all variables are similar across low to moderate emissions pathways (Representative Concentration Pathway (RCP) 4.5 and RCP6.0), but increase for a higher emissions pathway (RCP8.5). The authors find that the effects of these climate impacts on global average yields, crop area, production and consumption are similar across shared socioeconomic pathways when trade policies are held constant. Incorporating changes in trade policy leads to sharp increases in trade and lower agricultural prices with liberalized trade and reduced trade with higher global prices in the restricted trade scenario. Yield impacts vary across emissions and socioeconomic scenarios, but the net yield changes realized in the economic model are reduced in all cases relative to the exogenous yield changes estimated by crop models and used as economic model inputs due to market adjustments (endogenous changes in prices and other variables).

2.2. Impacts on forests and markets
Using the climate projections described in Monier et al (2016), Kim et al (2017) simulate changes in global forest productivity, carbon storage, and wildfire activity. The authors use an ensemble of scenarios investigating sources of uncertainty (GHG emissions, climate sensitivity, and natural variability), and find a wide range of outcomes based on these parameters. Generally, global forestry stocks increase in the future under the climate change scenarios considered, with the largest increases projected in tropical forest regions. The primary driver of the increases in forest carbon stocks is CO₂ fertilization. Higher levels of climate change, excluding CO₂ fertilization effects, were found to reduce global forest carbon, which the authors attributed to an increase in wildfires and climatic effects such as droughts. In many regions, especially in the temperate zone, these negative impacts more than offset gains in forest productivity associated with higher temperatures and precipitation.

Using the global forest productivity projections from Kim et al (2017), Tian et al (2016) integrates future climate change impacts into a dynamic forestry economics model. The author’s results suggest that climate change will cause forest outputs (such as timber) to increase by approximately 30% over the century. Aboveground forest carbon storage is also projected to increase, by approximately 26 Pg C by 2115, as a result of climate change, potentially providing an offset to emissions from other sectors. Reduced warming from climate mitigation in the energy sector leads to a smaller increase in forest outputs and a reduction in the sink capacity of forests of around 12 Pg C by 2115.

2.3. Integrated agriculture and forestry analyses
Studies simultaneously modeling climate impacts on both agriculture and forests are limited. In this issue, Beach et al (2015) integrate output from biophysical models simulating changes in US crop and forest yields under the climate scenarios described in Monier et al (2015), in an economic optimization model of the US agricultural and forestry sectors. At a spatially disaggregated level, this approach simulates interactions between different land uses, transfers between sectors, and the resulting implications for market outcomes. Focusing on the differences between high and low GHG emission scenarios, Beach and colleagues find that global GHG mitigation: (a) generally results in higher agricultural yields across most crop types, leading to lower crop prices, with modest differences across scenarios accounting for natural variability, (b) provides larger benefits to many irrigated crops compared to dryland management, regardless of climate model choice, (c) results in changes in forest productivity that ranged from small positive to small negative impacts from mitigation across climate models, and (d) provides cumulative net welfare gains to society of about $50.5 billion for the 2015–2100 period (using 3% discount rate).

3. Synthesis of findings
Together, the papers in this focus issue provide a new avenue by which to assess the risks of climate change from different scenarios by focusing on the opportunity of avoiding potential future damages through climate mitigation. One of the key takeaways of this focus issue is that despite use of different methodological approaches and the inherent variability of impacts on the heterogeneous global agricultural sector, all studies that examined agricultural yields found net benefits to crop yields associated with global reduction in GHG emissions for their region of focus (US, EU, or global). There was considerable variability between the econometrically-derived yield projections

4 This reflects the fact that the climate models used tended to have relatively greater levels of precipitation in key crop production regions under the scenario with greater climate change. Therefore, reductions in precipitation under the mitigation scenario partially offset the benefit from lower temperatures for dryland crops.
described in Sue Wing et al (2015) and the process-based model yield projections presented in Beach et al (2015) and Wiebe et al (2015). There was also variability across process-based crop models, consistent with the findings of crop modeling intercomparison exercises (Rosenzweig et al 2014). In addition, there was a great deal of spatial and temporal heterogeneity in the magnitude and often sign of yield impacts within a study, and between studies. Unlike agriculture, forest productivity was found to decrease under mitigation scenarios relative to unconstrained climate change in both Kim et al (2017) and Tian et al (2016), while Beach et al (2015) had a mix of increasing and decreasing forest productivity depending on the climate model used.

