*Climatic impacts of land-use change due to crop yield increases and a universal carbon tax from a scenario model**

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Climatic Impacts of Land-Use Change due to Crop Yield Increases and a Universal Carbon Tax from a Scenario Model*

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ABSTRACT

Future land cover will have a significant impact on climate and is strongly influenced by the extent of agricultural land use. Differing assumptions of crop yield increase and carbon pricing mitigation strategies affect projected expansion of agricultural land in future scenarios. In the representative concentration pathway 4.5 (RCP4.5) from phase 5 of the Coupled Model Intercomparison Project (CMIP5), the carbon effects of these land cover changes are included, although the biogeophysical effects are not. The afforestation in RCP4.5 has important biogeophysical impacts on climate, in addition to the land carbon changes, which are directly related to the assumption of crop yield increase and the universal carbon tax. To investigate the biogeophysical climatic impact of combinations of agricultural crop yield increases and carbon pricing mitigation, five scenarios of land-use change based on RCP4.5 are used as inputs to an earth system model [Hadley Centre Global Environment Model, version 2–Earth System (HadGEM2-ES)]. In the scenario with the greatest increase in agricultural land (as a result of no increase in crop yield and no climate mitigation) there is a significant −0.49 K worldwide cooling by 2100 compared to a control scenario with no land-use change. Regional cooling is up to −2.2 K annually in northeastern Asia. Including carbon feedbacks from the land-use change gives a small global cooling of −0.067 K. This work shows that there are significant impacts from biogeophysical land-use changes caused by assumptions of crop yield and carbon mitigation, which mean that land carbon is not the whole story. It also elucidates the potential conflict between cooling from biogeophysical climate effects of land-use change and wider environmental aims.

1. Introduction

Climatic analyses of land-use change have shown the importance of biogeochemical, biogeophysical, and combined land-use change (LUC) effects to world and regional temperature, water, and carbon cycles (Bathiany et al. 2010; Betts et al. 2007; Claussen et al. 2001; Dirmeyer et al. 2010; Friedlingstein et al. 2006; Meiyappan and Jain 2012; Pongratz et al. 2010). Building on this knowledge, understanding of future LUC needs an integrated approach, considering the climatic effect of the individual and combined effects of key drivers of LUC (Hibbard et al. 2010). Four representative concentration pathways (RCPs) have been selected for phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al. 2012) ranging from low (RCP2.6) to high (RCP8.5) climate forcing with two intermediate (RCP4.5 and RCP6.0) scenarios (Moss et al. 2010). Each has a different land-use scenario (Hurtt et al. 2011) and the biogeophysical radiative forcing from this land use is not accounted for in the climate forcing, although the land carbon emissions are

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included in RCP4.5. Here we aim to reveal the embedded LUC climatic impacts of crop yield increases and a carbon tax on all greenhouse gas emissions in RCP4.5. We separate the biogeophysical land-use change climatic impacts from the other non-land-use change forcings (greenhouse gases, aerosols, etc.) to allow a straightforward comparison of the climatic implications of the land-use changes of key assumptions within RCP4.5.

The major determinant of LUC in RCP4.5 and other future scenarios is the extent of agricultural land expansion (Ewert et al. 2005; Foley et al. 2011). The primary controlling factors of agricultural land increase originate from changes in demand for agricultural products or policies that limit the supply of agricultural land (Smith et al. 2013). Crop yield increases (an increase in the amount of crop yield per unit area achieved year on year) act to increase the supply of agricultural products without increasing the extent of agricultural land. Supply-side policies can also restrict the increase in agricultural land by valuing alternative land uses highly. Policies that include land carbon emissions in taxes on carbon emissions can therefore restrict agricultural expansion by valuing the carbon in forested land more highly than the potential income from agricultural land. Both yield increases and emissions taxes, as well as other demand and supply factors, vary within the RCPs, with the result that they are nonlinear in their LUC scenarios compared to the non-land-use forcings. The agricultural fraction (crop and pasture area) in RCP2.6 and RCP8.5 increases considerably from 2005 to 2100, whereas in RCP4.5 and RCP6.0 it decreases (Hurtt et al. 2011).

In most areas of the world crop yield increase (or agricultural productivity growth) is projected to increase in the future under climate change, from a combination of carbon dioxide fertilization, technological advances, and efficiency improvements (Parry et al. 1999). However, uncertainty as to the strength of carbon dioxide fertilization, the extent of ozone pollution damage, and the impact of drought and temperature increases means that even the direction of global yield changes in the future is uncertain (Gornall et al. 2010; Schmidhuber and Tubiello 2007; Jaggard et al. 2010; Gross 2013). Moreover, stagnant yields in many regions and crops over recent years suggest that projections of yield increases may be optimistic (Lobell et al. 2011; Ray et al. 2012). Increasing yields has proven challenging, with yield gaps (the difference between actual and potential yields; Lobell et al. 2009; Licker et al. 2010) and stagnation in yield potential both providing major issues (Sinclair et al. 2004). In RCP4.5, the yield increases are taken from the Food and Agriculture Organization (FAO) regional estimates up until 2035 (Bruinsma 2003), then assume a slightly smaller 0.25% annual increase in all regions thereafter (Thomson et al. 2011). This amounts to a total yield increase of 18% in the 2035–2100 period. The crop yield increases in the RCPs serve to reduce substantially the amount of extra agricultural land required, but are not reflective of the full range of crop yield projections. Therefore the effect of RCP4.5's moderate increase in crop yields is an important assumption for LUC.

