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Climate change impacts on US agriculture and forestry: benefits of global climate stabilization

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LETTER

Climate change impacts on US agriculture and forestry: benefits of global climate stabilization

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Supplementary material for this article is available online

Abstract

Increasing atmospheric carbon dioxide levels, higher temperatures, altered precipitation patterns, and other climate change impacts have already begun to affect US agriculture and forestry, with impacts expected to become more substantial in the future. There have been numerous studies of climate change impacts on agriculture or forestry, but relatively little research examining the long-term net impacts of a stabilization scenario relative to a case with unabated climate change. We provide an analysis of the potential benefits of global climate change mitigation for US agriculture and forestry through 2100, accounting for landowner decisions regarding land use, crop mix, and management practices. The analytic approach involves a combination of climate models, a crop process model (EPIC), a dynamic vegetation model used for forests (MC1), and an economic model of the US forestry and agricultural sector (FASOM-GHG). We find substantial impacts on productivity, commodity markets, and consumer and producer welfare for the stabilization scenario relative to unabated climate change, though the magnitude and direction of impacts vary across regions and commodities. Although there is variability in welfare impacts across climate simulations, we find positive net benefits from stabilization in all cases, with cumulative impacts ranging from $32.7 billion to $54.5 billion over the period 2015–2100. Our estimates contribute to the literature on potential benefits of GHG mitigation and can help inform policy decisions weighing alternative mitigation and adaptation actions.

1. Introduction

Agricultural and forestry production are highly sensitive to climate conditions. Climate change is projected to alter the spatial and temporal distribution of temperature and precipitation as well as the frequency and severity of extreme events such as storms, flooding, drought, and wildfires as well as pest and disease outbreaks (IPCC 2013, 2014). These changes are all likely to affect future agriculture and forestry productivity, influencing the global supply of agricultural and forestry commodities. In addition to changes in mean yields, climate change has already been linked to increased yield variability that has led to greater price volatility (Diffenbaugh *et al* 2012)[9].

[9] When referring to yields, we are always defining them in terms of output per unit area, whether for crops or forestry.

Given the likelihood that future climate conditions will be outside the range of recent historical experience, landowners will likely find it more difficult to accurately assess the future risks they are facing and to successfully adapt by such means as land use change, crop switching, or modifying production practices. As a result, it may become more difficult for landowners to manage risk and domestic and global market volatility for agricultural and forest product commodities will likely increase (Wheeler and von Braun 2013).

A number of papers have explored the potential impacts of climate change on US agriculture (e.g., Adams *et al* 1990, Mendelsohn *et al* 1994, Boote *et al* 1996, Boote *et al* 1997, Reilly *et al* 2003, Schlenker *et al* 2005, 2007, Long *et al* 2006, Schlenker and Roberts 2006, Greenstone and Deschenes 2007, US Climate Change Science Program (CCSP) 2008, Beach *et al* 2010a). In addition, there have been studies examining the potential impacts of climate change on natural vegetation, including forests, in the United States (e.g., Daly *et al* 2000, Irland *et al* 2001, Bachelet *et al* 2004, Lenihan *et al* 2008, Shaw *et al* 2009). There have also been a few studies that explore climate change impacts on both agriculture and forests simultaneously, including the interactions between alternative land uses and implications for market outcomes (e.g., Irland *et al* 2001, Alig *et al* 2002). However, there is a total lack of detailed analyses of the effects of stabilization scenarios relative to unabated emissions scenarios. Such analyses are important for developing estimates of the benefits of those stabilization scenarios, which can play a vital role in assessing tradeoffs associated with allocating resources across alternative mitigation and adaptation activities.

The effects of climate change on agriculture and forests are extremely complex because of multiple vegetation types, regional and temporal differences, and interaction effects among numerous categories of impacts. For instance, a moderate increase in temperatures may positively affect growth rates of some crops, particularly if water availability is increasing, but will also tend to increase damages from weeds, insects, and elevated ozone levels (IPCC 2014). Past a certain threshold, increases in temperature are likely to have damaging effects on crop yields (Schlenker and Roberts 2006). However, below such thresholds, changes in climate in conjunction with carbon dioxide (CO_2) fertilization may result in higher yields and benefits to US agriculture (Mendelsohn *et al* 1994, Mendelsohn and Dinar 2003, Massetti and Mendelsohn 2011, Attavanich and McCarl 2014). Climate impacts are expected to become more significant in the future as temperatures more frequently exceed thresholds that result in significant reductions in crop growth and water availability becomes more severely constrained in many regions.

However, net impacts on regional and national yields could be positive or negative depending on changes in precipitation, temperature, CO_2 fertilization, and other factors relative to the baseline climate

for a given region (Adams *et al* 1990, Reilly *et al* 2003). In addition, location-specific differences in resource availability will affect adaptation possibilities. Thus, the ability of landowners to adapt to climate change impacts is expected to vary considerably across US regions. It is vital to reflect this regional variability when quantifying changes in productivity in order to obtain a more accurate picture of the national impacts.

In this study, we quantify the potential impacts of climate change on agriculture and forests based on a specific set of stabilization scenarios developed under the US Environmental Protection Agency's Climate Change Impacts and Risk Analysis (CIRA) project (Waldhoff *et al* 2015). Using a consistent set of inputs and assumptions across a large number of impact sectors, the CIRA project seeks to quantify and monetize the risks of inaction and the potential benefits (i.e., avoided impacts) to the United States of global GHG mitigation in the form of stabilization scenarios. The use of the CIRA scenarios for this study on agriculture and forestry ensures that these impacts are more directly comparable with those in other sectors of the US economy, as estimated within the CIRA framework, and provides the first instance of totally consistent agricultural and forestry responses under a stabilization scenario.

We used projected impacts of climate change on US crop yields for the period 2010–2115 from the Environmental Policy Integrated Climate (EPIC, version 1120) crop process model and forest yields from the MC1 dynamic global vegetation model (Oregon State University 2011, Bachelet *et al* 2001)[10]. These biophysical impacts were then incorporated into the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOM-GHG; Adams *et al* 2005, Beach *et al* 2010b), which is an economic optimization model of the US forest and agricultural sectors that includes land transfers between these sectors. Yield impacts were incorporated following the procedures used in Reilly *et al* (2003) and Irland *et al* (2001), which applied the percentage changes in yields under climate change estimated in biophysical models to shift the baseline yields in FASOM-GHG for climate change scenarios. Similarly, we do not calibrate FASOM-GHG yields to match those in EPIC or MC1, but assume that the relative yield changes simulated in those models can be used to represent the impacts of climate change within FASOM-GHG. The use of FASOM-GHG captures interactions between alternative land uses at a spatially disaggregated level for the US. In applying the CIRA GHG emission and climate scenarios, we are able to compare the estimated economic impacts of unmitigated climate change and GHG mitigation on US agriculture and forests in the

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[10] Although EPIC generated impacts through 2115, the current version of the FASOM-GHG model only reports outputs through the end of the century. Thus, we do not present results for economic impacts past 2100.

form of a stabilization scenario as part of a coordinated, multi-sector set of analyses.

2. Emission scenarios and climate projections

Emissions scenarios for the CIRA project were developed using the Massachusetts Institute of Technology's Integrated Global System Model (IGSM) version 2.3 (Dutkiewicz *et al* 2005, Sokolov *et al* 2005). Descriptions of the specific scenarios developed are provided in Paltsev *et al* (2015) and Waldhoff *et al* (2015).

We use two of the CIRA emissions scenarios. The first is the Reference scenario, where global emissions are unconstrained and a total radiative forcing of 10 W m^{-2} is reached by 2100. The second is a stabilization scenario with a total radiative forcing of 3.7 W m^{-2} by 2100 (labeled Policy from now on)[11]. For the purposes of this paper, we do not incorporate any incentives for GHG mitigation from the US forestry or agriculture sectors (including bioenergy expansion; biofuels volumes required under the US Renewable Fuel Standard (RFS) are included in all scenarios, but there are no policy incentives included for increasing volumes above RFS levels); RFS biofuels volumes are included in all scenarios), implicitly assuming that mitigation under the Policy scenario takes place in other regions and sectors. This enables us to focus specifically on the benefits of global mitigation for the sectors due solely to changes in climate impacts.

