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LETTER

Assessing climate change impacts, benefits of mitigation, and uncertainties on major global forest regions under multiple socioeconomic and emissions scenarios

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Abstract

We analyze a set of simulations to assess the impact of climate change on global forests where MC2 dynamic global vegetation model (DGVM) was run with climate simulations from the MIT Integrated Global System Model-Community Atmosphere Model (IGSM-CAM) modeling framework. The core study relies on an ensemble of climate simulations under two emissions scenarios: a business-as-usual reference scenario (REF) analogous to the IPCC RCP8.5 scenario, and a greenhouse gas mitigation scenario, called POL3.7, which is in between the IPCC RCP2.6 and RCP4.5 scenarios, and is consistent with a 2 °C global mean warming from pre-industrial by 2100. Evaluating the outcomes of both climate change scenarios in the MC2 model shows that the carbon stocks of most forests around the world increased, with the greatest gains in tropical forest regions. Temperate forest regions are projected to see strong increases in productivity offset by carbon loss to fire. The greatest cost of mitigation in terms of effects on forest carbon stocks are projected to be borne by regions in the southern hemisphere. We compare three sources of uncertainty in climate change impacts on the world's forests: emissions scenarios, the global system climate response (i.e. climate sensitivity), and natural variability. The role of natural variability on changes in forest carbon and net primary productivity (NPP) is small, but it is substantial for impacts of wildfire. Forest productivity under the REF scenario benefits substantially from the CO_2 fertilization effect and that higher warming alone does not necessarily increase global forest carbon levels. Our analysis underlines why using an ensemble of climate simulations is necessary to derive robust estimates of the benefits of greenhouse gas mitigation. It also demonstrates that constraining estimates of climate sensitivity and advancing our understanding of CO_2 fertilization effects may considerably reduce the range of projections.

1. Introduction

Climate change is underway and in the last century almost the entire globe has experienced surface warming (Stocker *et al* 2013). Over 31% of global land surface is forested, though the forested area has steadily declined by 3% over the last 25 yr (World Bank 2016) largely due to competition with agriculture. Forests provide an array of ecosystem services to society, including direct products such as timber, plant and animal products, tourism and recreation; and indirect products such as watershed protection and, critical to climate change, carbon storage (Pearce 2001). However, the future of forests is uncertain, as forest ecosystems are vulnerable to climate change even under low-warming scenarios (Scholes *et al* 2014).

The future of the world's forests will be shaped by multiple driving forces that will have complex interactions among them, including climate change, economics and development, mitigation policies, natural resource management, land use and land-use change, logging, wildfire, and insect and pathogen outbreaks. Simulating all of these drivers together in an earth system model is an ideal toward which partial progress has been made but more is needed to reach this ideal. Indeed, even the commonly used global land-use change projections under the Representative Concentration Pathways (RCP) scenarios (Hurtt *et al* 2011) do not explicitly account for natural disturbances, climate-induced vegetation migration or the impact of climate change on land productivity. Modeling frameworks that integrate both economically driven land-use change decisions and climate change impacts on terrestrial ecosystem productivity are not common and generally do not account for wildfire or pest and disease (Melillo *et al* 2009, Reilly *et al* 2012). Few studies have examined the influence of natural disturbances on future land use, but they are limited to specific regions, like Northern Eurasia (Kicklighter *et al* 2014). Therefore, there exists a need to assess the role of wildfire, climate-induced vegetation migration and productivity in relation to climate change scenarios on a global scale.

The primary objective of the present study is to assess the impacts of climate change on the world's forests, using a dynamic global vegetation model that can simulate future potential changes in terrestrial ecosystem productivity, climate-driven vegetation migration, wildfires, the resulting competition between vegetation types and the associated forest regrowth and carbon dynamics. In particular, we perform a set of uncertainty analysis to (a) assess the effect of natural variability in the climate system on projected future forest conditions, and (b) compare three sources of uncertainty in climate change projections and how they translate to climate impacts on the world's forests. The study seeks to evaluate the degree to which climate-change-induced changes in forest productivity, forest migration and fire regimes are important drivers of forest ecosystem changes that need to be accounted for in global land-use change modeling frameworks; and that the uncertainty arising from climate sensitivity and natural variability are significant at the global and regional scales. Additionally, we aim to characterize the regional differences in mechanisms of forest response to climate change, and the regional differences in the benefits of mitigating climate change, both of which can have major implications for forestry markets and management policies.

A secondary objective of this study is to provide estimates of future potential climate impacts on the world's forests using a set of emissions and climatic scenarios that are consistent with assumptions used in other efforts to assess multi-sectoral impacts—in particular, the United States Environmental Protection Agency's (EPA) Climate Change Impacts and Risk Analysis (CIRA) project. CIRA aims to evaluate the effects of global climate change on multiple economic sectors in the United States and to evaluate the benefits of greenhouse gas mitigation policies using consistent socioeconomic and climatic projections (Waldhoff *et al* 2015). There have been many simulations of potential future forest patterns and characteristics on a global scale (Cramer *et al* 2001, Gonzalez *et al* 2010, Sitch *et al* 2008), but it is problematic to use the existing simulation outputs for quantifying and comparing climate change impacts across multiple sectors, because the sets of climate change scenarios or realizations were not coordinated among the multi-sector studies. The outputs from the MC2 simulation described herein were used to drive the Global Timber Model (GTM) (Sohngen *et al* 2001, Sohngen 2014) to study the market effects of climate change on global timber markets (Tian *et al* 2016). GTM takes as input from MC2 variables that broadly characterize future potential forest conditions under the different climate change scenarios: estimates of forest productivity (e.g. net primary productivity) and carbon stock, afforestation/deforestation, and forest carbon loss to fire. The same variables are also used in this paper to characterize climate change impacts on the major forest regions of the world.

Below, we describe key facets and findings of this paper: the development of the integrated economic and climate scenarios using the MIT Integrated Global System Modeling (IGSM-CAM) framework (Paltsev *et al* 2015, Monier *et al* 2015); the calibration and validation of the MC2 dynamic global vegetation model (DGVM), given in detail; the global and regional effects of climate change under two contrasting scenarios; and an analysis of uncertainties arising from climate realizations.

2. Methods

2.1. Climate change scenarios and realizations

Our study uses an ensemble of climate change projections simulated by the MIT Integrated Global System Model-Community Atmosphere Model (IGSM-CAM) modeling framework (Monier *et al* 2013a). The climate ensemble is composed of different emissions scenarios (unconstrained versus stabilized radiative forcing), different global climate system response (climate sensitivity), and different realizations of natural variability (initial conditions) (table 1). The ensemble was prepared for the US Environmental Protection Agency's Climate Change Impacts and Risk Analysis (CIRA) project (Waldoff *et al* 2015), which examines the benefits of global mitigation actions to

Table 1. Thirteen climate realizations from IGSM-CAM used as input to MC2 DGVM and their characteristics. The ensemble climate realizations is composed of different emissions scenarios (REF, POL3.7 and POL4.5), different climate sensitivity, and different natural variability (initial conditions). See section 2.1 Climate change scenarios and realizations for a detailed description of the realizations.