The preservation of forested land in the face of an increasing agricultural land requirement can be achieved by valuing the carbon stored within it. Although efforts are being made to include forest preservation and land carbon in carbon calculations (Searchinger et al. 2008) and in mitigation agreements (Fearnside 2012), most socioeconomic models do not include them. Of the four RCPs, only RCP4.5 values land carbon emissions equally with fossil fuel carbon emissions (van Vuuren et al. 2011; Wise et al. 2009a). This value of land carbon results in more mitigation through afforestation and forest preservation, giving an overall increase in forest fraction and a decrease in crop fraction by 2100. Without valuing land carbon, achieving the same $4.5\,\mathrm{W\,m^{-2}}$ scenario results in the opposite LUC because of increased biofuel crops in order to meet fossil fuel mitigation targets (Jones et al. 2013). A "business as usual" (BAU) scenario without the $4.5\,\mathrm{W\,m^{-2}}$ mitigation target also drives agricultural land expansion, but for a different reason. The cropland increases in a BAU scenario are necessary to provide an equally sized but higher income population than RCP4.5 with a more meat-intensive diet than in RCP4.5 (Thomson et al. 2011; Tilman et al. 2011). Clearly LUC is not directly predictable from the climate forcing, carbon mitigation type, or integrated assessment model used for the scenario. Thus the specific carbon valuation mitigation scenario is crucial to the resultant LUC.

Since the exact scenario of carbon valuation and yield increase significantly affects the LUC, it is important when considering the climatic impacts of LUC to look at specific scenarios in isolation. Here we examine the climatic impact of the land cover change from the different land-use scenarios in RCP4.5 business as usual no climate policy, RCP4.5 climate mitigation with no crop yield increase, and business as usual with no crop yield increase (see Table 1). This is an extension to Thomson et al.'s (2010) work on the effectiveness of agricultural productivity growth and a tax on all greenhouse gas emissions in limiting deforestation to considering the resultant climatic impacts. We isolate the land-use change climatic impacts by comparing them to a no land-use change control scenario. This gives an essential insight for policy into the extent to which different assumptions of yield increases and carbon mitigation methods can impact climate via land-use change.

TABLE 1. Key characteristics of the scenarios used in this work, all of which only alter the land cover change, while all other aspects remain as in RCP4.5. The RCP4.5 scenario is the standard scenario used in CMIP5. The acronyms of the scenarios correspond to those created by Thomson et al. (2010). The percentage changes to forest and crop fraction shown are global changes between the 2005–15 mean and the 2090–2100 mean. Forest fraction is defined here as the combined total of broadleaf and needleleaf tree plant functional types. The negative agricultural fraction change and forest fraction change in zAPG is caused by an initial increase in agricultural fraction, followed by a decrease to below the 2005 level (see Fig. 1f). Since the return to natural forest is relatively slow, the forest fraction change remains negative by 2100. Characteristics that are not applicable to a scenario are denoted by N/A.

Scenario	RCP4.5	No LUC	BAU	zAPG	zAPG/BAU
Agricultural productivity growth	Normal	N/A	Normal	None	None
Climate policy	Tax on all greenhouse gas (GHG) emissions	N/A	None	Tax on all GHG emissions	None
Agricultural fraction change	−15%	0%	+21%	−6%	+50%
Forest fraction change	+11%	+2%	−12%	−5%	−40%
Land carbon (PgC)	+334	+293	+250	+284	+106

2. Methods

We use the Met Office Hadley Centre's coupled earth system model [Hadley Centre Global Environment Model, version 2–Earth System (HadGEM2-ES); Collins et al. 2011; Martin et al. 2011]. HadGEM2-ES incorporates the Met Office Surface Exchange Scheme, version 2 (MOSES2), land surface scheme (Essery et al. 2001); the Top-Down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) dynamic global-vegetation model in dynamic mode (Cox 2001); the Hadley Centre Global Environment Model, version 1 (HadGEM1; Martin et al. 2006); and interactive ocean biogeochemistry, terrestrial biogeochemistry, and dust and interactive atmospheric chemistry and aerosols. The atmosphere component contains 38 levels at 1.875° × 1.25° horizontal resolution and interacts with water, energy, and carbon within the land surface scheme (Essery et al. 2003) and the dynamic vegetation model. Five plant functional types (broadleaf tree, needleleaf tree, C_3 and C_4 grasses, and shrubs) are simulated. The soil component is based on a four-pool Rothamsted soil carbon model (RothC; Jones et al. 2005).

The model setup is as for the CMIP5 simulations, described in Jones et al. (2011). The simulations are initialized from a historical simulation that ran from 1850 to 2005 and then run for 95 years up to 2100. For all our simulations, all non-land-use forcings (greenhouse gas concentrations, other aerosol forcings, etc.) are prescribed as for RCP4.5 (Meinshausen et al. 2011; Thomson et al. 2011). The total agricultural fraction (cropland and pasture) from the land use in the Global Change Assessment Model (GCAM) integrated assessment model is imposed as a disturbed fraction area in HadGEM2-ES where broadleaf and needleleaf trees and shrubs cannot be grown. Increases in disturbed fraction within a grid box are preferentially expanded into grasses, only converting trees to disturbed fraction when other plant function types are not available.

Four land-use scenarios are used, comprising gridded datasets of annual pasture and crop fraction for the scenarios based on RCP4.5 described in Thomson et al. (2010). In all these scenarios, the population projections are as for RCP4.5, peaking at 9 billion and stabilizing at 8.6 billion. The "normal" yield increases are as the standard RCP4.5 (Thomson et al. 2011). The business as usual land-use scenario is the GCAM group's reference scenario, with no carbon tax or other mitigation strategy (Thomson et al. 2010).

The scenarios (Table 1) have changes to disturbed fraction over the 95-yr run from −15% to +50%, which result in simulated changes in forest fraction of similar signal and magnitude (see Fig. 1). The scenario of no crop yield increase and land carbon pricing has a decrease in both agricultural fraction and forest fraction because of the ramifications of land carbon pricing with regard to pasture. There are smooth changes in agricultural fraction over the 95 years, with the rate of change decreasing substantially after 2065 (Fig. 1f) and the forest fraction changes follow this smooth trajectory.

The five regions analyzed here (Fig. 1e) are based approximately around the areas of largest changes in forest fraction (broadleaf and needleleaf trees). The two low-latitude areas (Congo and Amazon) encompass the major forested areas and other parts of the continent on the same latitude. Of the three midlatitude regions, North America and Europe are roughly based on areas of historically strong LUC identified by de Noblet-Ducoudré et al. (2012) and northeastern (NE) Asia highlights a particularly sensitive region in these scenarios.