The climate projections used in this analysis were developed using the IGSM Community Atmospheric Model (CAM) framework (Monier *et al* 2015). The IGSM-CAM, which projects a relatively wetter future for Eastern and Central regions of the contiguous United States than historical conditions, was simulated five times for each scenario using slightly different initial conditions to generate five ensemble members[12]. Because there are major uncertainties associated with future climate projections and substantial variability across GCMs (Beach *et al* 2010a), we also used another climate projection from a GCM that tends to be comparatively drier to provide another comparison point and a more balanced assessment, the Model for Interdisciplinary Research on Climate (MIROC3.2-medres). The IGSM pattern scaling

methodology was employed to develop a balanced set of regional patterns of climatic change (see Monier *et al* 2015, for methodological details and comparisons amongst the different projections). This approach preserves all of the CIRA socioeconomic and emission drivers, but for an alternative set of climate conditions. Additional detail regarding the climate projections is provided in the online supplementary material.

3. Methods

The climate projections for each emission scenario were used in the biophysical simulation models. Gridded results for temperature, precipitation, vapor pressure, and other climate characteristics were mapped to be consistent with the spatial disaggregation necessary for use in the EPIC crop simulation model (Williams 1995) and the MC1 dynamic vegetation model (Bachelet *et al* 2001, 2003) and were bias-corrected using the delta method (see Mills *et al* 2015 for a discussion of adjustments to the climate data)[13]. EPIC and MC1 were simulated under three sets of climate assumptions: (1) no climate change ('fixed climate'), (2) Reference, and (3) Policy. Percentage changes in crop and forest yields for the Policy and Reference scenarios were calculated relative to yields with no climate change. These percentage changes were incorporated into FASOM-GHG to generate results for the Reference and Policy cases associated with differences in yields relative to the baseline FASOM-GHG scenario, which does not include climate change impacts.

Differences in the FASOM-GHG results between the Reference and Policy cases were then calculated in order to assess differences in market outcomes given climate-induced shifts in regional yields, similar to previous analyses of climate change impacts on market outcomes in the US forestry and agriculture sectors that implemented yield shifts in a similar manner (see Irland *et al* 2001 and Reilly *et al* 2003), although this study focuses specifically on the benefits of mitigation rather than only the impacts of climate change. Each of these models and their application in this study are described below.

3.1. EPIC crop yield simulation
Climate data were incorporated into the EPIC model to estimate annual impacts of alternative climate scenarios on crop yields for barley, corn, cotton, hay, potatoes, rice, sorghum, soybeans, and wheat over the period 2010–2115, in addition to a baseline period of 1980-2009. The EPIC model is a field level biophysical

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[11] There are multiple methods used to calculate radiative forcing. Using the simplified equations for calculating radiative forcing, such as those defined in IPCC's Third Assessment Report and used in development of the representative concentration pathways (RCPs), the CIRA Reference scenario has a total radiative forcing of 8.8 W m^{-2} and the Policy has a value of 3.6 W m^{-2}. The CIRA scenarios are independent of the RCPs, but a comparison of the total radiative forcing indicates that our Reference has forcing a bit higher than RCP8.5 while our Policy scenario provides mitigation between that of RCP4.5 and RCP2.6.

[12] In this paper, when we refer to ensemble members, we mean the five different initializations of the IGSM-CAM model that we are using to represent natural variability within the IGSM-CAM model.

[13] EPIC was simulated at the 8-digit hydrologic unit code (HUC) level (there are about 2100 8-digit HUCs in the US, about 1400 of which have crop production in the baseline period). MC1 was simulated at a 0.5° × 0.5° grid level (latitude/longitude, ~1600 km^2 per cell). The EPIC and MC1 data were then mapped to the FASOM-GHG 6-region level covering the contiguous United States (see Adams *et al* 2005 or Beach *et al* 2010b for more information on FASOM-GHG regions).

process model that simulates crop yield/biomass production, soil evolution, and their mutual interaction given detailed farm management practices and climate data (Williams 1995). Crop growth is simulated by calculating the potential daily photosynthetic production of biomass.

Daily potential growth is based on the concept of radiation-use efficiency by which a fraction of daily photosynthetically-active solar radiation is intercepted by the plant canopy and converted into plant biomass. Daily gains in plant biomass are affected by vapor pressure deficits, atmospheric CO_2 concentrations, environmental controls and stresses such as limitations in water and nutrients. Thus, EPIC can account for the effects of climate-induced changes in temperature, precipitation, and other variables, including extreme temperature and precipitation events affecting agriculture, on potential yields. EPIC also accounts for the effects of change in CO_2 concentration and vapor pressure deficit on the radiation-use efficiency, leaf resistance and transpiration of crops (Stockle *et al* 1992a). This feature combined with EPIC's comprehensive representation of agroecosystems processes makes it able to simulate the probable effects of CO_2 and climate change on complex cropping systems that vary in soil, crops, crop rotations and management practices (Stockle *et al* 1992b)[14].

Consistent with the expectation that crop production regions may change over time under climate change scenarios, the EPIC model was used to simulate the potential migration of crops into new production areas (following Adams *et al* 2004 and Beach *et al* 2010a). In particular, crop production was simulated on potentially suitable areas within 100 km of historical production regions in all directions[15, 16].

[14] It is now well known that CO_2 fertilization response of crops can be reduced by environmental factors such as ozone damage to crops, pests, diseases and weeds that are not currently simulated by EPIC. Therefore, it is unlikely that increased CO_2 will be as ideally beneficial as simulated in EPIC based on chamber studies (Stockle *et al* 1992a, 1992b). Updating the CO_2 fertilization response equations within EPIC to reflect lower realized yield gains from higher CO_2 concentrations would tend to increase the estimated benefits of mitigation.

[15] Although we considered focusing expanded production in regions to the north of current production areas, we decided against that for two main reasons. The first is the importance of precipitation in determining yield potential. It is possible that an area to the south of an existing production region could receive sufficient additional precipitation that its yield would increase relative to the baseline even with higher temperatures. The second is that shifts in crop production depend on relative productivity of alternative crops. There could be cases where crops would move into new production regions because they are relatively less impacted by the change in climate than crops currently grown in the region. Such relative productivity effects could potentially lead to shifts in cropping patterns for individual crops that differ from the overall northward trend typically projected to occur in the US under higher temperatures.

[16] To define parameters for regions that do not contain historical production data in the model but could potentially start producing under climate change, we use the parameters from the closest region available that is producing the relevant crop/production process combination in the base period.

The entire range of potential area for each crop was simulated under both dryland and irrigated conditions for each of the IGSM-CAM ensemble members and for the MIROC climate projections as were changes in crop timing and maturity dates. The main focus was on generating results for potential yields and irrigated crop water under existing cropping practices and possible adaptations for incorporation into FASOM-GHG. These scenarios are based on climate and environmental conditions, but unconstrained by potential limits on water availability for irrigated crop use for incorporation into FASOM-GHG (see section 3.3 below), which establishes crop mix and production practices based on economic considerations and irrigation constraints.

Finally, EPIC was simulated with the CO_2 concentration pathways from each scenario (reaching about 830 ppm by 2100 under the Reference and 460 ppm under the Policy scenario) as well as with holding CO_2 concentrations constant at baseline levels (400 ppm) in both scenarios throughout the simulation period. This sensitivity analysis enables the examination of the influence of other climate impacts separately from the influence of CO_2 fertilization of crops.

3.2. MC1 forest yield simulation

The IGSM-CAM (all five ensemble members) and MIROC climate projections were incorporated into the MC1 dynamic vegetation model to assess differences in forest growth rates. MC1 is a spatially explicit gridded model that contains linked modules simulating biogeography, biogeochemistry, and fire disturbance (Bachelet *et al* 2001, 2003). The MC1 simulations (Mills *et al* 2015) accounted for the estimated effects of CO_2 fertilization on plant growth. The model was simulated annually from 2010–2115 for each of the scenarios, along with a baseline period of 1980–2009.

The variable used to capture differences in growth was net primary productivity of aboveground forest, mapped to FASOM-GHG forest types and regions. To smooth out the large level of annual variability from dynamic vegetation models like MC1 (Mills *et al* 2015) and to provide FASOM-GHG with long-term yield trends, a 30 year moving average was used[17]. The difference in forest yield was assumed to be equal to the percentage difference in net primary productivity between future years and the average for the baseline as in Irland *et al* (2001). Importantly, the effects of

[17] As noted by an anonymous reviewer, using a 30-year moving average for yields tends to smooth out the impacts of yield shocks due to extreme events and associated price shocks. However, because we have a long-term forward-looking model that does not model short-term price dynamics, we chose to rely on changes in overall trends over time to drive behavior in our model.

wildfire, pest, and disease on yield are not reflected in the net primary productivity estimates[18].