Realization	Climate sensitivity			Net aerosol forcing			Initial conditions				
	2	3	4.5	0.25	0.70	0.85	i1	i2	i3	i4	i5
REF-r1	■			■			■				
REF-r2		■			■		■				
REF-r3		■			■			■			
REF-r4		■			■				■		
REF-r5		■			■					■	
REF-r6		■			■						■
REF-r7			■			■	■				
POL3.7-r1		■			■		■				
POL3.7-r2		■			■			■			
POL3.7-r3		■			■				■		
POL3.7-r4		■			■					■	
POL3.7-r5		■			■						■
POL4.5-r1		■			■		■				

the United States. In the core analysis of our study, we consider two emissions scenarios: a reference scenario (REF) that represents unconstrained emissions similar to the Representative Concentration Pathway RCP8.5 scenario (Riahi *et al* 2011), and a greenhouse gas (GHG) mitigation scenario (POL3.7) that stabilizes radiative forcing at 3.7 W m^{-2} by 2100. The POL3.7 scenario was designed to fall between the RCP2.6 (van Vuuren *et al* 2011) and RCP4.5 (Thomson *et al* 2011) scenarios and is consistent with a 2 °C global mean warming from pre-industrial by 2100. We focus our analysis on the simulations with a climate sensitivity of 3 °C, and for each emissions scenario we use a five-member ensemble with different initial conditions, thus limiting the total number of climate simulations to ten and keeping our core analysis to a manageable number of MC2 simulations. We analyze the mean over the different initial conditions in order to obtain robust estimates of the anthropogenic signal and filter out the noise from natural variability, and identify the changes due to GHG mitigation. This approach allows us to account for the significant uncertainty in natural variability, highlighted in a number of studies (Hawkins and Sutton 2009, Deser *et al* 2012, Monier *et al* 2013b, 2015, 2016).

We further expand upon our uncertainty analysis by analyzing the range of climate impacts on the world's forests associated with different global climate system responses, analyzing simulations with a climate sensitivity of 2.0 °C and 4.5 °C, obtained via radiative cloud adjustment (see Sokolov and Monier 2012). We also analyze a slightly less stringent GHG scenario (POL4.5), similar to a RCP4.5.

Although the climate ensemble used in this study is derived using a single climate model, it accounts for the uncertainty in the emissions scenarios, the global climate response, and natural variability, which account for a substantial share of the uncertainty in future climate projections (Monier *et al* 2015). More details on the emissions scenarios can be found in Paltsev *et al* (2015), details on the climate projections for the US can be found in Monier *et al* (2015), and the implication for future changes in extreme events is given in Monier and Gao (2015).

2.2. MC2 dynamic global vegetation model

Dynamic global vegetation models (DGVM) simulate terrestrial biosphere's response to climate by modeling vegetation biogeography, vegetation dynamics, biogeochemistry, and biophysics (Fisher *et al* 2014). DGVMs are the best tools for representing vegetation dynamics at global scales (Quillet *et al* 2010), and have been used by many to study vegetation dynamics at global scales (e.g. Cramer *et al* 2001, Friedlingstein *et al* 2006, Sitch *et al* 2008). MC1 DGVM (Bachelet *et al* 2001) has been applied at many scales, including continental and global scales (e.g. Bachelet *et al* 2015, Beach *et al* 2015, Drapek *et al* 2015, Gonzalez *et al* 2010). MC2 is MC1 DGVM re-written in C++ to improve computing speed and code organization. The design of MC1 and MC2 is comparable in complexity with other DGVMs (Fisher *et al* 2014, Quillet *et al* 2010). MC2 design is detailed elsewhere (Bachelet *et al* 2001, Conklin *et al* 2016), thus we highlight only the essential features and limitations of MC2 here.

MC2 represents land surface as a grid. It reads as input elevation, soil, and climate data and runs on a monthly time step. In each grid cell, the terrestrial ecosystem is represented as a web of above- and below-ground carbon pools. Plant growth, carbon and water fluxes are calculated monthly, using CENTURY Soil Organic Matter Model (Parton 1996) as a submodel. In each grid cell, a representative tree and grass compete for light and water. Monthly temperature, precipitation, and vapor pressure data drive calculations of plant productivity, decomposition, and soil water balance. Net primary productivity (NPP) is calculated directly as a function of temperature and available soil water. MC2 identifies the representative tree annually using a set of biogeography rules, recognizing a total of 35 plant functional types (table S2). Simulations require extensive computing resources, and are run on a high performance parallel computing platform. MC2 simulates CO_2 effects on NPP and potential evapotranspiration (PET) as simple multipliers, which vary linearly from 350 and 700 ppm of CO_2 concentrations.

As noted in the Introduction, we recognize that forests will be shaped by a complex interaction among multiple driving forces, including an array of disturbance regimes, including land cover change, logging, fire, and insect and pathogen outbreaks. Simulating all types of disturbances is ideal, but it remains a goal yet to be achieved by the earth system modeling community. Although climate change may significantly alter disease and insect outbreaks in forests (Dale *et al* 2001), specific mechanisms of how forest, insects, and fire interact are poorly understood (e.g. Andrus *et al* 2016, Harvey *et al* 2014). More importantly, insect and pathogen outbreaks are highly variable depending on organisms involved and are difficult to model on a global scale. We are not aware of any DGVM implementation that has successfully simulated interactions among forest, insects, and fire on a global scale. In this study, we focus on evaluating the role of wildfire as a major disturbance regime. MC2 is able to simulate grazing effects on grass, but it was disabled for this study. This is a limitation common to all DGVMs (Fisher *et al* 2014, Quillet *et al* 2010).

MC2 simulates fire occurrence as a function of the current vegetation type and fuel conditions. MC2 calculates fire consumption of vegetation and the associated ecosystem carbon pools based on the current weather. Conklin *et al* (2016) provide a detailed description of the MC2 fire module.

2.2.1. *Model protocol and calibration*

We configured MC2, source code revision r87, to simulate the globe at 0.5° resolution from 1901 to 2012. We used 0.5° resolution monthly temperature, precipitation and vapor pressure data from the CRU TS3.21 Dataset (Harris *et al* 2014). Soil depth, bulk density, and texture information (% rock, sand, clay, silt) for three soil layers required by MC2 was extracted from the Harmonized World Soil Database, Version 1.1 (FAO *et al* 2009). Following established MC1 simulation protocol (Bachelet *et al* 2001), we first ran MC2 in equilibration and spinup modes using 1901–1930 climatology and detrended 1901–2012 climate data, respectively, before simulating the 1901 to 2012 period. Global simulations take many hours to run. To allow many repeated runs during the calibration process, we ran MC2 on an 11% sample of the full grid, obtained by selecting every third cell of the full grid along latitude and longitude, and then validated the model on the entire global scale.

DGVMs are highly complex models that are difficult to calibrate and standard methodologies do not exist. Perhaps for those reasons, the calibration process is rarely described in publications focused on DGVM simulation results (e.g. Bachelet *et al* 2015, Gonzalez *et al* 2010, Pavlick *et al* 2013, Poulter *et al* 2014, Prentice *et al* 2011, Quegan *et al* 2011, Shafer *et al* 2015). Our approach was to use the MC1 calibration used for Gonzalez *et al* (2010) as a starting point, and improve upon it by focusing on three key processes in order: NPP, vegetation biogeography, and then fire. Below, we outline our calibration approach. A list of parameters adjusted and their values are provided in the online supplement (tables S1, S2, S3 available at stacks.iop.org/ERL/12/045001/mmedia). Parameter values were adjusted manually; we did not use an optimization algorithm, because we did not believe it would give a geographically balanced calibration.