3. Results

The simulations begin to be noticeably differentiated by midcentury and although the change does not continue

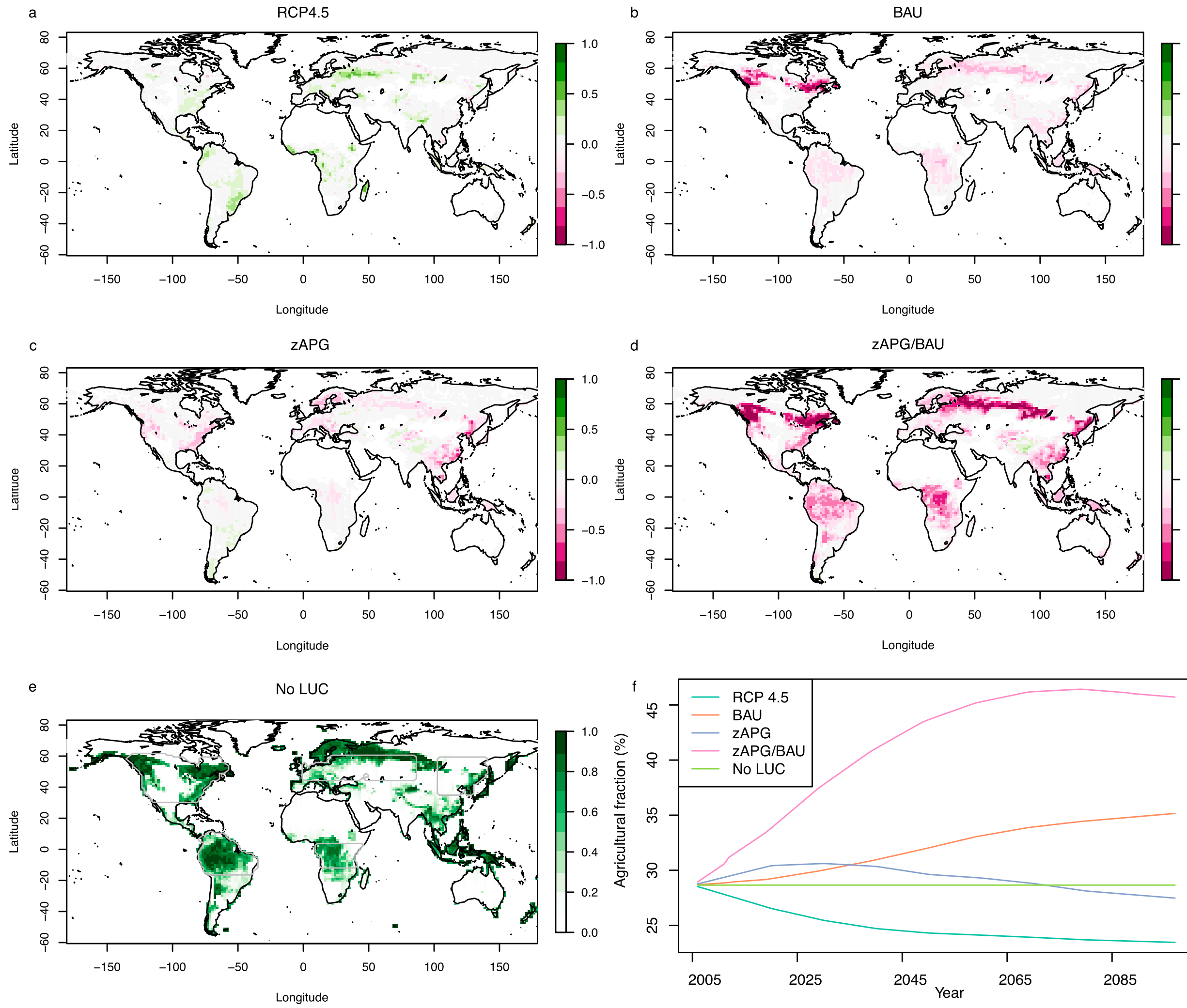

FIG. 1. (a)–(d) Anomalies of the fractional area of forest anomaly for the last 10 years of the simulation, compared to the No LUC control scenario. Anomalies shown are significant at $p < 0.05$ using a Wilcoxon rank sum test. (e) Fractional area of forest in the No LUC control scenario, for the last 10 years of the simulation. Overlaid contours in gray are the five regions referred to in the text. Clockwise from top left: North America, Europe, NE Asia, Congo, and Amazon. Names given are representative only and are not intended to have any political connotations. (f) Global agricultural land (disturbed fraction) as a percentage of total global land area, over time.

linearly, RCP4.5 gives a 0.13-K warming by 2090–2100 compared to the control (No LUC) (Fig. 2). The widespread deforestation in the scenario with no yield increases and no carbon mitigation (zAPG/BAU) gives a worldwide cooling by 2100 of 0.49 K compared to No LUC. Regionally, zAPG/BAU shows significant cooling in most terrestrial areas (see Fig. 2), with the strongest cooling focused in the mid- to high-latitude areas of boreal deforestation. This pattern is consistent with many previous findings of a strong snow albedo feedback (see, e.g., Betts 2000; Betts et al. 2007; Bonan 2008; Brovkin et al. 2006; Claussen et al. 2001; Runyan et al. 2012). In the no carbon mitigation scenario (BAU), only the boreal deforestation in North America gives significant cooling. The no yield increase (zAPG) simulation has only a small area of cooling in northeastern North America, which is correlated with a decrease in forest fraction. RCP4.5 is a less consistent picture, with warming having some correlation with increases in forest fraction, but also significant areas of ocean warming that are more difficult to directly attribute to changes on the land surface.