3.3. FASOM-GHG forest and agricultural sector market simulation

The effects of climate change on production, crop mix, and markets were simulated using the model FASOM-GHG for a six-region aggregation of the United States[19]. This regional differentiation is important for reflecting the different conditions across the United States and therefore generating an accurate picture of the potential national-level impacts. FASOM-GHG (Adams *et al* 2005, Beach *et al* 2010b) is a forward-looking model of the forest and agriculture sectors that simulates the allocation of land across both sectors over time and the associated impacts on commodity markets. The model solves a constrained dynamic optimization problem that maximizes the net present value of the sum of producers' and consumers' surplus over time. The model is constrained such that total production is equal to total consumption, technical input/output relationships hold, and total US land use remains constant (with some land migrating out to developed uses and becoming unavailable for forestry and agriculture). In addition, the model includes detailed accounting for changes in net GHG emissions.

Land categories included in the model are specified as follows:

- Cropland is land suitable for crop production that is being used to produce either traditional crops (e.g., corn, soybeans) or dedicated energy crops (e.g., switchgrass).

- Cropland pasture is managed land suitable for crop production (e.g., relatively high productivity) that is being used as pasture, but can be used for crops without additional improvement.

- Pasture is grassland pasture that is less productive than cropland pasture and would need to incur costs to be improved before it could be used as cropland.

- Grazed forest is woodland area used for livestock grazing. Grazed forest areas are assumed to produce

no forest products and cannot be converted to any other alternative use.

- Rangeland is unimproved land where a significant portion of the natural vegetation is native grasses and shrubs. This land is used for livestock grazing, but is considerably less productive than our other grassland categories and is not permitted to transfer to other land uses.

- Forestland refers to private timberland, which has several subcategories based on productivity, some of which can convert to cropland or pasture. Public forestland is not explicitly tracked and is assumed to remain constant over time, but supplies an exogenous amount of timber into FASOM-GHG forest commodity markets consistent with recent policy.

- Developed land is assumed to increase over time at an exogenous rate for each region based on projected changes in population and economic growth.

- Conservation Reserve Program (CRP) land is specified as land that is voluntarily taken out of crop production and enrolled in the USDA's CRP. This land is generally marginal cropland

Landowners choose how to allocate land based on the net present value of the relative returns to alternative forest types and management regimes compared with the returns to alternative crop production activities, all within constraints on land suitability for alternative activities. For instance, when a forest landowner harvests their timber, they would compare whether they could receive higher returns from reforesting (under any one of multiple potential management regimes) relative to other potential uses of their land and could decide to plant crops or convert to pasture instead of reforesting.

FASOM-GHG was run under the model's typical baseline assumptions, which include fixed climate (future climate is assumed not to change from historical averages so there are no climate change effects on yields). The yield data in FASOM-GHG was then modified relative to the fixed climate baseline using EPIC crop yields and MC1 forest yield projections under the Reference and Policy climate scenarios (all assuming full CO_2 fertilization). The percentage differences in potential agricultural and forestry yields from EPIC and MC1 were calculated for regions consistent with those in FASOM-GHG and applied to the FASOM-GHG fixed climate baseline regional crop and forest yield data[20]. Agricultural yield data are based on USDA data for historical values and projected out to 2115 to represent technological

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[18] As described in Mills *et al* (2015), wildfire-burned area, as projected using MC1, is estimated to increase across the US in both of the CIRA scenarios. Rogers *et al* (2011) similarly found very large potential increases in forest area burned by wildfires in the Pacific Northwest by the end of the century using MC1 and multiple alternative GCMs. They found that future climate change could increase area burned for the Pacific Northwest by 76% to 310%, accounting for up to 1.2 petagrams of cumulative carbon emissions by the end of the century. Further, climate change will likely change pest and disease incidence. Given this, the forestry yields used in the FASOM-GHG modeling are likely overestimates of potential future yields.

[19] The model can be run at a couple different levels of spatial aggregation, but was run using the most aggregated version for this study given resource constraints.

[20] Although the biophysical models simulate yields, we do not use the yields from those models directly. Instead, we apply the percentage changes in simulated yields between scenarios to the historical and baseline projection data in FASOM-GHG. See the supplementary material for more information on the use of EPIC and MC1 outputs to inform FASOM-GHG modeling.

improvements using annual percentage or absolute differences in yields calculated from historical data on crop yield improvements (Beach *et al* 2010b). Annual yield growth rates for crops range between 0% (rye) to 1.9% (silage), while those for livestock range between 0.4% (eggs) to 2.3% (milk). Therefore, baseline fixed climate yields in 2100 may be several times higher than in 2000 for some commodities[21]. Yields have grown rapidly over past decades and most models projecting future production include technological progress, though there is of course uncertainty regarding its magnitude. Forestry yields are assumed constant for a given management intensity classification, though landowners can shift between management intensity classifications following harvest. FASOM-GHG was solved out to 2115 in 5 year intervals, yielding a dynamic simulation of prices, production, management, consumption, and GHG emissions, along with other environmental and economic indicators[22].

As noted in section 3.1, EPIC was used to simulate potential yields in areas adjacent to historical production areas and for both dryland and irrigated production for each crop. To account for climate effects on water availability for irrigation, water supply shifts were supplied to FASOM-GHG based on data obtained from a water supply-and-demand model used in the CIRA project (Boehlert *et al* in review)[23]. However, the actual production areas, yields, outputs, and other market outcomes simulated for this study are all determined within FASOM-GHG. In addition to accommodate potential crop expansion and/or adoption of irrigation in new areas, it is also possible that production and/or irrigation for certain crops will cease in some existing production areas depending on how differences in yields and production costs affect relative profitability of different land uses.

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[21] The biophysical models hold crop characteristics constant to generate estimates of climate change impacts independent of technical progress. Thus, we are assuming that the percentage changes relative to the baseline yields are consistent with the percentage changes that would be experienced in the future even though yields would have changed. For instance, if EPIC estimated that the yield of a particular crop was reduced by 10% in 2050, but technical progress would have increased the yield of that crop by 50% by 2050 within the model, then the net yield under climate change would be a 10% reduction relative to the no climate change case, or $1.5 \times 0.9 = 1.35$ times higher than the base year.

[22] Although the model was run out to 2115, results are presented through 2100. FASOM-GHG (and many other simulation models) is typically run beyond the final year reported to reduce the influence of terminal period effects.

[23] The EPIC simulations assume that crops can be irrigated to a level that eliminates water stress, which does not capture the risk of reduced water supply in some areas. To fully capture this risk requires integration of crop modeling with hydrologic modeling to project estimates of future water supply. A full linkage with hydrologic models is outside the scope of the current study. FASOM-GHG characterizes supply and demand for water and there is an upward-sloping supply curve that increases costs of irrigation as the quantity of water used for irrigation increases.