We calibrated MC2 NPP to the MODIS Terrestrial Gross and Net Primary Production Global Data Set, version MOD17 (Zhao *et al* 2005). Although MODIS is not pure observation data, currently there is no other global gridded NPP product, and it can play an informative role in calibrating a model, to adjust productivity on a broad spatial scale, and to adjust productivity parameters to bring the model calibration into a reasonable range of values. MODIS data products evaluate well across many broad spatial scales and biomes (Heinsch *et al* 2006, Pan *et al* 2006, Sjöström *et al* 2013, Turner *et al* 2006, Zhang *et al* 2012), and, despite it not being a pure observational dataset, many studies have used MODIS data for terrestrial biosphere model evaluation (e.g. Collins *et al* 2011, Dury *et al* 2011, Pavlick *et al* 2013, Poulter *et al* 2014, Randerson *et al* 2009, Tang *et al* 2010). We calibrated MC2's biogeography thresholds (table S1) using ISLSCP II Potential Natural Vegetation Cover (Ramankutty and Foley 2010) as a benchmark.

For calibrating the fire module, we used the Burned Area data from the Global Fire Emissions Database Version 4 (GFED4) (Giglio *et al* 2013). Initially, MC2 estimates of area burned by wildfire compared poorly with GFED4 estimates for 1996 to 2011. Therefore, we modified MC2 fire occurrence algorithm so that it stochastically determines the occurrence of fire, and the probabilities for occurrence of fire within each of the 34 vegetation types simulated by MC2 were set to approximate the fire occurrence probabilities given in GFED4 for the 11% sample grid. The altered algorithm allows more than one fire to occur in a given grid cell each year. We also modified the algorithm for determining area burned within a cell so that it is computed as a function of fuel conditions, and parameters were set to so that the burned area in the 11% sample grid approximates burned area given in GFED4. Further details on the alterations made to the fire algorithm are given in the online supplementary materials.

2.2.2. *Model validation*

For model validation, we ran MC2 for the full 0.5° global grid from 1901 to 2012, and compared the output with benchmark datasets resampled to the 0.5° grid. This represents two-fold cross-validation (Jopp *et al* 2011, Kleijnen 2008), appropriate when computational costs are heavy (Schwartz 2008). Since MC2 was modified to stochastically simulate the occurrence of fires, we ran 12 replicates for the 1901–2012 period, and calculated the mean and mode statistics of output variables. The comparisons with benchmark data were tabulated for the 16 major forest regions of the world (Sohngen *et al* 2001, Sohngen 2014) (figure 1). We compared MC2's estimates of NPP for 2000–2011 with MODIS NPP MODIS Terrestrial Gross and Net Primary Production Global

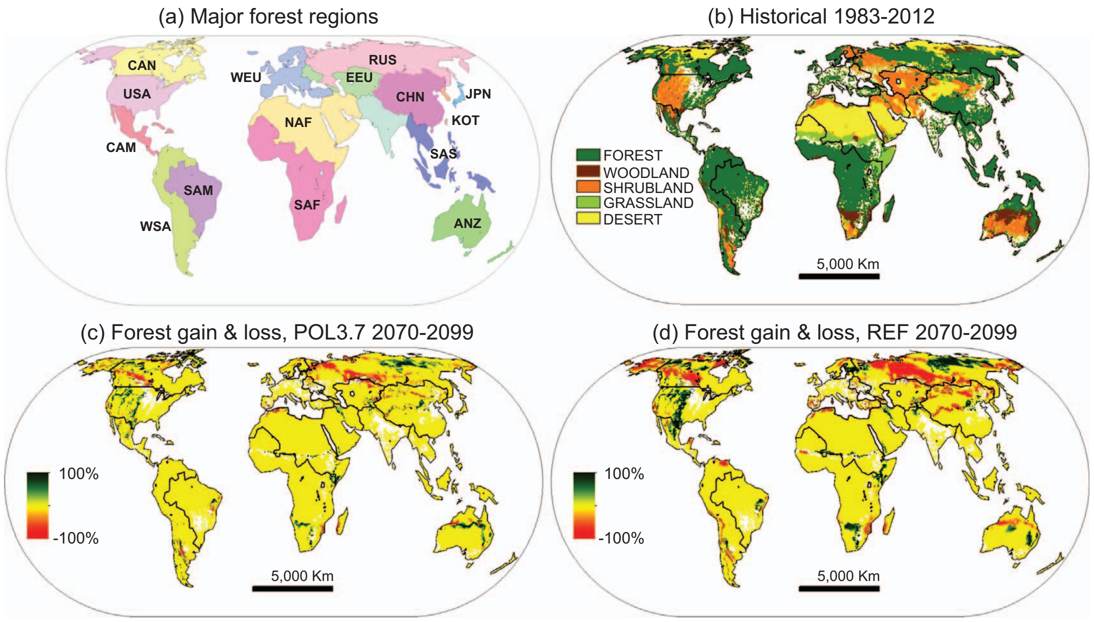

Figure 1. Global forest regions and forest change projections. The sixteen major global regions (Sohngen *et al* 2001) are Canada (CAN), United States of America (USA), Central America (CAM), Western South America (WSA), South America (SAM), Western Europe (WEU), Eastern Europe (EEU), North Africa (NAF), Southern Africa (SAF), Russia (RUS), India (IND), China (CHN), Korea and Taiwan (KOT), Japan (JPN), South Asia (SAS) and Australia and New Zealand (ANZ) (*a*). Biomes projected by MC2 DGVM for 1983–2012 (*b*) and forest gain and loss for 2070–2099 under POL3.7 and REF climate change scenarios ((*c*), (*d*)). Forest gain and loss maps show percentage of simulations across multiple climate realizations and replicates that simulated conversion into or out of forest biome type. Agricultural and developed areas per GLC2000 have been masked out.

Data Set, version MOD17 (Zhao *et al* 2005). We compared MC2's projection of locations of vegetation biomes with ISLSCP II Potential Natural Vegetation Cover (Ramankutty and Foley 2010), as well as the GLC2000 global land cover dataset (Bartholomé and Belward 2005). The land cover types in each dataset were translated to the biome types MC2 simulates (desert, shrubland, grassland, woodland, and forest) and Cohen's kappa was calculated in comparison to MC2 output. ISLSCP II did not distinguish between woodland and forest, so for that comparison the two MC2 biomes were combined. Finally, we compared MC2 estimates of burned area with GFED4 data (Giglio *et al* 2013). All comparisons, except the comparison with ISLSCP II, were made after agriculture and developed areas shown in the GLC2000 land cover data were masked out. For comparing NPP and burned area, MC2 outputs ($g\,m^{-2}\,y^{-1}$ and %, respectively) were multiplied by the area of each grid cell. The validation results are described in the Results section below.

To run simulations with future climate realizations, we compared 30 yr averages of total live vegetation carbon stock (C_{veg}) from the 12 replicates of the full grid, 1901–2012 MC2 simulations, and selected the replicate with C_{veg} the most similar to the ensemble average value of C_{veg}. We used the 1979 state of the selected simulation as the starting state for the future simulations. We first ran IGSM-CAM to produce global climate realizations, then used the climate realizations to drive MC2. The IGSM-CAM climate realizations were downscaled from their native resolution to 0.5° degree resolution using the delta method (Fowler *et al* 2007). For each climate realization, we ran 10 replicates of MC2, and, as for the validation analysis, agriculture and developed areas were masked out for analysis.