The positive relationship between temperature and forest fraction seen at the global level is clearer in midlatitude (Northern Hemisphere) summer [June–August (JJA)] and winter [December–February (DJF)], and can even be seen at low latitudes (Fig. 3). The main biogeophysical mechanism responsible appears to be

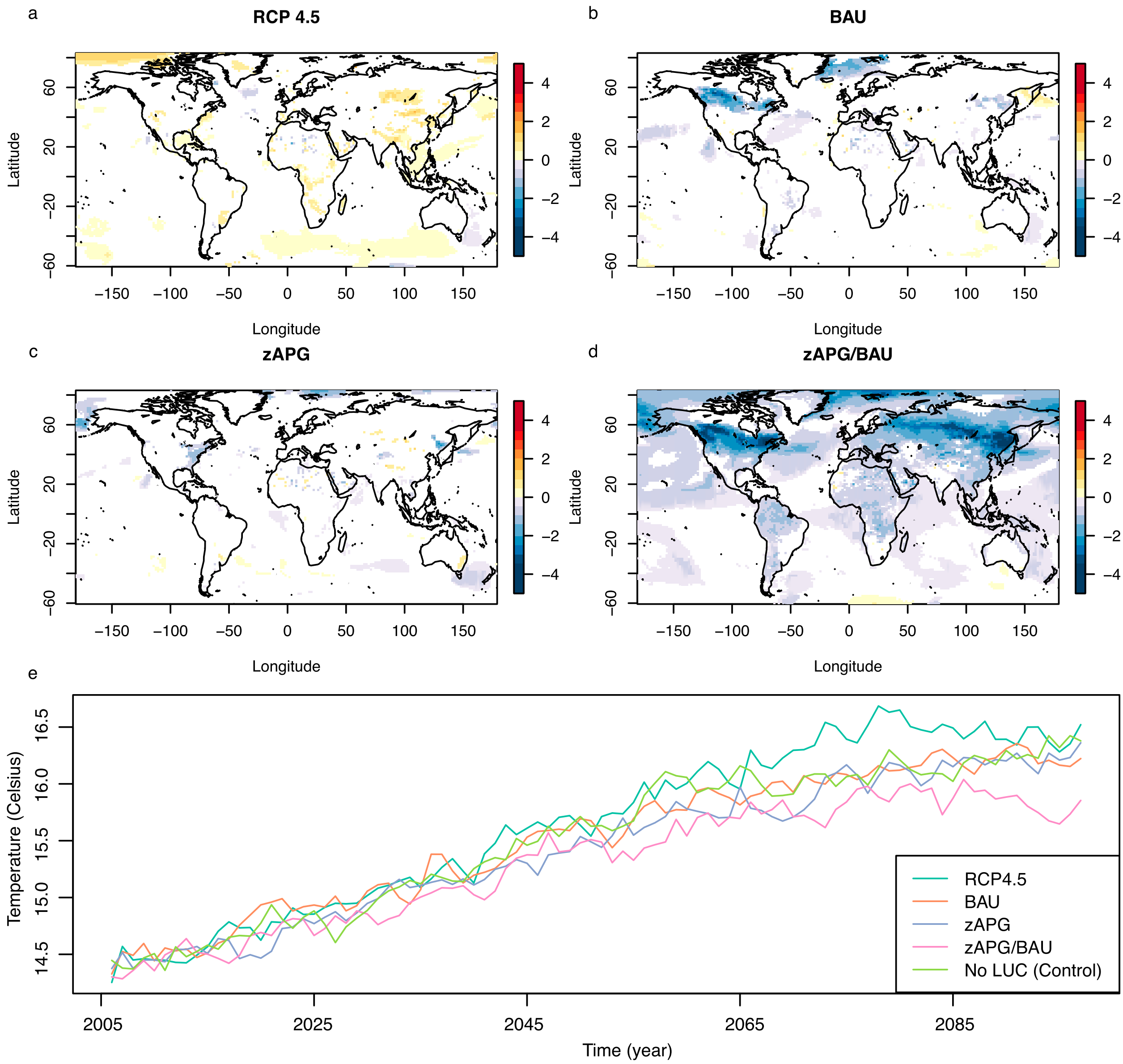

FIG. 2. Mean annual temperature maps of end of the century anomalies with the No LUC scenario for (a) RCP4.5, (b) BAU, (c) zAPG, and (d) zAPG/BAU. Anomalies are only shown for grid boxes where a Wilcoxon rank sum test gives a p value <0.05. (Box–Jung test for autocorrelation shown in Fig. S1 of the supplemental material) (e) Mean annual global temperature over time, for the 95-yr model simulations from 2005 to 2100.

the increase in albedo from the decrease in forest fraction. The change from tree to grass doubles the vegetation dependent snow-free albedo parameter and more than doubles the albedo parameter with snow (Essery et al. 2001). The change in albedo has a clearer linear relationship with temperature (Fig. 3), especially in midlatitude summer. There is a similar sensitivity of temperature to forest fraction change in both summer and winter in the midlatitudes (shown in Table 2), with less than 10% difference. The temperature sensitivity to a change in albedo, on the other hand, is substantially seasonally different, with the winter sensitivity just 20% of the summer sensitivity. The large range of sensitivity in temperature response to albedo in the midlatitudes is because of the seasonal change in total incoming shortwave (SW) radiation, which is much higher in summer. This gives a larger response in temperature to a small change in albedo, resulting in a similar temperature change in both summer and winter as a response to net downward shortwave flux (Fig. 3 and Table 2). From the r^2 values shown in Table 2, we can see that there is a highly significant relationship between the changes