4. Results and discussion

Our primary emphasis in this paper is assessment of the benefits of a stabilization scenario relative to unabated climate change, accounting for agriculture–forestry interactions within a market setting. A summary of results is presented below, with additional information provided in the online supplementary material.
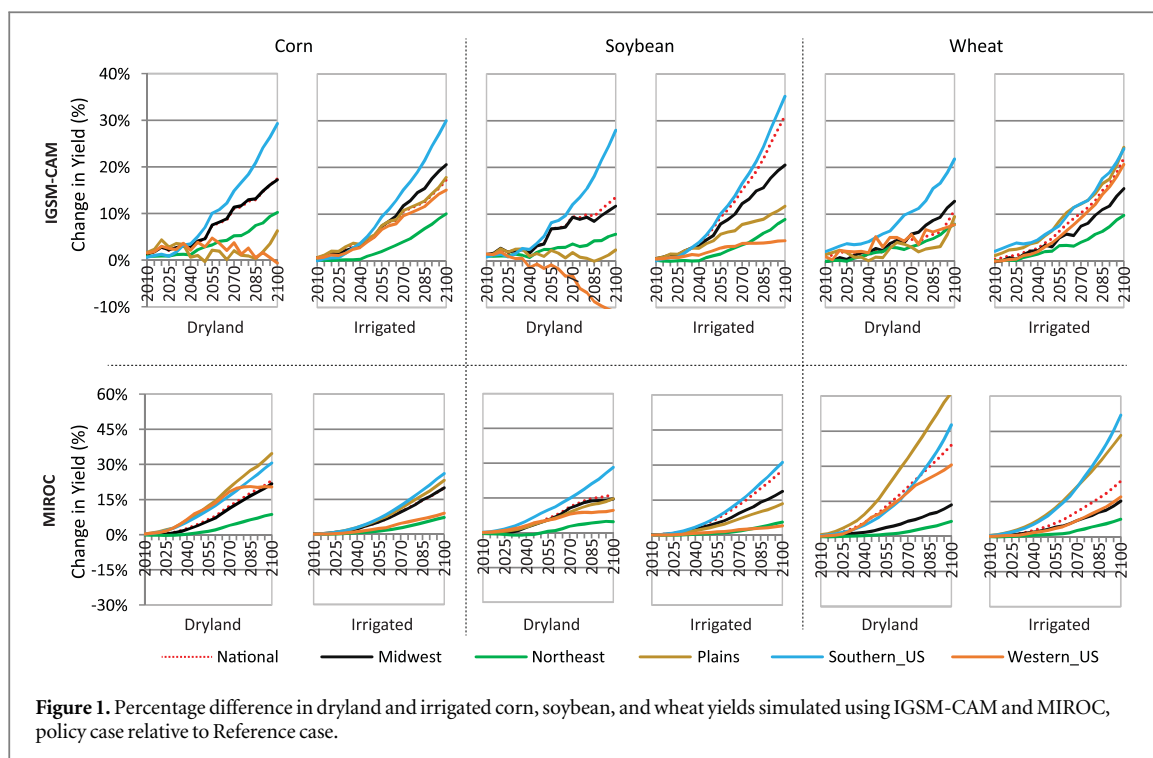
4.1. Crop yield

The biophysical simulation results reveal sizable effects on productivity from the Policy scenario relative to the Reference scenario, mostly positive but some negative. Yield impacts vary considerably across scenarios and between dryland versus irrigated areas. Generally, yields are most positively affected by the emissions stabilization scenario in the Southern US region, while the Northeast benefits the least. Greater yield benefits of stabilization in the Southern US are consistent with expectations and with the results of our Reference scenario, which indicate that the Southern US would experience some of the most negative effects on yields with unabated climate change. However, the patterns of simulated yield differences for a given climate scenario are complex and depend heavily on the individual crop, irrigation status, interactions with changes in precipitation that affect water availability, regional soils, and many other factors.

The IGSM-CAM (wetter of our two GCMs) simulations project increases in national average yields for all three of these crops under the Policy scenario relative to the Reference case for both irrigated and dryland conditions (see figure 1). The relative yield benefits of the Policy scenario increase over time across all regions for irrigated crops and across most regions for dryland crops as well. Exceptions are dryland corn and soybeans in the Plains and Western United States, where the yield gains are very small and/or flat over time and are even negative for soybeans in the Western United States. In the MIROC (drier) model, the results for both irrigated and dryland crops are consistently positive for all crops across all regions.

Wheat is typically considered a cooler weather crop than corn or soybeans. However, as shown in figure 1, percentage increases in wheat yields are less than or similar to corn and soybeans for IGSM-CAM. For MIROC scenarios, percentage increases in wheat yields are similar to or higher than corn and soybeans. In general, the level of temperature increase simulated in MIROC scenarios results in less temperature stress and more favorable conditions then the IGSM-CAM scenarios for wheat. Overall, our simulations of future differences in wheat yields are of similar magnitude to Rosenzweig *et al* (2013).

Although both Reference and Policy scenarios have similar directional effects on yields in many, but

Figure 1. Percentage difference in dryland and irrigated corn, soybean, and wheat yields simulated using IGSM-CAM and MIROC, policy case relative to Reference case.

not all (e.g., dryland hay and cotton), cases, our focus here is on the difference between the scenarios. Our study differs from Nelson *et al* (2013), for instance, in that we are focusing on the benefits of stabilization. Thus, while both Policy and Reference cases may lead to negative impacts on crop yields, consistent with their findings on potential yield effects under climate change, our focus on the benefits of *reducing* the impacts of climate change results in an improvement in yields relative to unabated climate change. Table 1 summarizes the relative difference in yields for major crops under the Policy case relative to the Reference case after the biophysical yield effects in EPIC (discussed above) are incorporated into FASOM-GHG, which determines production practices (e.g. irrigation) and the regional distribution of production based on economic optimization. Therefore, these yield effects reflect both the biophysical differences in yields and the net adjustments in production practices (e.g., irrigation) and regional distribution of production simulated in FASOM-GHG. Overall, the differences in yields tend to be fairly consistent in the direction of impacts across the IGSM-CAM and MIROC climate models, but yield impacts for dryland crops tend to be less positive or more negative under IGSM-CAM. This is consistent with the wetter model finding less negative climate change impacts and conversely, smaller benefits of avoiding climate change. Although the Policy case generally exhibits increased yields under both GCMs, IGSM-CAM and MIROC are consistent in simulating negative impacts for dryland wheat and sorghum and irrigated cotton by the end of the century. The crop that experiences the largest difference in yield impacts between the GCMs is

dryland hay, which has rising yields over time with the Policy under MIROC but falling yields over time with the Policy under IGSM-CAM.
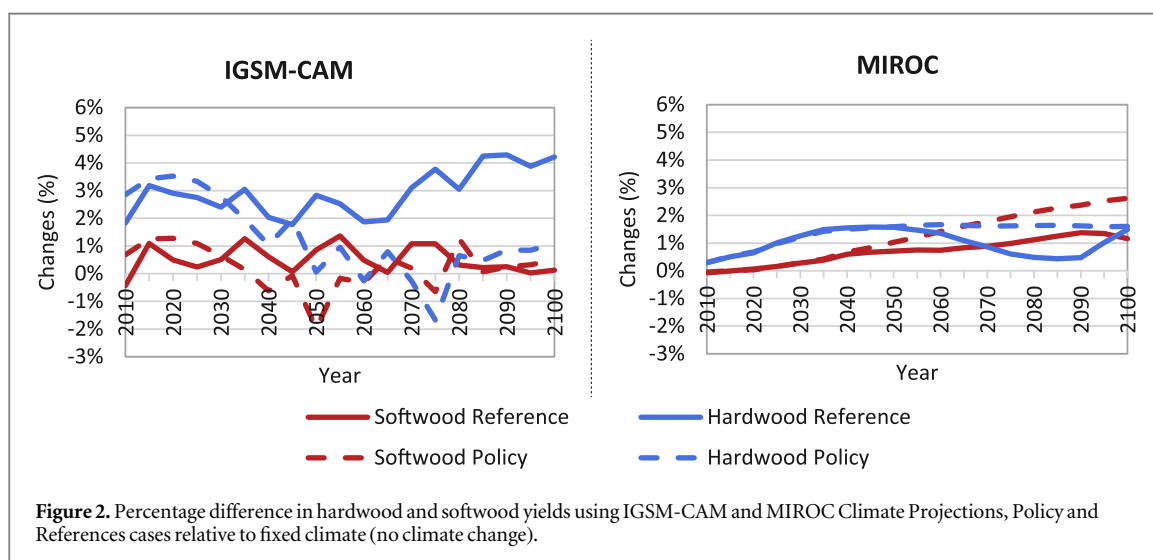
Although our primary focus in this study is on the results with CO_2 fertilization, because the literature finds there will be benefits of higher CO_2 concentrations for plant growth (Ainsworth and Long 2005, Sharkey *et al* 2007), we also conducted a sensitivity analysis to explore the impacts of climate change in isolation from CO_2 benefits. However, we found relatively small differences in the benefits of the stabilization scenario for yields with both increases and decreases in the potential yield benefits across individual crops. Refer to the supplemental online material for selected results from the EPIC scenarios simulated without CO_2 fertilization.