In addition to the biophysical impacts of GHG mitigation on crop and forest productivity, four of the papers in this issue explore market responses to those impacts and demonstrate the importance of accounting for economic behavior by landowners. Landowners shift between land uses and management strategies in response to changes in expected net returns under different climate scenarios. Decisions by individual producers result in endogenous changes in regional and global average yields, production, prices, and trade that have major implications for US agricultural markets (Beach et al 2015, Sue Wing et al 2015), global forest stocks and harvests (Tian et al 2016), and global food security (Wiebe et al 2015). Several papers (Monier et al 2016, Kim et al 2017, Tian et al 2016, Beach et al 2015) utilize an framework of climate projections considering uncertainty sources including: GHG emissions, climate sensitivity, natural variability, and assumptions regarding CO₂ fertilization. Results across these studies show how uncertainties surrounding future impacts are better constrained when using such ensembles. While such approaches have not been standard in past impact studies, increasing availability of ensemble member results from global climate and Earth system model simulations should facilitate greater exploration of how these multiple dimensions of uncertainty affect our understanding and confidence in climate impact projections.

While scientific understanding has advanced, the magnitude of plant response to increased CO₂ concentration in the atmosphere remains a significant source of uncertainty. A common method to explore the magnitude of this effect was to conduct simulations both with and without CO₂ fertilization considered in the crop modeling. This results in large differences in plant productivity projections, particularly toward the end of the century (Müller et al 2015, Urban et al 2015, Sue Wing et al 2015, Kim et al 2017).

4. Conclusion

Estimating how climate change will affect food and timber production represents an important research area as the world will need to feed and support a global population of nearly 10 billion by mid-century (UN 2015). This focus issue provides policy-relevant estimates for both biophysical (e.g. yield, change in carbon stock, land allocation) and market (e.g. crop and timber prices, consumer and producer welfare) metrics. Further, the papers of the issue should serve as a basis for future work in a number of important areas for further research:

Climate projections: characterization of changes in the probability of extreme events; information on how concentrations of ozone and other air pollutants that affect plant growth vary under alternative climate scenarios; and narrowing the range of uncertainty for spatial projections of precipitation, in particular given the outsize influence of water availability on agricultural and forest productivity.

Sectoral models: better understanding structural uncertainties across crop simulation models; comparing the results of econometric simulation with crop simulation models for assessing productivity changes; assessing climate impacts on livestock (both direct heat stress and indirect impacts of changing crop and pasture productivity); assessing potential impacts of changing rates of extreme events on optimal forest management, crop failure, and food security; examining implications of changing rates and magnitudes of wildfire, disease, and pest outbreaks; narrowing uncertainties around the magnitude of CO₂ fertilization impacts on different types of crops, grasslands, and forests; and understanding how climate change affects the way food, feed, fiber, fuel, and forest products will be produced in the future.

Economic models: improving representation of adaptation in both crop and timber models; further examining interactions between alternative land uses at the national, regional, and global levels; more exploration of the implications of environmental, trade, and other policies; improved characterization of extreme events and decision-making under uncertainty; and better accounting for interactions with other key impact sectors (e.g. water resources, energy production).

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References

Asseng S et al 2013 Uncertainty in simulating wheat yields under climate change Nat. Clim. Change 3 827–32

5 Noting that Sue Wing et al (2015) and Beach et al (2015) were driven with a consistent set of emission and climate projections, while Wiebe et al (2013) used different inputs, making a direct comparison with that study more difficult.