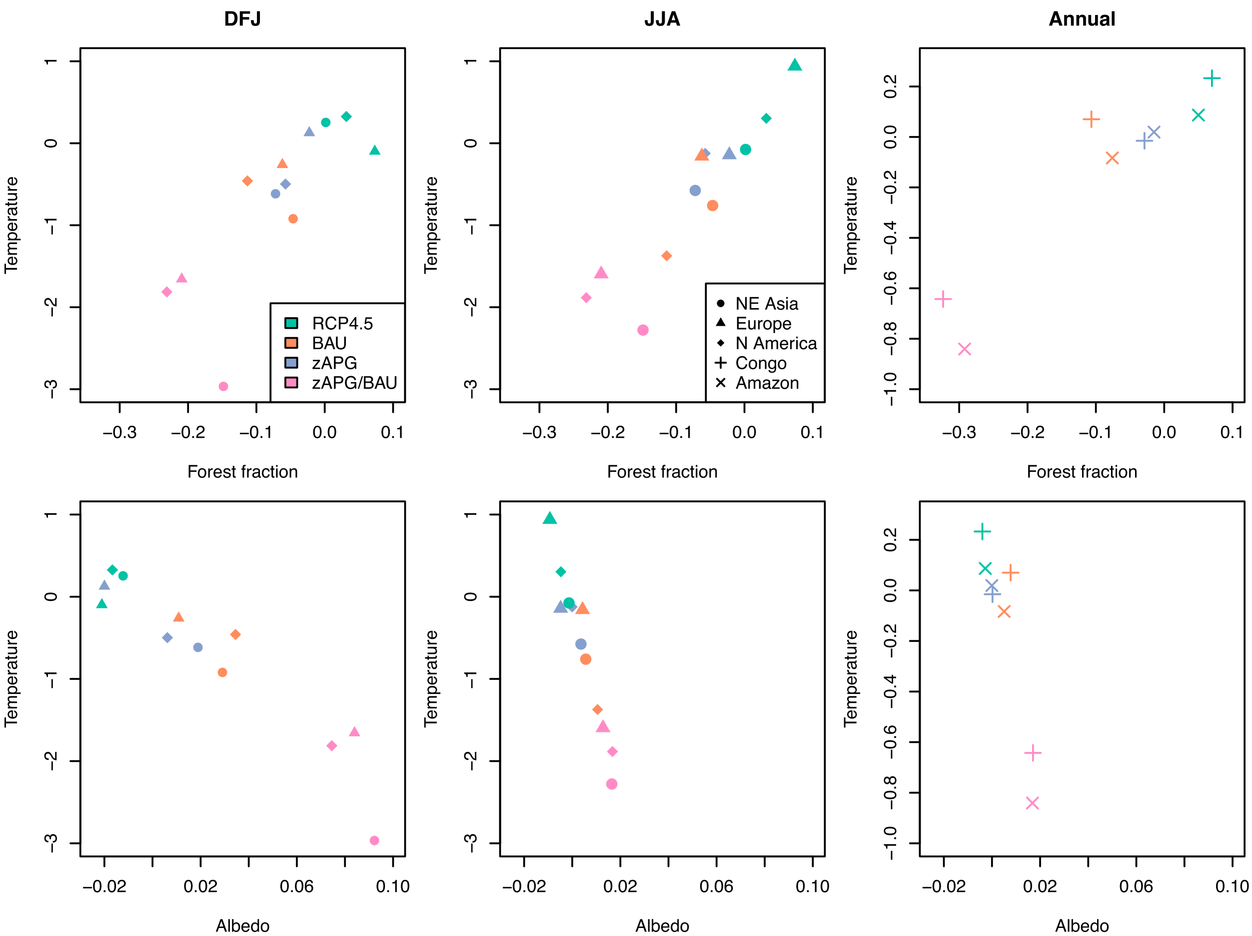

FIG. 3. (top) The positive relationship between temperature anomaly and forest fraction anomaly. (bottom) The negative relationship between temperature anomaly and albedo anomaly. The relationships are shown for summer (JJA) and winter (DJF) in the Northern Hemisphere midlatitudes and the mean annual value for the low latitudes. Values are all anomalies of the last 10 years of the simulation minus the same period for the No LUC scenario. Regions used here can be found in Fig. 1e.

as a result of forest fraction and the temperature since the $r^2 > 0.90$ in all cases except the low-latitude albedo to temperature relationship. Similarly, the low p values (<0.05) suggest that these results are very unlikely to have occurred by chance, especially for the midlatitude seasonal albedo–temperature relationship.

The low latitudes show no pronounced seasonal pattern (not shown) but follow the same relationship between temperature and forest fraction because of the change in albedo (Fig. 3). This suggests that the change in albedo from deforestation is dominating the temperature signal. Previous tropical deforestation simulations tend to show that warming resulting from a reduction in evapotranspiration dominates over albedo cooling (Bonan 2008; Costa and Foley 2000; Feddema et al. 2005a,b; Matthews et al. 2004; Snyder et al. 2004). Although

TABLE 2. The relative sensitivities of temperature shown by the slope and intercept of the linear model for temperature per forest fraction, albedo, and net downward SW surface flux. These equations are for the anomaly of the No LUC control, over the last 10 years of the runs. The r^2 and p values of the relationships are also shown. An asterisk denotes p values <0.01.

	Temperature (K) per forest fraction				Temperature (K) per albedo				Temperature (K) per net downward SW surface flux ($W\,m^{-2}$)			
	Slope	Intercept	r^2	p value	Slope	Intercept	r^2	p value	Slope	Intercept	r^2	p value
Midlatitude DJF	9.9	0.11	0.93	0.023	−22	−0.15	0.97	0.0095*	0.35	−0.13	0.97	0.010
Midlatitude JJA	9.3	0.074	0.98	0.0060*	−105	−0.13	0.97	0.0089*	0.24	−0.14	0.95	0.018
Tropics annual	2.9	0.069	0.95	0.016	−50	0.053	0.89	0.038	0.27	0.071	0.95	0.016

there is only a mean annual temperature decrease of −0.84 K for a 46% decrease in forest in the Amazon for zAPG/BAU, a cooling signal consistent with the change in albedo in the Amazon and Congo appears as early as 2050. It is known that the increase in albedo affects the scale of change to the climate in the low latitudes (Dirmeyer and Shukla 1994), although the changes in albedo here are not extreme (the sensitivity is around 50% of the midlatitude summer temperature sensitivity to albedo). Comparisons of HadGEM2-ES with the models analyzed by de Noblet-Ducoudré et al. (2012) suggest that this model is at the high end of sensitivity of albedo change from forest fraction change in a comparison of historical land use. This suggests that the snow-free albedo cooling effect from deforestation may be relatively strong, resulting in albedo driven cooling dominating the expected warming effect in the tropics in the transient short term.