4.2. Forest yield

Forest productivity generally increases with climate change in our simulations, rising under both Reference and Policy cases compared with fixed climate. The yield gains using the IGSM-CAM are larger under the Reference than the Policy, especially for hardwoods, indicating that abatement would reduce yields compared with the Reference (see figure 2). One potential driver of this higher forest productivity under the IGSM-CAM Reference case in the future is likely the enhanced positive effects of CO_2 fertilization along with the response to increases in precipitation that take place across much of the forested area in the US. The MIROC climate projections, on the other hand, have higher hardwood yields under the Reference case through 2050, with abatement resulting in

Table 1. Differences in national average yields of major crops following market adjustments for both climate models, Policy case relative to Reference case (% change).
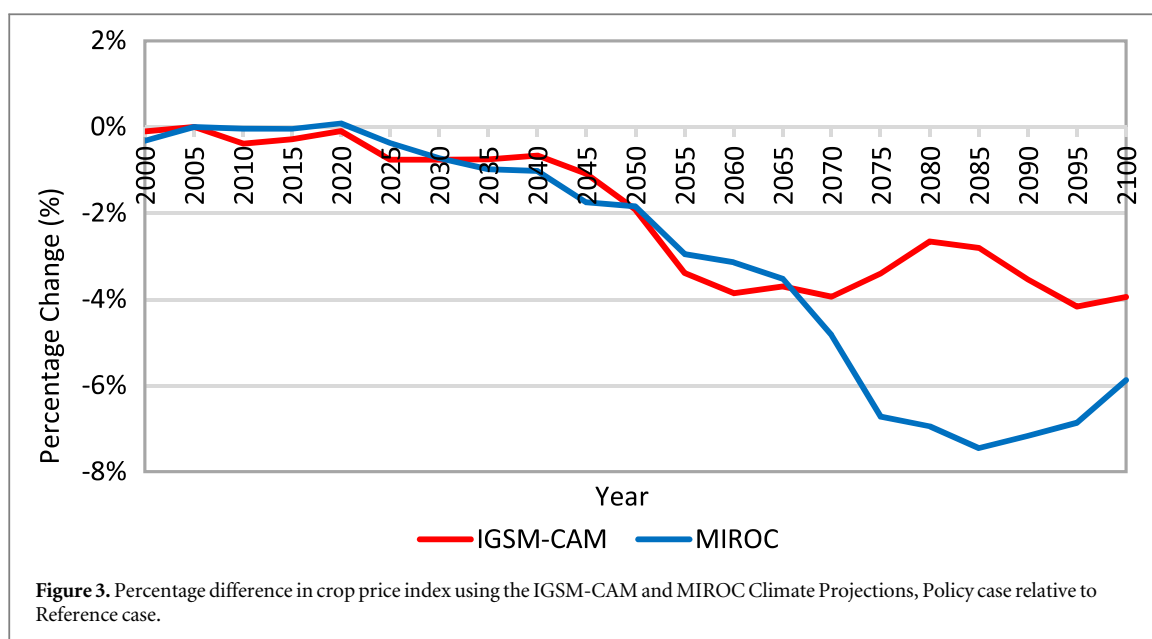
	IGSM-CAM			MIROC		
	2010	2050	2100	2010	2050	2100
Barley, dryland	1.8%	11.6%	48.7%	0.5%	11.5%	53.7%
Barley, irrigated	0.8%	10.8%	56.3%	0.2%	6.4%	35.6%
Corn, dryland	1.3%	3.9%	16.6%	0.1%	4.1%	21.8%
Corn, irrigated	0.7%	5.4%	14.7%	0.1%	4.7%	23.1%
Cotton, dryland	1.2%	−8.3%	9.5%	0.1%	7.9%	19.9%
Cotton, irrigated	−0.2%	5.2%	−4.4%	−0.2%	9.6%	−10.9%
Hay, dryland	−0.1%	−4.8%	−11.8%	−0.2%	6.1%	10.3%
Hay, irrigated	0.1%	−0.4%	1.7%	0.1%	0.2%	0.9%
Rice, irrigated	0.3%	1.2%	8.6%	0.1%	2.6%	2.7%
Sorghum, dryland	1.9%	2.5%	−6.0%	0.0%	5.4%	−4.0%
Sorghum, irrigated	0.6%	7.8%	12.2%	0.1%	4.2%	19.9%
Soybeans, dryland	1.3%	3.5%	14.1%	−0.1%	4.5%	14.2%
Soybeans, irrigated	0.0%	7.0%	32.4%	0.1%	5.9%	43.8%
Wheat, dryland	0.9%	0.8%	−1.6%	0.3%	4.2%	−0.6%
Wheat, irrigated	0.2%	9.0%	10.3%	0.1%	1.9%	75.2%

Figure 2. Percentage difference in hardwood and softwood yields using IGSM-CAM and MIROC Climate Projections, Policy and References cases relative to fixed climate (no climate change).

higher yields in 2060 and beyond. For softwoods, MIROC results show little differentiation until 2045, when abatement begins to result in higher yield growth and maintains that advantage through 2100. These gains from the Policy case in later years may stem from the increasingly negative effects of the hotter and drier future under the MIROC GCM. It is important to note that these yield estimates do not include the effects of wildfire, which would likely decrease simulated productivity, especially under unmitigated climate change (Rogers *et al* 2011, Mills *et al* 2015). Our results on potential changes in forest productivity in the US are much more positive than some European studies. For instance, Hanewinkel *et al* (2013) finds that between 21%–60% of European forestlands will be suitable only for a low-valued oak forest by the end of the century. One reason for such differences is that we placed more restrictions on the ability of forests to switch types based on standing inventory and economic considerations rather than permitting changes

in forest types based primarily on ecological considerations.

In contrast, our study of the US has much smaller negative or even net positive impacts on forests due to CO_2 fertilization that largely outweighs negative climate impacts and reallocation of forests amongst other marketable species. This result is consistent with Kirilenko and Sedjo (2007), who examined the potential impacts of climate change on global forestry. They found that there may be sizable impacts on global forestry production due to climate change as forests shifted towards the poles, but that the United States may face relatively small net impacts of climate change on the forestry sector due to the large stock of existing forests across multiple climate zones, rapid technological change in timber production, and the ability to adapt quickly. Susaeta *et al* (2014) examined the impact of climate change and new disturbance regimes for timber production in the US South and found that the net impacts depended on tradeoffs between increased

Figure 3. Percentage difference in crop price index using the IGSM-CAM and MIROC Climate Projections, Policy case relative to Reference case.

forest productivity and higher probabilities of loss due to disturbances. When landowners were able to adapt through switching tree species and other adjustments, Susaeta *et al* (2014) found that it was possible for them to substantially reduce potential losses or even experience net benefits. The fact that our forest yield impacts are relatively small in magnitude and can be higher under the Reference case than Policy case for some region/climate scenario combinations is consistent with our model reflecting the higher productivity associated with climate change, but not capturing the change in disturbances other than through the impact of fire on average yields.