3. Results

3.1. Model validation

For a recent historical period (1983–2012) the global proportions of biomes projected by MC2 were comparable to the proportions derived from GLC2000 and ISLSCP II datasets (figure 2). MC2 projected 52% of land grid cells to be forest and 6% to be woodland, while the proportions derived from GLC2000 was 34% for forest and 5% for woodland. The proportion of woodland and forest combined projected by MC2 was 58%, while the combined proportion derived from ISLSCP II was 43%. The proportions for grassland and desert varied widely among all three data sources, while the proportions for shrubland were within 3 percentage points. Cohen's kappa for the globe between MC2 and ISLSCP II was 0.46, and with GLC2000 it was 0.43. Global average annual NPP simulated by MC2 for 2000–2011 was only 0.99 Pg (2%) over the MODIS MOD17 estimate, while the area burned simulated by MC2 for 1996–2011 was 109 Mha (31%) below the value reported by GFED4.

We compared MC2 simulated global net biome production (NBP) and NPP with the values generated

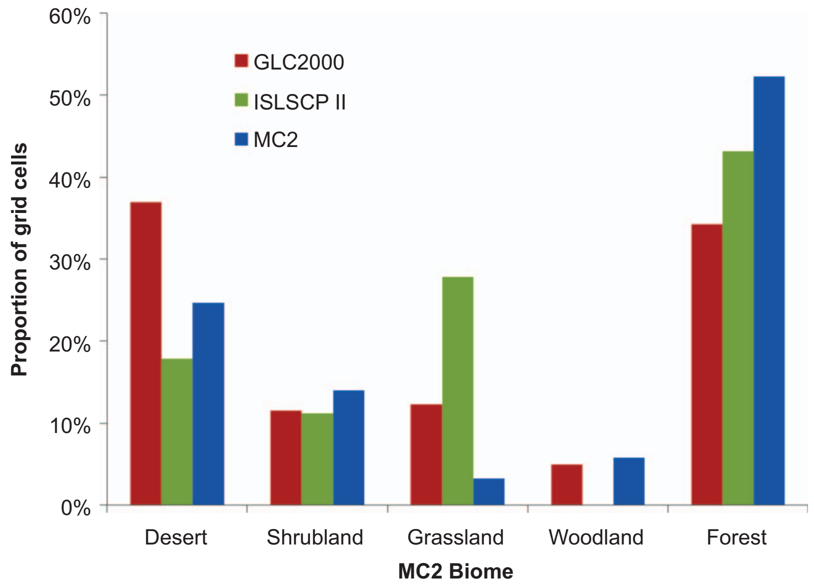

Figure 2. Global proportion of biomes projected by MC2 for 1983–2012 compared to biomes indicated in GLC2000 (Bartholomé and Belward 2005) and ISLSCP II (Ramankutty and Foley 2010) land cover datasets. ISLSCP II combines woodland and forests into a single biome, and is plotted here as forest.

Table 2. Comparison of MC2 output with benchmark datasets for each of the major forest region and the globe. Land cover data from ISLSCP II and GLC2000 were translated to the biome types used by MC2, and Cohen's kappa (κ) was calculated between them and MC2's projected biome for a recent historical period (1983–2012). ΔNPP is the difference between MC2's average annual net primary production (NPP) 2000–2011 and MODIS NPP (Zhao *et al* 2005). ΔBurned Area is the difference between the total burned area simulated by MC2 from 1996–2011 and the values reported by GFED4 (Giglio *et al* 2013).

	Canada	USA	W. Europe	E. Europe	Russia	
$\kappa_{ISLSCP\ II}$	0.36	0.44	0.39	0.22	0.34	
$\kappa_{GLC2000}$	0.44	0.42	0.30	0.09	0.37	
ΔNPP (Pg)	−0.34 (−14%)	−0.76 (−26%)	−0.49 (−24%)	−0.07 (−11%)	−2.16 (−45%)	
ΔBurned area (Mha)	1.4 (80%)	2.2 (101%)	−0.1 (−10%)	−4.8 (−50%)	1.0 (13%)	
	Central America	N. Africa	India	China	Korea-Taiwan	Japan
$\kappa_{ISLSCP\ II}$	0.47	0.50	0.53	0.39	1.00	0.49
$\kappa_{GLC2000}$	0.42	0.47	0.35	0.35	0.46	0.49
ΔNPP (Pg)	-0.01 (-1%)	1.56 (185%)	0.40 (64%)	0.62 (29%)	0.01 (7%)	0.01 (3%)
ΔBurned area (Mha)	10.0 (575%)	-18.1 (-35%)	12.4 (803%)	2.4 (124%)	0.0 (26%)	0.0 (98%)
	W. S. America	S. America	S. Africa	S. Asia	Australia-New Zealand	Global
$\kappa_{ISLSCP\ II}$	0.36	0.40	0.39	0.48	0.25	0.46
$\kappa_{GLC2000}$	0.40	0.42	0.36	0.42	0.12	0.43
ΔNPP (Pg)	−0.63 (−10%)	0.17 (3%)	1.44 (17%)	0.08 (2%)	1.10 (54%)	0.99 (2%)
ΔBurned area (Mha)	6.2 (68%)	8.6 (71%)	−112.1 (−59%)	−1.5 (−23%)	−16.5 (−33%)	−109.0 (−31%)

by 10 DGVMs included in Piao *et al* (2013) model inter-comparison study. The average NBP simulated by MC2 for the 1980–2009 period was 1.7 PgC y^{-1}, in the middle of the range of values generated by the ten DGVMs, and falls within the residual land sink value range reported by Friedlingstein *et al* (2010). The average NPP simulated by MC2 for the 1980–2009 period was 56.2 PgC y^{-1}. MC2 does not calculate gross primary productivity (GPP) published in Piao *et al* (2013), but assuming NPP is 50% of GPP (Waring *et al* 1998), MC2's GPP value falls within the range of values generated by the 10 DGVMs.

A region-by-region comparison of MC2 output for biome biogeography, NPP, and burned area with benchmark datasets is tabulated in table 2. The levels of agreement of biome biogeography with benchmark datasets were similar to the level of agreement for the globe, with kappa values for the majority of the regions ranging between 0.39 and 0.53. Kappa was 1.0 in Korea-Taiwan, because both MC2 and ISLSCP II projected 100% forest. Eastern Europe and Australia-New Zealand regions had particularly low agreement, with kappa values as low as 0.09 and 0.12. The average annual NPP for 2000–2011 simulated by MC2 were within 25%

of the NPP reported by the MODIS MOD17 dataset for 10 of the 16 world forest regions. In North Africa and Australia-New Zealand, both of which contain much arid and semi-arid biomes, NPP simulated by MC2 far exceeded the values reported by MODIS MOD17 dataset. Area burned simulated by MC2 was within 33% of GFED4 values for five of the 16 regions: Western Europe, Russia, Korea-Taiwan, South Asia, and Australia-New Zealand. For another seven regions, the values deviated less than 100% from GFED4 values. For the remaining four regions—USA, Central America, India and China—the burned area simulated by MC2 deviated over 100% from GFED4. The worst of these was India, where burned area was 12.4 Mha (803%) over the value obtained from GFED4.

3.2. Patterns of global change

For each climate change scenario (i.e. REF and POL3.7), we calculated the probability of forest gain as the percentage of simulation replicates that indicated a biome conversion from non-forest to forest from a recent historical period (1980–2009) to the end of the century (2070–2099). For this analysis we aggregated all the forest vegetation types simulated by MC2 into a single 'forest biome' type. We calculated the probability of forest loss in a similar way, by calculating the percentage of simulation replicates that indicated conversion from forest to non-forest. A map of the combined percentages for each climate change scenario is shown in figure 1. The biogeography of forest biomes projected by MC2 was stable across most of the globe. Where there were shifts, MC2's projections were highly consistent across the multiple realizations and replicates within a scenario. That is, the areas showing forest gain and forest loss generally had high and low percentage values, with only a limited number of grid cells showing intermediate levels of agreement.