The unexpected cooling in the tropics is combined with a localized drying that concurs with other studies of tropical deforestation (Costa and Foley 2000; Cox et al. 2004; Garcia-Carreras and Parker 2011; Gedney and Valdes 2000; Hasler et al. 2009; Huntingford et al. 2008). Compared to the No LUC control, the zAPG/BAU scenario has a precipitation reduction of $-0.35\ \mathrm{mm\ day^{-1}}$ in the Amazon ($p = 0.019$ using the Wilcoxon rank sum test, mean for the last 10 years of the simulation). The deforestation is associated with a decrease in latent heat, reducing continental moisture recycling and convective rainfall. The reduction in net shortwave radiation causing the cooling may also be partially responsible for the decrease in precipitation through decreased vertical motion in the atmosphere caused by surface level cooling (Eltahir 1996). The relationship between change in forest fraction, latent heat, and precipitation is not directly linear and afforestation in the Amazon (in RCP4.5) does not lead to an annual increase in latent heat and the associated increase in precipitation. Since these transient runs are unlikely to be in equilibrium such nonlinearity is not too surprising and, in terms of scale and processes associated with the drying in the tropics because of LUC, appears to be robust.

Increased albedo is associated with decreased precipitation in the tropics, but in the Northern Hemisphere midlatitudes it is related to increased summer precipitation, as found by previous studies (Irvine et al. 2011; Ridgwell et al. 2009; Singarayer et al. 2009). The precipitation and corresponding latent heat increase are not directly correlated to the changes in forest fraction or albedo, but instead appear to be caused by alterations in circulation caused by surface heating changes. Since circulation is subject to considerable internal variability, it follows that the variation in precipitation is not linearly related to changes in albedo or deforestation. These changes in summertime precipitation are not statistically significant at the regional level but can have important consequences on other aspects of the climate system, such as net primary productivity (NPP).

Globally, the zAPG/BAU scenario gives an 8% increase in NPP at the end of the century compared to the No LUC control and RCP4.5 has a 3% decrease. The increase in NPP is strongly associated with the change from forest to grasses in both the mid- and low latitudes. In the midlatitudes, NPP is linked with forest fraction through the seasonal cycle (Fig. 4) because of the differences in leaf phenology and temperature range between the plant functional types. In broadleaf trees, leaf mortality increases by a factor of 10 for each degree below zero. The C_3 grasses are considered perennial and although the lower temperature for photosynthesis is the same for C_3 as broadleaf trees (0°C), the leaf area index (LAI) is not affected (Cox 2001). During winter, the cold mean temperature means little photosynthesis occurs and consequently there is no difference across the scenarios (left, Fig. 4). Spring [March–May (MAM)] enhances the increase in NPP with tree fraction, as trees increase their LAI and NPP when they come into bud and cooler temperatures are disadvantageous to early photosynthesis. This effect, along with the change in tree fraction, gives a slight positive relationship between temperature change and forest NPP and a slight negative relationship in grasses, of which the forest influence is greater (left center, Fig. 4). Summer reverses the spring trend for total NPP, as the grasses' negative relationship takes precedence (right center, Fig. 4). In optimum conditions grasses have higher net primary productivity than trees because of higher respiration of woody plants reducing the gross primary productivity more. The positive relationship between forest NPP and temperature is similar to spring, possibly reduced by the lower maximum photosynthesis temperatures of needleleaf trees being disadvantageous in warmer mean temperatures of the RCP4.5 scenario with more forest fraction. Summer also has a range of precipitation anomalies that is a factor of 2 bigger than any other season, which has a positive correlation with NPP (not shown). Overall, summer NPP is dominated by the stronger negative relationship between temperature and NPP of the grasses. Autumn sees the summer trend level off as temperatures cool and less photosynthesis occurs. The overall effect of this seasonal pattern of NPP is a slight increase of NPP in the deforested scenarios, as the summer NPP anomaly is larger than the other seasons.

In the low latitudes the NPP has the same positive relationship between forest fraction and NPP as the midlatitude summer all year round. Like the midlatitudes, there is a negative relationship between temperature and