4.3. Crop prices

Consistent with the observed differences in yields over time and across crops, global GHG mitigation under the Policy scenario generally results in lower crop prices compared to the Reference case, although there is almost no difference through 2020 and prices do not really start diverging substantially until 2050. The differences in prices becoming more sizable over time is reflective of the increasing climate change impacts on yields and hence the greater impact of avoiding them through stabilization.
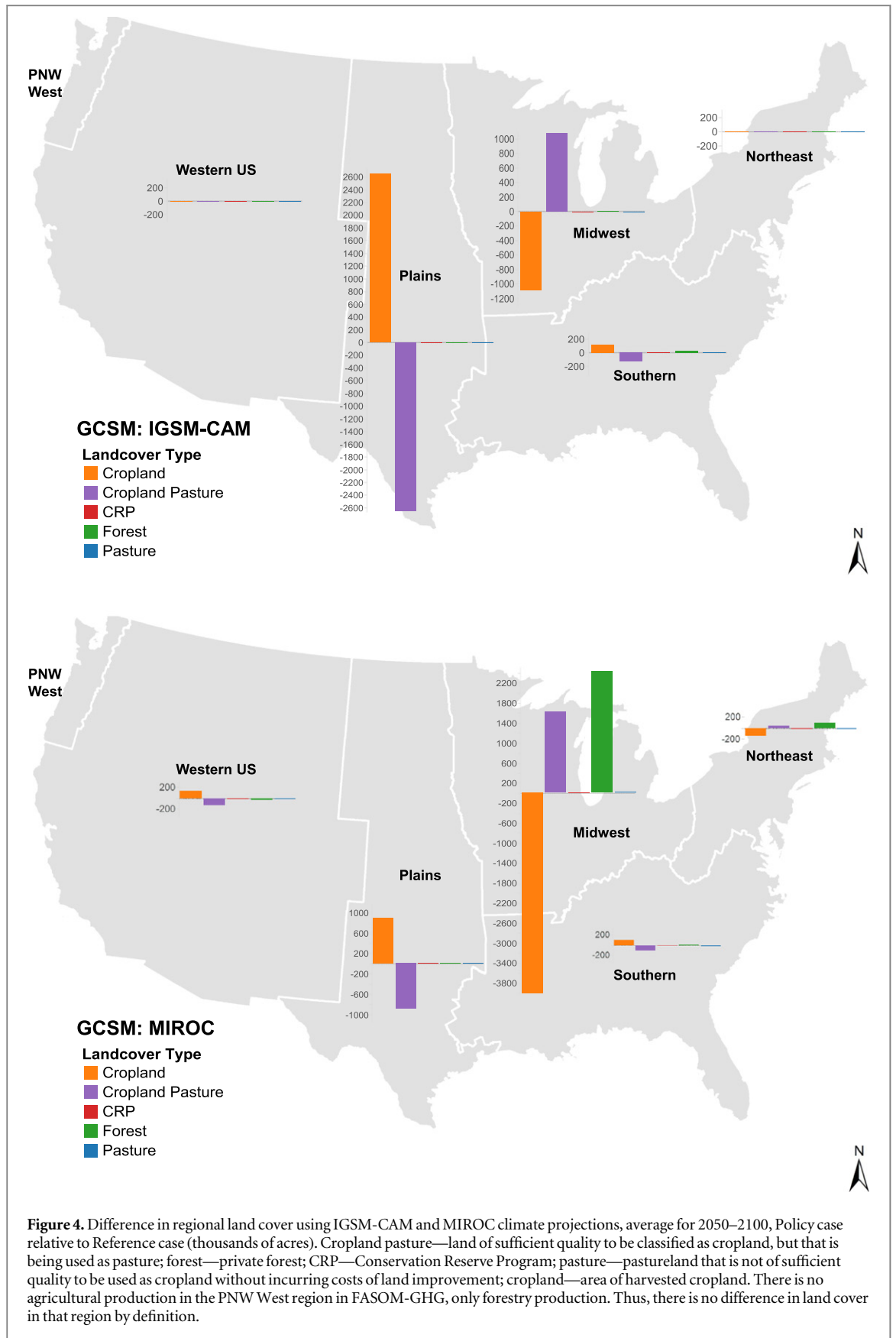
A decline in prices does not necessarily have to be the outcome of higher yields, but often results from the greater production efficiency experienced leading to higher production volumes. That is what we are seeing in our scenarios, an increase in production of most commodities due to higher yields even though they are using less land in many cases. As a consequence of higher production and lower prices, US exports become more competitive and exports rise for the majority of traded agricultural commodities. The increased diversion of domestic production to export markets will tend to increase domestic prices relative

to having no increase in exports, but we are still seeing domestic prices fall over time.

Under the IGSM-CAM projections, the Policy scenario results in lower crop prices for most of the century for seven out of the nine crops directly simulated using EPIC, with hay and barley being the only crops with consistently higher prices under the Policy case. For the MIROC projections, the Policy scenario results in lower crop prices compared to the Reference case for eight out of the nine crops, with hay being the only crop with higher prices under the Policy case. Figure 3 presents the crop price index generated using FASOM-GHG, which is a weighted average of all crop price changes in the model. As would be expected, generally rising yields under the Policy case relative to the Reference case result in less pressure on land resources and declining commodity prices. Because MIROC has more positive impacts on yields overall, it is not too surprising that the crop price index declines more under MIROC than under IGSM-CAM.

4.4. Land cover

The differences in expected yields and prices as well as in yield and price variability for both crops and forests between the Policy and Reference scenarios result in differences in acreage allocation. Figure 4 presents the average simulated differences in land cover at the regional level under both IGSM-CAM and MIROC climate conditions over the latter half of this century. Overall, the higher crop yields experienced under the Policy case compared with the Reference result in less cropland being brought into production relative to the Reference case under MIROC climate conditions, as less land is required to meet demand. Cropland tends to convert to cropland pasture and forests, with most of the cropland reductions and forest increases concentrated in the Midwest region.

Figure 4. Difference in regional land cover using IGSM-CAM and MIROC climate projections, average for 2050–2100, Policy case relative to Reference case (thousands of acres). Cropland pasture—land of sufficient quality to be classified as cropland, but that is being used as pasture; forest—private forest; CRP—Conservation Reserve Program; pasture—pastureland that is not of sufficient quality to be used as cropland without incurring costs of land improvement; cropland—area of harvested cropland. There is no agricultural production in the PNW West region in FASOM-GHG, only forestry production. Thus, there is no difference in land cover in that region by definition.

Under IGSM-CAM climate conditions, there is a small net increase in cropland, occurring primarily in the Plains region, while the Midwest experiences a

decline in cropland. Forest productivity is relatively higher under the Policy scenario under MIROC climate conditions but is just the opposite for IGSM-

CAM, which influences decisions about land conversion based on the relative profitability of alternative land uses.

The changes experienced within individual regions are up to a few million acres, but are generally relatively small in percentage terms given the large US land area. Most changes in land cover are less than 1%, though there are some exceptions such as cropland pasture in the Plains region, which declines by almost 13% in the Policy relative to the Reference as that land shifts into cropland.

Reallocation of land between cropland and other uses has implications for the provision of ecosystem services, including promoting habitat and biodiversity (Lawler *et al* 2014). Given the large quantities of carbon sequestered in forests, even relatively small land movements can have sizable impacts on net GHG emissions. In addition, given that we are finding increases in crop yields under the Policy case relative to the Reference case that result in reduced demand for cropland, global stabilization may result in an increased provision of ecosystem services and wildlife habitat relative to unabated climate change. This is particularly true in the Midwest, which experiences the largest reduction in cropland. For instance, the prairie pothole region, which is important habitat for migratory birds, would potentially face less pressure to convert natural lands to cropland in the Policy case compared with the Reference case.

4.5. Crop allocation

We find substantial reallocation of where crops are grown as an adaptation in response to climate change impacts on relative agricultural productivity, consistent with adjustments found by Adams *et al* (1990, 2004, 2005) and Reilly *et al* (2003) (see figure 5). This effect is overshadowed by a general reduction in crop area, however, due to increasing yields under the Policy case relative to the Reference that results in a lower overall demand for land. Switching between crops varies across regions as production of major crops other than wheat tends to decrease substantially in the major production center of the Midwest and shift to the Northeast, Plains, and Southern United States. Under IGSM-CAM, there is movement of cotton from the Midwest to the Plains region and 'other crops' moving from the Midwest and Plains regions to the Northeast and Southern regions. Hay and wheat tend to be expanding in multiple regions as they have relatively low or even negative yield impacts under the Policy case, resulting in a demand for more land to meet demand for those commodities. Under MIROC, we see sorghum moving from the Western US, Midwest, and Northeast into the Plains region, while 'other crop' shift from the Midwest and Northeast to the other three regions. As with IGSM-CAM, wheat is again increasing in most regions given

its relative lack of yield benefit from the Policy case. Hay, on the other hand, experiences a net decrease in area under MIROC, with a large decrease in the Midwest and only small increases in the Plains and Northeast as the net increase in hay yields results in decreased demand for hay land area relative to the Reference.

4.6. GHG emissions

As is readily apparent from figure 6, the IGSM-CAM results show large increases in net GHG emissions from agriculture and forestry under the IGSM-CAM Policy case, almost all of which are due to differences in forest management (i.e., net carbon losses or reduced gains in carbon storage on existing forestland)[24]. Under the IGSM-CAM projections, the generally lower forest productivity under the Policy scenario results in substantially less forest carbon sequestration over time because of the direct effects of slower forest growth (less sequestration). Under MIROC climate conditions, however, forests become a larger sink under the Policy than occurs in the Reference case as forest productivity is enhanced. Emissions from livestock rise under the Policy case for both GCMs as higher crop yields result in lower feed prices and expanded livestock production, but GHG emissions related to crop production are generally declining as less area is devoted to crops, given the higher yields. As is often the case in assessing agricultural and forestry sector emissions, changes in forest carbon sequestration greatly outweigh all other sources. In this case, differences in forest productivity effects between the GCMs analyzed yield opposite signs for the change in net GHG emissions with GHG stabilization Policy.