For both climate change scenarios, MC2 simulated poleward migration of forest biomes, where, in the leading-edge of the migration, lower-productivity biomes (e.g. grassland and woodlands) convert to forests under climate change; while at the trailing edge, forests convert to another biome (e.g. shrubland, grassland, or woodland) due to lower productivity or frequent fires. Large expanses of boreal forests in Canada and Russia shifted northward under the REF scenario, and to lesser degrees under the POL3.7 scenario. In the southern hemisphere, forest expanded southward in Southern Africa. Poleward migration of forests was not distinct in Western South America, where there the forest contracted along elevation gradients. In Australia, the tropical forests in the north contracted northward as they lost productivity and became woodlands. Simultaneously, MC2 simulated increased growth of trees in the woodlands in western Australia, converting those areas to forests.

Although MC2 simulated forest biomes to be geographically stable across much of the globe, the total live forest carbon stock increased dramatically and consistently under both climate change scenarios, gaining 447 Pg C (59%) and 410 Pg C (54%) under the REF and POL3.7 scenarios, respectively. MC2 simulated the vast majority of the total live forest carbon gain to occur in the southern hemisphere: Western South America, South America, and South Asia (figure 3(*a*)). Although the other regions—with the exception of Russia—also gained total live forest carbon, the amount gained were less than 20 Pg. Russia lost as much as 17 Pg (23%) of the total live forest carbon under the REF scenario, due to conversion of forest biomes to non-forest biomes. For Asia and Europe only small increases were projected, while Russia was projected to see a significant decline.

3.3. Global impacts of climate mitigation

To analyze the global impact of GHG mitigation on the world's forests, we show the range of changes among the 5-m ember initial condition ensemble for each emissions scenario for important metrics of global forest conditions: changes in forest carbon, NPP, forest carbon consumed by fire, forest area and burned area (figure 4). The analysis reveals large increases in forest carbon under both scenarios, along with increases in NPP, increases in wildfire, burned area and forest carbon consumed by wildfire, along with decreases in forest areas. The magnitude of the climate change effects are reduced by GHG mitigation under the POL3.7 scenario compared to the REF scenario, both the positive effects (increases in carbon stocks and NPP) and the negative (increase in wildfire and decreases in forest areas).

Our analysis also estimates the uncertainty associated with natural variability, and thus provides a basic signal-to-noise analysis to test the robustness of the impact of climate mitigation. The role of natural variability on changes in forest carbon and NPP is small (figure 4(*b*)), but it is substantial for changes in forest carbon consumed by wildfire (figure 4(*c*)) and burned area (figure 4(*e*))—to the point where the ranges of the two emissions scenarios overlap—and to a lesser degree for changes in forest area (figure 4(*d*)). These results highlight the importance of relying on an ensemble of climate simulations with perturbed initial conditions to quantify the noise associated with natural variability and identify the robust impacts of climate policy. However, while identifying the aggregated impact of climate mitigation provides useful information for decision-making, it does not capture potentially heterogeneous responses at the regional scale. For this reason, we analyze the regional drivers of change next.

3.4. Regional changes and their drivers

The exposure of the regions of the globe to climate change, as represented by change in mean annual

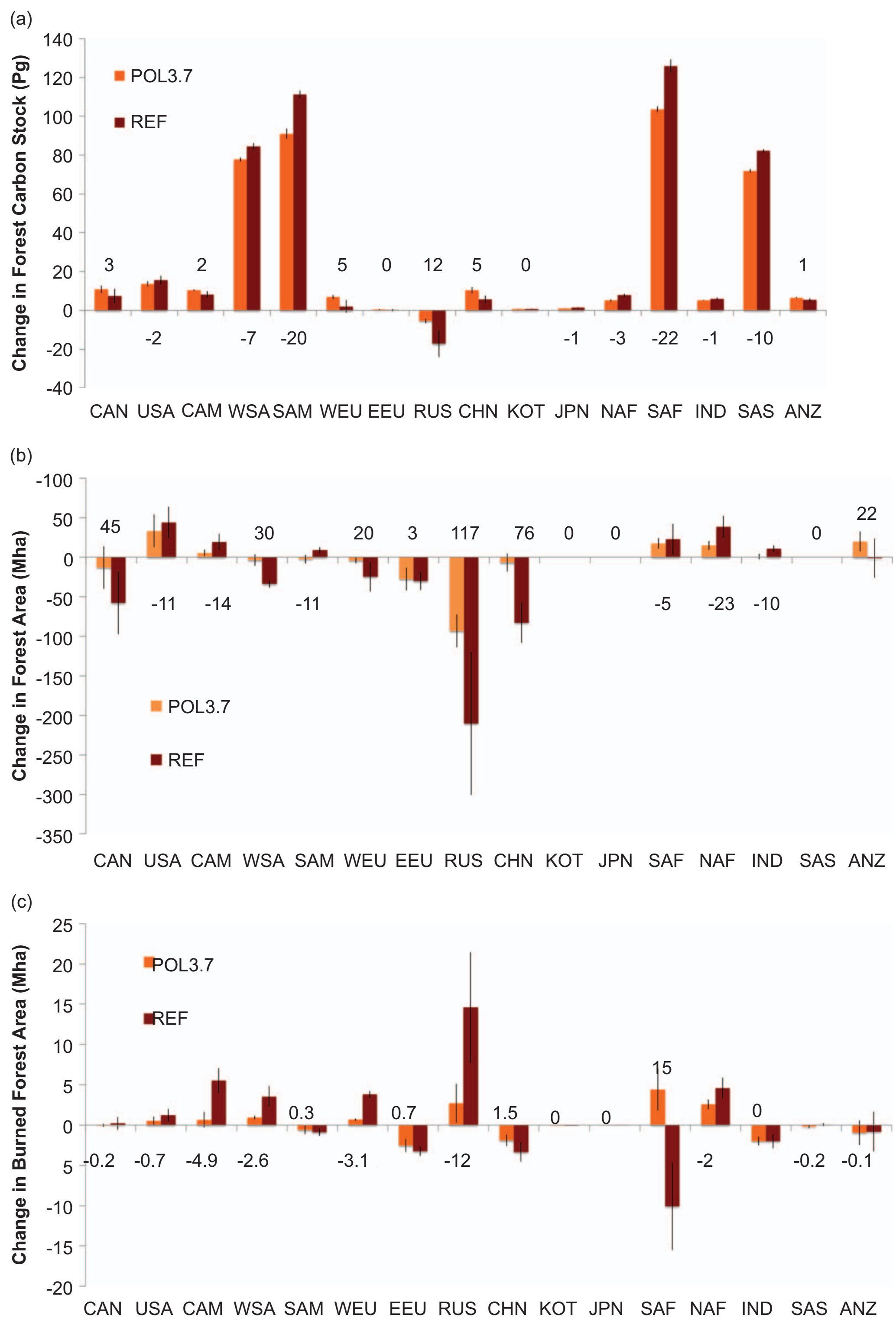

Figure 3. Regional changes in forest carbon stock, and benefits of mitigation. Change in forest carbon stock (*a*), forest area (*b*) and forest area burned by wildfire (*c*) from 1980–2009 to 2070–2099 under REF and POL3.7 climate change scenarios. Numbers positioned above and below columns represent benefit or cost of mitigation, the difference between POL3.7 and REF for the variable plotted. The regions are Canada (CAN), United States of America (USA), Central America (CAM), Western South America (WSA), South America (SAM), Western Europe (WEU), Eastern Europe (EEU), North Africa (NAF), Southern Africa (SAF), Russia (RUS), India (IND), China (CHN), Korea and Taiwan (KOT), Japan (JPN), South Asia (SAS) and Australia and New Zealand (ANZ). Change per continent per decade for the REF scenario with respect to 1980–2009 (*b*).