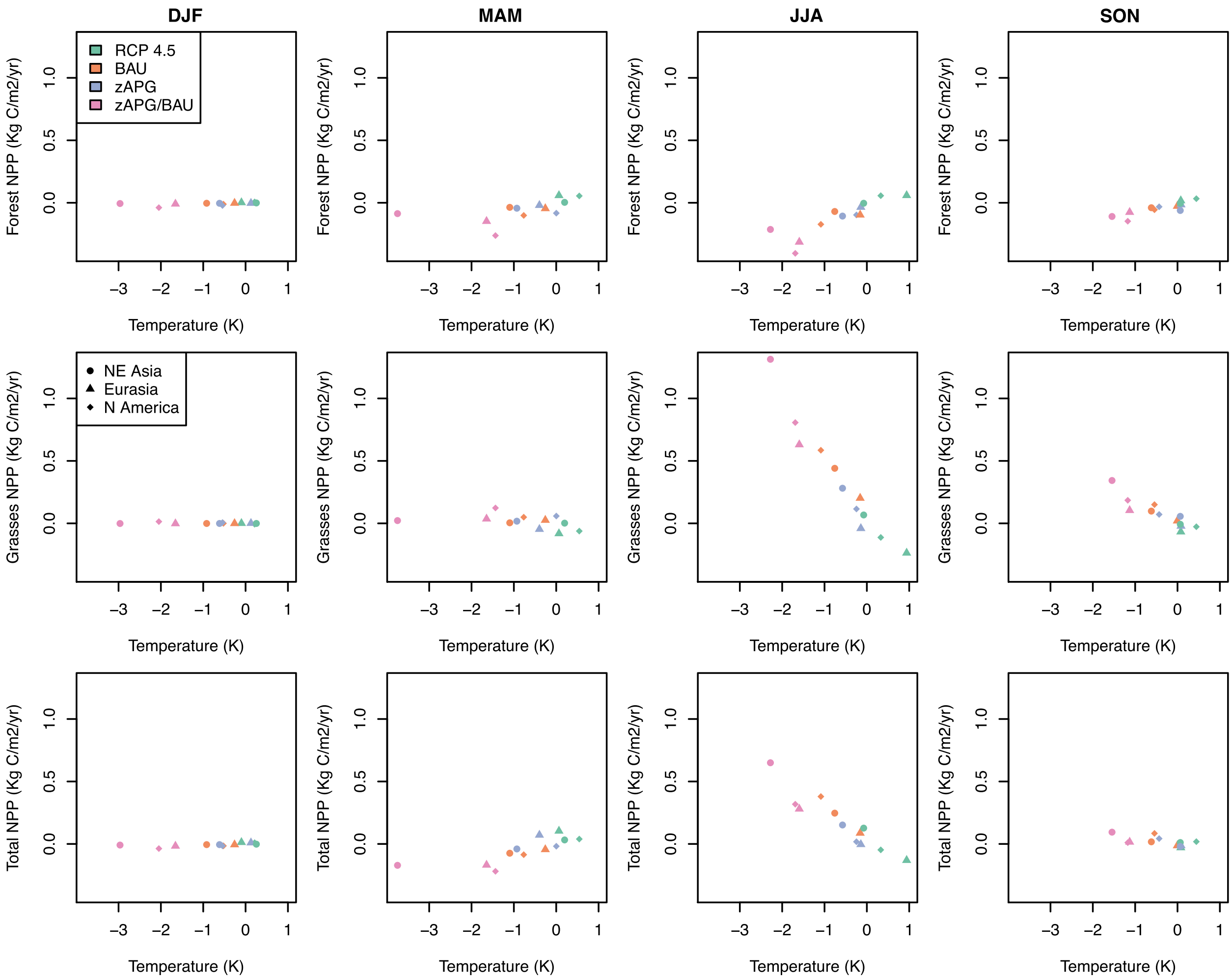

FIG. 4. The seasonal pattern in the relationship between changes in NPP and changes in temperature in the midlatitudes for (top) broadleaf and needleleaf trees, (middle) C_3 and C_4 grasses, and (bottom) all plant functional types. The anomaly is for the last 10 years of the simulations minus the same period for the No LUC control. Regions used here can be found in Fig. 1e. SON denotes the NH fall season (September–November).

NPP. In the Amazon there is an increase in NPP of $0.41\,\mathrm{kg\,C\,m^{-2}\,yr^{-1}}$ (20%) for the zAPG/BAU scenario compared to the control. However, the relationship between precipitation and NPP in the low latitudes is opposite of the midlatitudes; NPP increases with decreasing precipitation (not shown). Overall, the impact to NPP from deforestation here is significant in the tropics. The change is larger than that in the midlatitudes and emerges as early as 2025. This suggests that the differences in respiration and phenology of the plant functional types may be more important than precipitation in determining the NPP resulting from deforestation, especially in the low latitudes.

The changes in NPP also imply a change in the carbon storage, as does the move from trees to grasses. These changes to carbon stores (Table 1) are not fed back to the atmosphere in these simulations, in order to isolate the biogeophysical effects of the LUC. However, they would have implications for the overall climate. The biogeophysical effect shown in Fig. 2 is a cooling in all the scenarios with deforestation compared to No LUC and a warming in the standard RCP4.5, but the biogeochemical effects would be likely to have the opposite signal. To compare the scale of the two effects, we use the transient response to cumulative emissions [TRCE; $\mathrm{K\,(EgC)^{-1}}$] as calculated by Gillett et al. (2013) and used in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Alexander et al. 2013). It has been found across many models that global warming is controlled more strongly by the cumulative emission of carbon than the time pathway, enabling a conversion factor from cumulative emission to temperature to be derived for each model. HadGEM2-ES has been found to warm by 2.1 K for every 1000 PgC

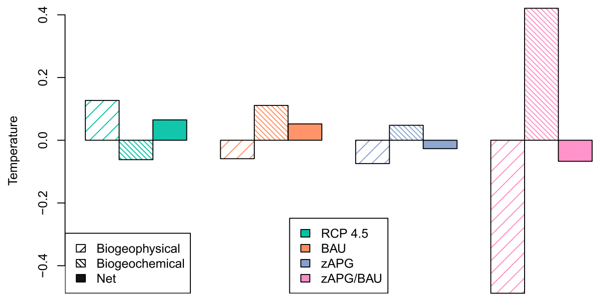

FIG. 5. Worldwide mean temperature anomaly (minus No LUC) in the last 10 years of the simulations from biogeophysical, biogeochemical, and the net (biogeophysical and biogeochemical) effects.

emitted (Gillett et al. 2013). Multiplying the net LUC emissions by the HadGEM2-ES TRCE gives an approximation of the temperature effect that would be associated with the biogeochemical changes (Fig. 5). For all scenarios except BAU the biogeophysical temperature is the determinant of the net temperature signal. This balance is mainly controlled by the location of the deforestation; deforestation in the low latitudes has a smaller cooling effect and a larger carbon impact than deforestation in midlatitudes, which is the opposite. However, the net effect (0.065-K warming in RCP4.5 and −0.067-K cooling in zAPG/BAU) is small and within the natural variability for all the simulations, making the net global temperature effect uncertain.

In contrast to the global perspective, there are distinct differences in regional biogeophysical cooling and carbon emissions. In the Amazon and Congo the decrease in forest fraction in the zAPG/BAU scenario gives a cooling of −0.79 K compared to the control in both regions and a carbon release of 36 and 26 PgC respectively, compared to the No LUC control. The midlatitudes give more cooling for the amount of carbon emitted. NE Asia has the largest cooling (−2.2 K) for the smallest carbon release (7.6 PgC). Europe is similar at −1.3-K cooling for a 15-PgC release. North America is different from the other two midlatitude regions in that it has a carbon release of the same magnitude as the Amazon (35 PgC) but a cooling of −1.6 K. Although the regions are not equally sized (see Fig. 1e), this difference is also reflected in the changes of carbon emissions per unit area. North America has a mean land carbon release of 2.3 $kg^{-1} m^{-2}$ in the zAPG/BAU scenario compared to the control, whereas NE Asia has 1.1 $kg^{-1} m^{-2}$ and the Amazon has 4.1 $kg^{-1} m^{-2}$. The main source of this difference in carbon emissions is the vegetation contribution, which is larger by a factor of 10 than the soil or litter carbon. The broader picture is of more biogeophysical cooling in the midlatitudes because of the winter snow cover and higher carbon storage in low-latitude forests. However, the balance of biogeophysical cooling and contribution to overall biogeochemical warming is highly spatially differentiated in ways that are more nuanced than a simple mid- and low-latitude divide.