One clear implication is that the climate model used has a profound influence on the estimated change in net GHG emissions. Our findings are consistent with a major difference in precipitation patterns observed across these models. While the MIROC model tends to have more precipitation under the Policy case than the Reference case for many key forest-growing regions, the IGSM-CAM model is just the opposite. The effect on forest growth rates and associated carbon storage is reflected very clearly in figure 6. While climate conditions such as those under IGSM-CAM would reduce the US LULUCF sink, conditions such as those under MIROC would increase it, other things being equal.

Figure 6 is showing only the change in cumulative emissions, however, not the absolute emissions. Total US GHG emissions from agriculture and forestry, land use, and land use change are estimated at about -343 MT CO_2eq in 2013 (USEPA 2015) (forestry sink more than outweighs emissions so net emissions from those sectors are currently negative). FASOM-GHG does

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[24] We do not incorporate feedback of these changes in emissions into the calculation of climate impacts in this study.
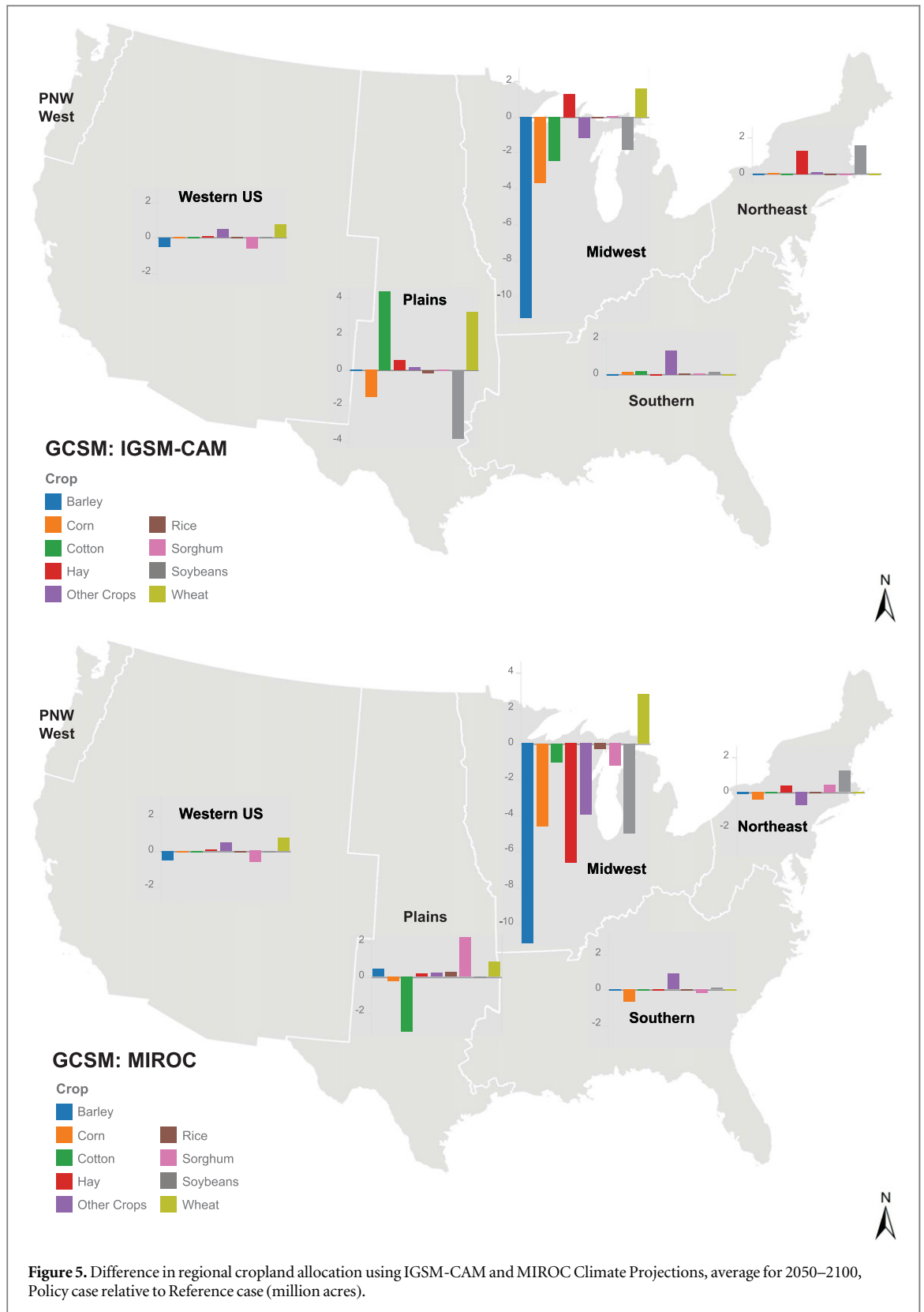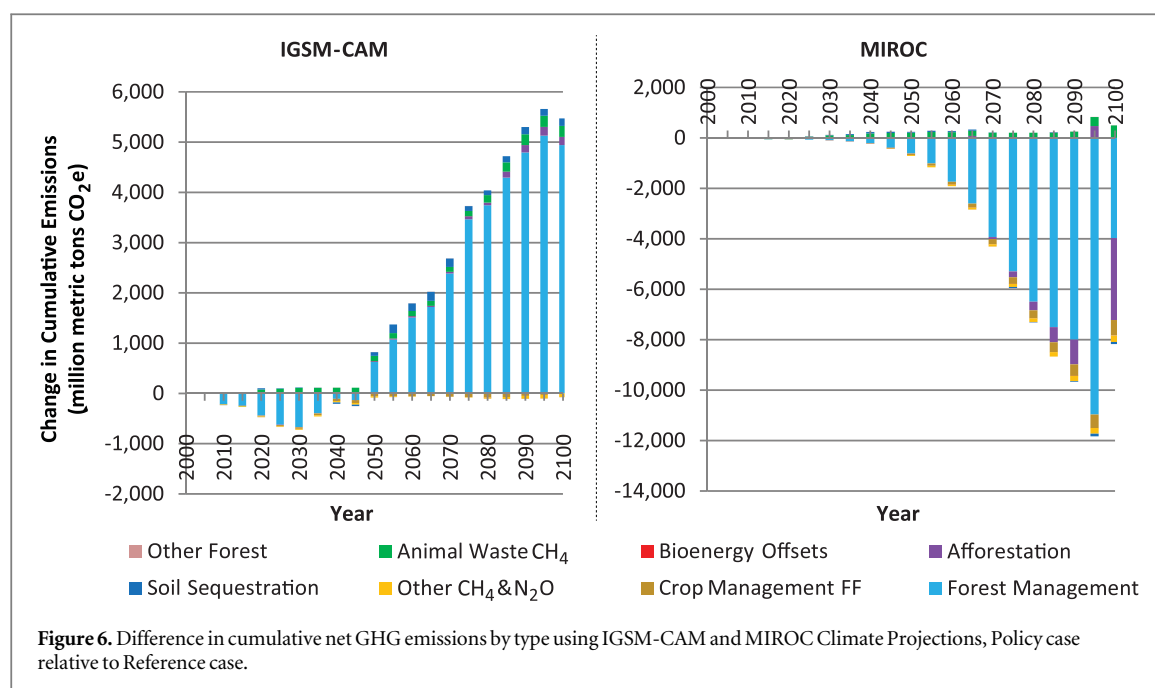
Figure 5. Difference in regional cropland allocation using IGSM-CAM and MIROC Climate Projections, average for 2050–2100, Policy case relative to Reference case (million acres).

not fully capture all emissions components that are in the US inventory, but based on the average cumulative changes from 2015–2100 (cumulative net source of 5394 MT CO$_2$eq for Policy relative to Reference over 90 years, or average of 59.9 MT CO$_2$eq increase in net GHG emissions per year over that timeframe), the average change under the Policy with IGSM-CAM is

equal to a reduction in the 2013 net sink by about 15–20%. Under MIROC, on the other hand, the Policy scenario provides a cumulative net sink of about 7685 MT CO$_2$eq, or an average sink of about 85.4 MT CO$_2$eq, which is equal to about 40% of the US sink from these sectors in 2013. Other things being equal, the effect of the Policy on net US GHG emissions will

Figure 6. Difference in cumulative net GHG emissions by type using IGSM-CAM and MIROC Climate Projections, Policy case relative to Reference case.

Table 2. Present value of cumulative differences in consumer and producer welfare using IGSM-CAM climate projections, Policy case relative to Reference case, 2015–2100 (million $2005).