temperature and precipitation from 1980–2009 to 2070–2099, are muted under the POL3.7 scenario but vary range widely under the REF scenario (figure 5(*a*)). For the majority of the 16 global forest regions, the REF scenario projects a temperature rise >3.5 °C and precipitation increase >12%. All of the major temperate and boreal forest regions (USA, Canada, and Russia) are exposed to a >5 °C warming under the REF scenario. For a small set of regions—Australia-New Zealand, Western Europe and Eastern Europe—

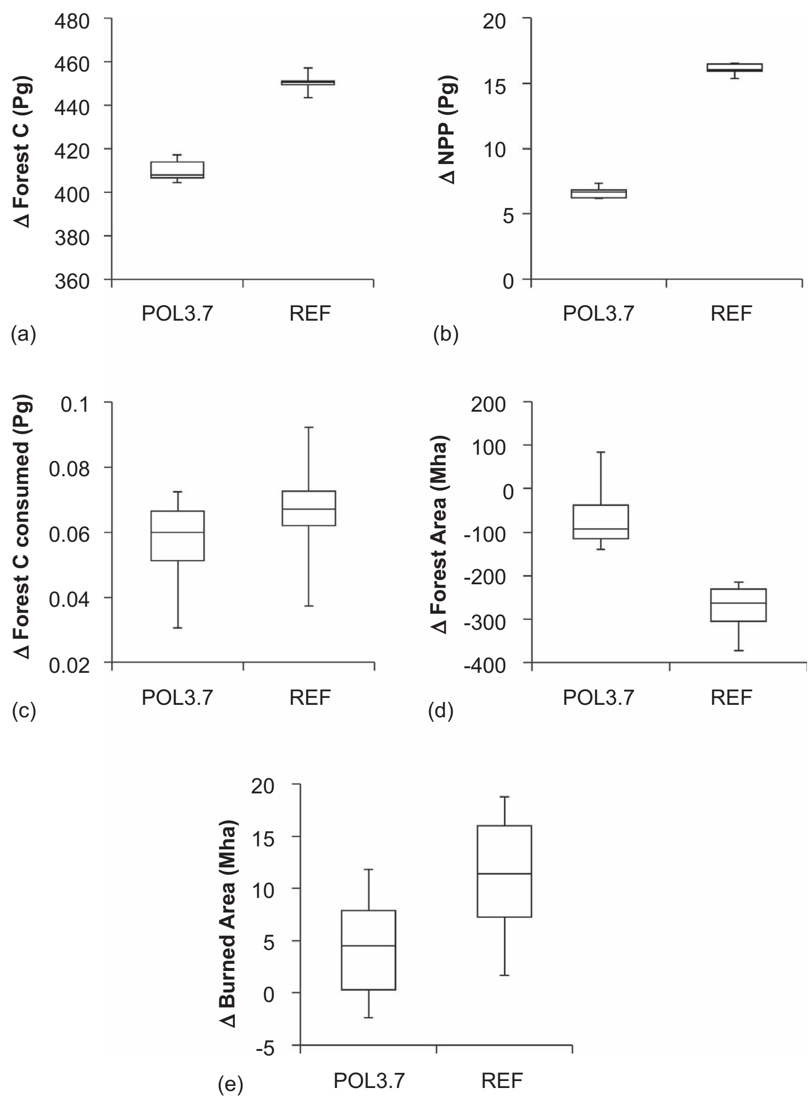

Figure 4. Global impacts of climate mitigation. We calculated changes in global forest C stock (*a*), net primary productivity (*b*), forest carbon consumed by wildfire (*c*), forest area (*d*), and forest area burned by wildfire (*e*), from 1980–2009 to 2070–2099 under POL3.7 and REF climate change scenarios. For each scenario, we used climate projections using climate sensitivity of 3.0 °C and five initial conditions, and ran 10 replicate simulations per initial condition.

the REF scenario projects the same magnitude of warming but only a small increase in precipitation (2%–4%). For Central America, the REF scenario actually projects a small reduction (−2%) in precipitation.

Forest responses to those climate change exposures are projected to vary regionally, without simple correlations to the intensity of those exposures. As noted above, the greatest increase in forest carbon stock are projected to take place in the southern hemisphere, even though the greatest exposure to climate change is projected for North Africa, USA, Canada and Russia (figure 5). Russia is, however, projected to undergo the largest contraction of forest area (210 Mha) under the REF scenario (figure 3(*b*)), with 14 Mha lost to fire (figure 3(*c*)). Significant contraction of forest area is also projected for China (83 Mha, figure 3(*b*)), but area burned by fire is projected to decrease for China (figure 3(*c*)). See figure S3 for a complete set of regional change projections.

Benefits of mitigation are also not evenly distributed across the global regions. For example, for Canada the POL3.7 scenario results in a net gain of 3 Pg of forest carbon stock when compared to REF scenario (figure 3(*a*)), while for USA it results in a net loss of 2 Pg. Nearly half of the regions are projected to benefit from mitigation through increases in forest area (figure 3(*b*)) and reduction in forest area burned by fire (figure 3(*c*)). The greatest cost of mitigation—that is, a negative impact on forests—is projected to be borne by the southern hemisphere regions (W. South America, South America, South Africa and South Asia) where the greatest carbon gains are projected under both POL3.7 and REF scenarios.

The drivers of forest changes also vary by region. Different regions are projected to experience changes in forest carbon stock of similar magnitude but associated with differing mechanisms: 1) expansion or contraction of forests, with further loss of acreage to wildfire; and 2) changes in vegetation productivity.