4. Discussion

A hypothetical scenario of no yield increase and no mitigation strategy (zAPG/BAU) land-use change leads to large-scale deforestation and, in our model, significantly cools the climate through the increases in albedo. In the RCP4.5 scenario, the land-use change accounts for 0.13 K of the 2-K temperature rise between 2005 and 2100. In the zAPG/BAU scenario the biogeophysical cooling of −0.49 K amounts to around 25% of the total warming although the net cooling after accounting for the carbon release is −0.067 K, around 3% of the total temperature rise in RCP4.5. The net biogeophysical and biogeochemical temperature impact is dominated by the biogeophysical signal. Separately, neither BAU nor zAPG significantly affects the biogeophysical global climate; rather, they have spatially differentiated effects due to their different patterns of land-use change. Similarly, land-use change in RCP4.5 also does not significantly warm the global climate, but warms proportionally to the relatively small increase in forest fraction, which drives the climatic change in all these scenarios.

The worldwide biogeophysical temperature changes of 0.61 K for a decrease in forest fraction of 51% (compared to RCP4.5) found in this study are broadly consistent with the experiment by Jones et al. (2013) of deforestation under no land carbon pricing, which found a −0.5 K cooling for a decrease in 52% of forest fraction. This intermodel agreement suggests that this biogeophysical temperature change is a robust result. The global temperature impacts of the biogeophysical and biogeochemical changes are of the same approximate magnitude and offset each other when compared to the No LUC control. However, the estimation of the temperature change used here only includes carbon emissions; emissions from land-use change of methane, nitrous oxide, ozone, etc. will also have an effect on the resultant climate and environment.

The spatiality in the biogeophysical temperature changes means that although the net global impact is small, the local impact could be substantial. Areas of considerable cooling, such as NE Asia with a mean −2.2 K biogeophysical cooling in the zAPG/BAU scenario compared to the control, would be likely to remain cooler despite the warming caused by global land carbon emissions. However, the regions where the net local effects would be cooling may not be areas most likely to benefit from cooling. For instance, a Ricardian analysis of the effects of climate change on agriculture in northern China suggests that in this region increased temperature may be beneficial to crop yield (Chen et al. 2013). Therefore, although there is likely to be net marginal cooling in some areas, these are not necessarily the areas that would most benefit from decreased temperatures.

Local impacts are also likely to include precipitation changes, driven by latent heat and Bowen ratio changes (Bonan 2008). The increase in summer precipitation resulting from albedo increases is a previously seen feature of the Hadley Centre model (Singarayer et al. 2009). However, the regional Bowen ratio changes, which probably drive it, vary widely between land surface models (de Noblet-Ducoudré et al. 2012). The precipitation reductions found in the tropics are more robust since the mechanisms are well documented, with surface albedo changes and evapotranspiration decreases both contributing to reduced moisture recycling. The precipitation change in the Amazon ($-0.36\ \mathrm{mm\ day^{-1}}$ for zAPG/BAU for 46% reduction in forest fraction) is consistent with the $0.42\ \mathrm{mm\ day^{-1}}$ reduction in precipitation found by Costa and Foley's (2000) total deforestation experiment and other deforestation simulations.

Since the climatic impacts are consistent and have an approximately linear relationship with deforestation, we may be able to infer the effect of greater deforestation than is seen in zAPG and BAU. This is important as the BAU and zAPG deforestation scenarios might well be conservative estimates because of the allocation of land within both GCAM and HadGEM2. The GCAM model assumes that there will be diminishing returns of yield with the increase into marginal agricultural land; the productivity varies by a factor of 3 worldwide (Wise et al. 2009b). As discussed in the introduction, the plateauing of yields in the last 30+ years (Ray et al. 2012) suggests that even high-yielding land may not achieve its potential. If this diminishing return is underestimated, this would mean that the crop and pasture fraction change would be larger in all the scenarios, having implications for agriculture-driven deforestation. Since the change in forest fraction is the key component to the climatic change, the HadGEM2 assumption is more salient. The land surface scheme (MOSES2) allocates the increase in total agricultural land within each grid box preferentially to first natural C_3 and C_4 grasses, then shrubs and trees; that is, all the natural C_3 and C_4 grass within a grid box must converted to agriculture before the model will convert trees to agricultural land. There are other methods of allocation used by land surface schemes, which for instance convert all plant functional types to agricultural land proportionally to their coverage in the grid box. Obviously the reality of such decisions is likely to be spatially and socially differentiated and cannot be adequately parameterized in a climate model. Note that 80% of the agricultural increase in zAPG/BAU results in deforestation, whereas in the BAU scenario it is only 57%. Therefore the BAU scenario may be underestimating deforestation by up to 23%, which would be likely to have noticeable climatic impacts.

The potential underestimation of the pace and scale of deforestation means that it is difficult to say that there would not be significant biogeophysical changes to climate from either BAU or zAPG separately. The deforestation effect in zAPG/BAU is clearly enhanced compared to the sum of the zAPG and BAU effects separately (40% global deforestation as opposed to 17%). The regional and global effects mainly scale proportionally with the reduction in forest fraction, so if the deforestation for agricultural land is underestimated, the BAU and zAPG scenarios could be considerably closer in impact to the zAPG/BAU scenario depending on the pattern of agricultural expansion into either forest or grassland natural ecosystems.

This study shows that different land-use change scenarios created by yield increases and a universal greenhouse gas tax have nontrivial climatic impacts on a regional scale and may even have global implications. The four scenarios of land-use change compared to a no land-use change control allow a direct comparison of the biogeophysical effects of different scenarios of future land-use change from yield increases and mitigation efforts, in isolation from the biogeochemical effects. To see the marginal cooling from the net biogeophysical and biogeochemical effects as a "positive" climate outcome would clearly be overly simplistic. As well as climatic impacts, the expansion of agricultural land into natural ecosystems would also have considerable implications for environmental issues and can undermine crucial ecosystem services (Foley et al. 2005). However, this does elucidate the potential tradeoff between the benefits of yield increases and land carbon pricing in terms of avoided deforestation and its consequent environmental impacts, and a small but uncertain global climatic benefit. It would severely underestimate the complexity of the issues, if policy were to consider only the climatic impact of carbon emissions from changes in land use.

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