	Consumer surplus			Producer surplus			TOTAL		
	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum
Agriculture	$6318	$24 921	$37 077	−$4330	$11 224	$27 168			
Forestry	−$162	$57	$440	$29	$298	$782			
TOTAL	$6211	$24 978	$36 915	−$4151	$11 522	$27 495	$32 764	$36 500	$43 100

Note: Agriculture + Forestry does not necessarily sum to totals because the table is independently calculating minimum, average, and maximum values for agriculture, forestry, and the combined totals across the five IGSM-CAM initializations.

become larger over time as seen in figure 6, though the percentage impact will depend on the evolution of the US inventory over time.

4.7. Welfare

The differences in prices and the level of production and consumption will lead to impacts on the economic welfare of consumers and commodity producers. One common method of measuring these effects on well-being is in terms of differences in economic surplus, which is a monetary measure of welfare. Consumers' surplus is the difference between the maximum amount consumers would have been willing to pay for a commodity and the actual price paid, whereas producers' surplus is the difference between the minimum amount producers would have accepted to supply a commodity and the actual price received.

Overall, the results of this study show that stabilization results in transfers from producers to consumers as commodity prices decline for goods with relatively inelastic demands. Although the magnitude and temporal distribution of benefits under the Policy case vary across the IGSM-CAM model initializations and MIROC projection, each of our scenarios results

Table 3. Present value of cumulative differences in consumer and producer welfare using MIROC climate projections, Policy versus Reference case, 2015–2100 (million $2005).

	Consumer surplus	Producer surplus	TOTAL
Agriculture	$52 665	−$2809	
Forestry	−$138	$777	
TOTAL	$52 527	−$2032	$50 495

in cumulative net gains to consumers that more than outweigh any losses to producers, as has been found in prior studies (e.g., Irland *et al* 2001). Based on the MC1 and EPIC simulated impacts on forest and agricultural productivity, the Policy case results in sizable increases in overall yields and reduced commodity prices compared to unabated climate change in the Reference case. As shown in tables 2 and 3, reducing global GHG emissions under the Policy case is found to increase total surplus in the forest and agriculture sector by a cumulative $32.7 billion to $54.5 billion for the 2015–2100 period across the two GCMs and the different model initializations of IGSM-CAM. The magnitude of welfare impacts in the agricultural sector are much larger than in the forestry sector.

There have been several previous studies examining the potential economic impacts of climate change on US agriculture, but many focus only on major crops, they do not necessarily report national welfare values, and they do not explicitly examine the benefits of mitigation. For instance, Reilly *et al* (2003), using predictions from GCMs from the Canadian Center Climate Model and Hadley Centre Model found that climate change from 2030–2090 would have positive impacts on welfare ranging between $0.8 billion (2000 $) in 2030 and $12.2 billion in 2090. The main driver of these productivity gains were projected increases in precipitation levels under climate change. Greenstone and Deschenes (2007) also found positive climate change impacts using the Hadley model, estimating an increase of $1.3 billion. Schlenker *et al* (2005) find much more negative impacts, estimating that economic effects of climate change on agriculture need to be assessed differently in dryland and irrigated areas and that pooling the dryland and irrigated counties could potentially yield biased estimates. Based on available data, they estimate the model for dryland counties and the estimated annual losses are about $5 to $5.3 billion for dryland non-urban counties alone. Temperature increases affect crop responses in a non-linear fashion. Using a 55 year panel data on crop yields, Schlenker and Roberts (2006) found increases in crop yields (for corn, soybeans, and cotton) with higher temperatures until reaching threshold values. Their results show very large decreases in crop yields toward the end of the century as temperatures exceed these threshold levels. The study estimates that yields of these three crops are expected to decline by 25–44% under a slow warming scenario and 60–79%, respectively, under a quick warming scenario at the end of the century. Thus, the negative effects on agriculture could become very large in the long-term future if temperatures begin to reach threshold levels.

In general, the findings from previous studies have depended heavily on the net changes in precipitation experienced under climate change, but the welfare results from this study fall within the general range of estimates that have been generated.

5. Conclusions

Our analytical approach of a combination of climate models, a crop process model, a dynamic vegetation model, and an economic model of the forest and agricultural sectors was applied to a Reference and Policy case, enabling us to conduct an integrated assessment of the potential benefits of climate stabilization on US forests and agriculture. The results of this paper are generally consistent with published studies focused on impacts in these sectors. Projections of adverse yields resulting from unmitigated climate change, large regional differences in crop response, increasing vulnerability of water supplies for irrigation, and the ability of adaptation to reduce adverse effects are consistent with the findings of the major climate science assessments (e.g., Nelson *et al* 2013, Hatfield *et al* 2014). However, our results augment previous studies through the use of an integrated forest and agricultural model to study the potential benefits of GHG mitigation, which can help inform policy decisions weighing the relative costs and benefits of mitigation and adaptation strategies.

First, global GHG mitigation generally results in higher agricultural yields across most of our disaggregated crop types compared to the unabated climate change scenario, even across different climate models, largely though avoiding decreases in yields due to climate change. The majority of the yield benefits occur after 2050, though, as the Reference climate impacts being avoided by Policy are relatively smaller over the next few decades and increase over time. Second, under both contrasting futures for precipitation in the United States, many irrigated crops benefit more from mitigation than dryland crops. In general, irrigated crops tend to gain from the reduced temperatures while being unaffected by changes in precipitation since they already irrigate to meet their water needs. This demonstrates the importance of assumptions concerning water availability and incidence for irrigation. Third, the effect of global GHG stabilization on projected forest yields is substantially (almost an order of magnitude) less than estimated differences in crop yields, and the direction of the effect depends strongly upon climate model and forest type (hardwood versus softwood). Consistent with the findings on crop prices, the majority of the impacts are concentrated in 2050 and beyond. One important caveat to that finding is that this study is using smoothed trends of forest productivity and does not reflect increases in disturbances such as pest damages, which may influence forest investment decisions when the possibility of large capital losses are reflected. Fourth, the impacts of climate change and the effects of stabilization are not equally distributed, with variations depending upon crop type, irrigation status, forest vegetation type, and other factors. This finding is consistent with previous studies that found that there may be modest agricultural impacts of climate change in the United States at the national level, but substantial distributional effects (Beach *et al* 2010a). Fifth, because of the positive impacts on crop yields, global GHG mitigation is projected to lower crop prices in general compared to the Reference scenario. This creates substantial benefits of mitigation for consumers that outweigh the losses incurred by producers. Sixth, we find a significant effect on net GHG emissions that is highly dependent on the climate scenario used for forestry yields. While the MIROC Policy case raises forest yields and increases the size of the US sink from agriculture and forests, IGSM-CAM has exactly the opposite effect. Additional work to refine estimates of the changes in forest carbon associated with mitigation

policy would be valuable and could be one piece of a larger future research effort to assess interactions between mitigation and adaptation activities. Finally, another interesting finding is that there are gains to consumers that outweigh losses to producers under our mitigation scenarios. Although producers may receive higher yields under the Policy scenario, it does not necessarily mean that they will become more profitable. In fact, the opposite is often the case. When yields rise for a large group of products making inelastic goods such as most food commodities, the price will tend to fall by more than the quantity sold rises, leading to a drop in revenue and profits. Depending on the structure and incidence of the costs of a potential mitigation policy, producers could be concerned about bearing costs of mitigation while also losing producer surplus due to the change in climate impacts, which may be a consideration for policy design.

One limitation of this study is that it does not reflect climate change impacts on international forests and agriculture, which would also affect relative returns to different uses of land and trade patterns and therefore affect land use decisions (Leclère *et al* 2014). For instance, including negative impacts on yields in the rest of the world would tend to drive up global prices and make US exports more competitive. Also, numerous uncertainties remain regarding issues such as future changes in crop technology, energy policy, and other interactions that will substantially affect market outcomes, which is one rationale for conducting model comparisons (Nelson *et al* 2013). The use of just one crop process model, one biophysical forest simulation model, and one market model, each of which contain their own structural uncertainties, should be noted given the importance of these uncertainties raised in recent model intercomparisons (Nelson *et al* 2013, Rosenzweig *et al* 2013). Finally, this analysis omits important aspects of climate change impacts to agriculture and forestry, including damages from extreme weather events, wildfire, and changes in weeds, pests, disease, and ozone damage. Additional research is necessary to better characterize and understand a variety of model uncertainties, explore the interactive effects between land-using sectors in more detail, and incorporate additional interactions with international markets.

Acknowledgments

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