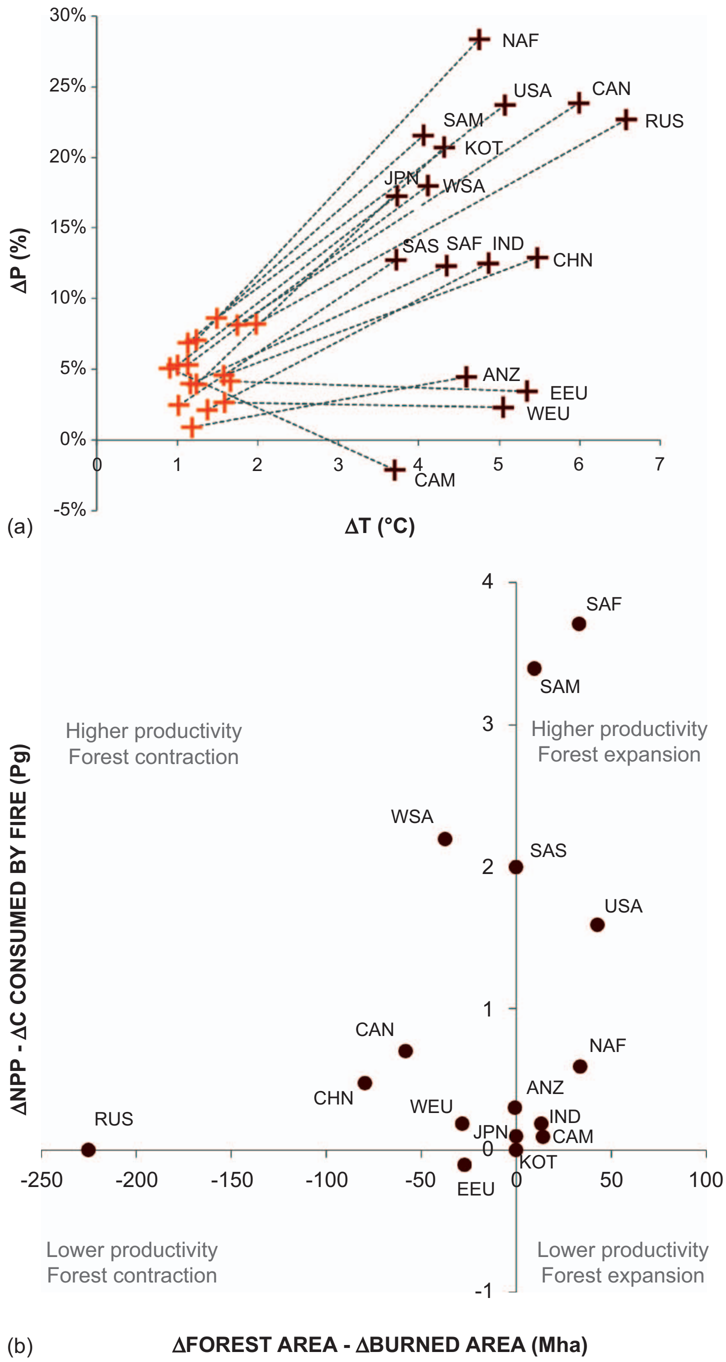

Figure 5. Regional exposure to climate and drivers of vegetation response. Exposure to climate change is represented in terms of change in mean annual temperature (ΔT) vs. change in mean annual precipitation (ΔP) from 1980–2009 to 2070–2099, for REF scenario (brown) and POL3.7 scenario (yellow), for the sixteen global timber regions (*a*). Abbreviations of regions are given in figure 3 caption. Simulated change in forest carbon stock is an interplay between afforestation/deforestation (*x*-axis) and increase/decrease in productivity and loss to wildfire (*y*-axis) (*b*). Each region can be categorized into one of four types of change, defined by the four quadrants of the *x*–*y* graph. Results are for REF scenario.

Plotted as a two-dimensional grid, these mechanisms have different levels of importance for the world's forest regions (figure 5(*b*)). The large increases in forest carbon stock projected for the southern hemisphere regions are driven primarily by increases in NPP, with little changes projected to the forest area or area burned. In contrast, the large decreases in forest carbon stock projected for Russia, and, to a lesser extent, for China, are both driven primarily by forest contraction, with only small changes projected in forest productivity. For USA, the increase in forest carbon stock is driven by a combination of forest expansion and increase in productivity. For Canada, forest contraction is balanced by an increase in productivity.

3.5. Integrated model uncertainties

To frame the uncertainty in our estimate of climate impacts on the world's forests, we examine the range of impacts using three different ensembles: the range over 5 initial conditions (for REF and climate sensitivity 3.0 °C), the range over 3 climate sensitivities, namely

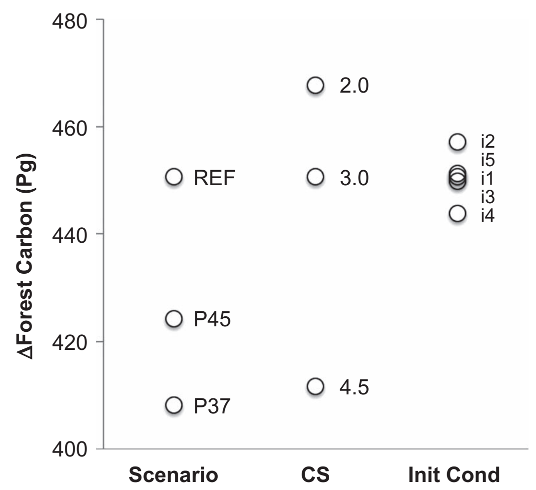

Figure 6. Simulated global forest carbon sensitivity to variations in climate projections. Projected changes in global forest carbon stock from 1980–2009 to 2070–2099 are as sensitive to climate sensitivity (CS) as they are to climate change scenario, and moderately sensitive to initial conditions. When varying climate change scenario, climate sensitivity was held constant at 3.0, and initial condition was set to i1. When varying climate sensitivity, the REF climate scenario was used, with initial condition i1. When varying initial conditions, the REF climate scenario was used, with climate sensitivity set to 3.0. Each data point is an average of 10 replicates. Standard deviations were small (<0.3) and not shown.

2.0 °C, 3.0 °C and 4.5 °C (for REF and initial condition member #1) and the range over the three emissions scenarios (for climate sensitivity 3.0 °C and initial condition member #1) (figure 6).

This analysis identifies two major findings. First, increased levels of climate change along the emissions scenario dimension are associated with a larger increase in total forest carbon, but along the climate sensitivity dimension it is associated with a smaller increase in total forest carbon. The major difference between these two dimensions of climate change is the role of CO_2 fertilization. Under the REF scenario, CO_2 concentrations (827 ppm by 2100) are substantially higher than under the POL3.7 (462 ppm by 2100), and therefore so is the CO_2 fertilization effect. Meanwhile, the simulations with different climate sensitivities have the same CO_2 concentrations, which allows distinguishing the role of climate change versus the role of increases in CO_2 concentrations and CO_2 fertilization. This analysis shows that, at the global mean level, forest productivity under the REF scenario benefits substantially from the CO_2 fertilization effect and that higher warming alone does not necessarily increase global forest carbon. Higher levels of climate change, under fixed CO_2 concentrations, have a negative impact on global forest carbon, likely caused by more wildfires, and climatic effects like droughts.

Second, the analysis shows there are substantial uncertainties associated with our estimates of the benefits of GHG mitigation on the world's forests, highlighted by the large range of outcomes between different levels of global climate system response (i.e. climate sensitivity) and different representations of natural variability (i.e. initial conditions). The role of natural variability is even larger at the regional level, as shown in figure 3 (and figure S3), which shows that the range of outcomes between REF and POL3.7 can overlap when the range over different initial conditions is taken into account. This finding further highlights the need to account for natural variability when trying to obtain robust estimates of the impact of climate mitigation on forests, at both the global and regional scale.

4. Discussion

4.1. Model skill

Confidence in model projections can only be founded on an objective evaluation of model skill, as its ability to reasonably simulate past conditions is a necessary, though not sufficient, requirement for simulating future conditions. Comparing MC2 output with empirically obtained datasets requires some caution, because MC2 simulates potential natural vegetation without simulating the effects of various anthropogenic effects on the landscape. We evaluated our calibration of MC2 DGVM by analyzing output variables from each of MC2's three main internal modules: NPP for the biogeochemistry module, burned area for the fire module, and biome biogeography for the biogeography module (table 2). MC2's global NPP output compared closely with MODIS MOD17 NPP (Zhao *et al* 2005), and the global estimates are within the wide range of values reported in literature (Field *et al* 1998, Kicklighter *et al* 1999). For 10 of the 16 world forest regions considered, MC2's NPP values were comparable to MODIS values. With the exception of Russia, the regions where MC2's NPP values compared poorly were regions with smaller timber production. The problematic areas, however, highlight the many challenges remaining in DGVM design (Quillet *et al* 2010). Although there is broad agreement among the models, large uncertainties remain across models (Friedlingstein *et al* 2006, Piao *et al* 2013, Sitch *et al* 2008).

Our reformulation of the fire algorithm and its calibration appears to underestimate the prevalence of fire globally, although the geography of fire is comparable to previous versions (Gonzalez *et al* 2010). In the key temperate forests of Canada and USA, MC2 appears to overestimate the prevalence of fire (table 2), which may lead to an underestimation of forest C stock. In key tropical forests of Western South America, South America, South Africa and South Asia, MC2 both over- and underestimates fire prevalence reported by GFED4, and the mixture of errors may balance each other.

The agreement between MC2 biome biogeography and the two benchmark datasets may be called 'fair to good' (Banerjee *et al* 1999) for the globe and a majority of the regions. For comparison, kappa between ISLSCP II and GLC2000 was 0.51. Some of the disagreements arise from the disparate systems used to classify land surface, from aggregation to the 0.5° grid, and from translation to MC2 biomes.

MC2 projects northward migration of boreal forests in Canada, Russia and Alaska (USA), with massive forest losses at the trailing edges. Natural range shifts, however, may be disrupted by the rapidity of climate change and land use changes (Davis and Shaw 2001, Soja *et al* 2007). Meanwhile, productivity in tropical forests is already increasing (Lewis *et al* 2009, Pan *et al* 2011) and MC2 projects large increases in NPP under the REF scenario, with only a little change in fire activity. This result contrasts with decline of tropical forests simulated by some studies (Brienen *et al* 2015, Cramer *et al* 2001). Also, deforestation may play a key role in the future for tropical forests (Cramer *et al* 2004), a process not simulated in our study. This may increase the expansion of the short-rotation plantation wood market globally (Sohngen *et al* 2001), as temperate forests enjoys a relatively small gain in productivity.

4.2. Benefits and costs of POL3.7 greenhouse gas mitigation scenario

MC2 simulates a shifting balance in global forest condition under the two climate change scenarios. Warmer temperatures, along with higher CO_2 concentrations and fertilization effects, drive forest C stock gains in all regions except Russia under REF and POL3.7 (figure 3(*a*)). The general trend simulated is consistent with many other terrestrial biome simulations (Friedlingstein *et al* 2006, Zscheischler *et al* 2014). However, because of distinct regional differences in climate change exposure (figure 5(*a*)), the drivers of change (figure 5(*b*)), and the resulting forest conditions (figures 3(*a*)–(*c*)), our models simulate divergent benefits and costs of mitigation for the global forest regions. For several regions the REF scenario is projected to bring significant increases in fire, while the POL3.7 scenario mitigates a significant fraction of those increases. Western Europe and Russia are projected to see significant increases in fire activity under the REF scenario. For Western Europe, the increase is likely driven by the singular increase in temperature without any increase in precipitation, consistent with CMIP3 and CMIP5 projections in the region (Christensen *et al* 2007, Collins *et al* 2013). Western Europe and Russia benefit from mitigation by reducing burned forest area by 3.1 and 12 Mha, respectively (figure 3(*c*)). For these two regions, the mitigation of fire ultimately contributes to the forest carbon stock gains seen under the POL3.7 mitigation scenario (5 and 12 Pg respectively for Western Europe and Russia, figure 3(*a*)). In contrast, for Western South America, the POL3.7 scenario mitigates burned forest area by 2.6 Mha (figure 3(*c*)), but the total forest carbon stocks are also reduced ultimately by 7 Pg under this scenario. The reduction in forest carbon stocks are also driven by lower forest productivity (figure 3(*a*)) and forest contraction (figure 5(*b*)). For this region, then, climate mitigation has both benefits and costs: mitigation reduces wildfires but also results in reduced forest carbon stocks. The US is under a similar dynamic, where mitigation reduces burned forest area by 0.7 Mha compared to the REF scenario, but the total forest carbon stock is also reduced by 2 Pg. In the US, higher fire suppression costs associated with increases in fire activity (Flannigan *et al* 2009, Mills *et al* 2015) may be particularly important in weighing the benefits and costs of mitigation.

4.3. Study limitations and uncertainties

Models are abstractions of the natural system, and their accuracy is limited by many types of uncertainties (Uusitalo *et al* 2015). MC2 simulations abstract the complex global land surfaces into discrete, coarse (0.5°) grid cells, where vegetation is represented by a limited set of plant functional types. Second generation DGVMs may resolve some of the uncertainties arising from coarse representation of vegetation at each grid cell (Scheiter *et al* 2013). Land use change and forest management practices can have large-scale effects on the forest carbon cycle (Houghton and Hackler 2000, Houghton *et al* 2000). While we excluded current developed and agricultural areas in our analysis, we also did not simulate the complex history of land use change and forest management practices that occurred on the natural lands. Nor did we simulate the effect of insect and pathogen outbreaks, which can have significant impact on forests, often through interaction with fire (Dale *et al* 2001). Our study used a single model (MC2) to simulate climate impact on forests. A multi-model ensemble approach could provide results with higher levels of confidence (Littell *et al* 2011).

All the limitations notwithstanding, running MC2 with a large ensemble of climate simulations allows us to confront the implications of our knowledge (Botkin 1977), and quantify uncertainties due to model formulation (Uusitalo *et al* 2015). Simulated global forest carbon stock responded in different directions when climate change was mitigated versus when climate sensitivity was decreased (figure 6). Two sources of uncertainty are at interplay here: the CO_2 fertilization effect and climate sensitivity. The CO_2 fertilization effect simulated by MC2 is considered to be moderate (Sheehan *et al* 2015), although CO_2 fertilization effect still remains poorly understood at the global scale (Körner 1993, Hickler *et al* 2008). Improving estimates of CO_2 fertilization effect for major vegetation types around the globe and improving estimates of climate sensitivity are needed to reduce uncertainties in projections of forest response. In addition, this study highlights the significant role of natural variability in future projections of vegetation productivity, fire activity, and biome biogeography, a finding consistent with Mills *et al* (2015). A reformulation of the fire occurrence and spread algorithm may further reduce uncertainties (Parisien and Moritz 2009, Mouillot and Field 2005, Thonicke *et al* 2001). Finally, the study's results are for realizations from a single climate model. The effects of mitigation policies on the forest carbon stock may be sensitive to climate model selection (Mills *et al* 2015).

5. Conclusions

Global climate change is projected to bring distinct climatic futures to the major forest regions of the world. While climate mitigation policies (e.g. POL3.7) may reduce the exposure of forests to significant changes in temperature, precipitation and CO_2 concentrations, our vegetation simulations suggest that even under the mitigation scenario, forest biomes may be significantly altered relative to recent historical conditions. Our analysis shows that climate mitigation can have both benefits (reduced wildfires) and costs (reduced forest carbon) at the global scale. It also highlights the complex interplay between direct climate change impacts (changes in temperature and precipitation) and the CO_2 fertilization effect on the world's forests. In addition, our simulation results illustrate varying mechanisms of changes to forests in 16 global forest regions, and varying benefits and costs to mitigating GHGs from the REF scenario down to the POL3.7 scenario, suggesting therefore different types and levels of incentives for mitigation policies as well as management and adaptation practices (though these aspects are not explored in this paper). Although we study multiple future scenarios and projections, the world will experience only a single version of the future. While multiple replicates of simulations depict broadly different sets of future potential forest conditions for the mitigation scenario compared to the reference scenario, our ability to distinguish the mitigation scenario from each other and from the reference scenario is clouded by uncertainties. Reducing uncertainties in climate sensitivity and natural variability and uncertainties in ecosystem modeling are likely to improve our projections. Simulations with additional climate models would also improve the robustness of the results.

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