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To cite this article: Natalie M Mahowald et al 2017 Environ. Res. Lett. 12 094016

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Are the impacts of land use on warming underestimated in climate policy?

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Abstract

While carbon dioxide emissions from energy use must be the primary target of climate change mitigation efforts, land use and land cover change (LULCC) also represent an important source of climate forcing. In this study we compute time series of global surface temperature change separately for LULCC and non-LULCC sources (primarily fossil fuel burning), and show that because of the extra warming associated with the co-emission of methane and nitrous oxide with LULCC carbon dioxide emissions, and a co-emission of cooling aerosols with non-LULCC emissions of carbon dioxide, the linear relationship between cumulative carbon dioxide emissions and temperature has a two-fold higher slope for LULCC than for non-LULCC activities. Moreover, projections used in the Intergovernmental Panel on Climate Change (IPCC) for the rate of tropical land conversion in the future are relatively low compared to contemporary observations, suggesting that the future projections of land conversion used in the IPCC may underestimate potential impacts of LULCC. By including a ‘business as usual’ future LULCC scenario for tropical deforestation, we find that even if all non-LULCC emissions are switched off in 2015, it is likely that 1.5°C of warming relative to the preindustrial era will occur by 2100. Thus, policies to reduce LULCC emissions must remain a high priority if we are to achieve the low to medium temperature change targets proposed as a part of the Paris Agreement. Future studies using integrated assessment models and other climate simulations should include more realistic deforestation rates and the integration of policy that would reduce LULCC emissions.

1. Introduction

The recent Paris COP21, with the follow-up agreements by governments, and Marrakesh COP22, suggest hopeful steps towards real climate action on the part of governments (Newsroom 2015, Peters et al 2015). However, the goal of keeping climate warming below 2°C is difficult or even impossible without drastic cutting of anthropogenic carbon dioxide (CO₂) emissions, especially from the energy sector (Peters et al 2015). Since emissions from land use change are currently estimated to be about 10% of total anthropogenic carbon dioxide emissions (Le Quéré et al 2016), most of the current policy focus is on cutting fossil fuel carbon emissions to reach the 2°C targets (Peters et al 2015). However, recent studies highlight the importance of land conversion of natural lands to agriculture or pasture and the ensuing greenhouse gas emissions and their impact on radiative forcing of climate (Ward and Mahowald 2015, Ward et al 2014). Currently, although only 20% of the accumulated anthropogenic rise in carbon dioxide originates from land use and land cover change (LULCC), 40% of the net positive radiative
forcing from human activities is attributable to LULCC sources (Ward et al 2014). This is because the LULCC co-emissions of methane and nitrous oxide enhance warming, while co-emissions of cooling aerosols by non-LULCC processes, like fossil fuel burning tend to offset non-LULCC radiative forcing (Ward et al 2014). In addition, there is some evidence that deforestation rates estimated in the Representative Concentration Pathways (RCPs) used for the IPCC estimates of future climate (van Vuuren et al 2011) may underestimate tropical deforestation in the future (e.g. Ward et al 2014, Ward and Mahowald 2015, Ciais et al 2013).

Much of the recent framing of the climate change challenge has focused on cumulative carbon dioxide emissions as a tool to estimate future warming, since studies have shown across a large range of scenarios that there is an approximately linear relationship between cumulative carbon dioxide emissions and temperature change up to 2100 (Matthews et al 2009, Allen et al 2009, Stocker et al 2013). This powerful linear relationship motivates much of how we think about climate and impacts climate policy, and specifically motivates the focus of climate policy on carbon dioxide emissions. The approach is especially useful for understanding the importance of moving from a high to low fossil fuel emission scenarios (Friedlingstein et al 2011). Using this framework, here, we use a previously published time-series of global radiative forcing computed separately for the LULCC and non-LULCC sectors of anthropogenic activities based on the RCPs (Ward et al 2014, Ward and Mahowald 2015) to determine each sectors’ individual impact on the relationship between the cumulative carbon dioxide emission and temperature. In addition, we seek to understand the importance of the current rate of deforestation, if it continues, for climate, especially in the light of the ambitious climate targets from the Paris Agreement.

2. Methods

We use previously published radiative forcing (RF) time series that were calculated for LULCC and other non-LULCC sources separately, and for different future scenarios using a hierarchy of models including the Community Land Model (CLM) within the Community Earth System Model (Hurrell et al 2013, Lawrence et al 2012a). These simulations are described in detail elsewhere (Ward et al 2014, Ward and Mahowald 2015). Here we review only the basics of these calculations, and then indicate where new calculations were made for this study, with more details provided in the supplemental material available at stacks.iop.org/ERL/12/094016/mmedia.

Our approach was to start with the RCPs used in the Coupled Model Intercomparison Project (CMIP5) that were generated and analyzed as part of the last Intergovernmental Panel on Climate Change (IPCC) (Clarke et al 2007, Fujino et al 2006, Riahl et al 2007, van Vuuren et al 2007, Wise et al 2009, Lamarque et al 2010, van Vuuren et al 2011, Ward et al 2014, Ward and Mahowald 2015). The difference between the estimates reported here (published in Ward et al 2014, Ward and Mahowald 2015) and previous estimates is that here we separated the radiative forcing into LULCC and non-LULCC components. Generally, our LULCC forcing included all related global-scale processes: land conversion, harvesting, agriculture emissions, agriculture fires, reduced wildfires from land conversion, and pasture use. We included all fossil fuel emissions in the non-LULCC emissions, along with concrete production and halocarbon emissions. Carbon dioxide emissions from LULCC were determined from global terrestrial model simulations using the CLM with historical and projected LULCC compared to a simulation without LULCC, using identical non-LULCC forcings (non-LULCC forcings follow RCP4.5 for 2005–2100). Associated changes in land surface albedo due to LULCC, as well as changes in emissions from wildfires and biogenic sources resulting from land cover changes, also were represented in these simulations. Agricultural emissions of trace gases and aerosols, including from agricultural fires, were compiled from existing inventories developed for the RCPs (Lamarque et al 2010, van Vuuren et al 2011, Ward et al 2014, Ward and Mahowald 2015).

The previous studies (Ward et al 2014, Ward and Mahowald 2015) that we drew upon in this paper used a combination of box model methods for long-lived forcing agents (greenhouse gases) and a global atmospheric model with aerosol/cloud interactions and complex chemistry to compute changes in concentrations of chemically-reactive, climatically important forcing agents due to LULCC. These calculations showed that the net impact of LULCC on methane was larger than the non-LULCC impact on methane, despite similar emissions from each sector, because non-LULCC emissions of nitrogen oxides and volatile organic compounds increased the oxidative capacity of the atmosphere which reduced the lifetime of methane, and thus reduced atmospheric methane as discussed in more detail in (Ward et al 2014). Anthropogenic nitrous oxide emissions were largely due to LULCC processes, and thus anthropogenic nitrous oxide radiative forcing also was predominately determined to be due to LULCC (Ward et al 2014). A previous study looked explicitly at the role of land conversion versus land management emissions, and split the results between these two processes (Ward and Mahowald 2015).

The estimates of radiative forcing used here that come from previous studies were made in a manner to ensure consistency with the IPCC 5th Assessment Report (Stocker et al 2013, Ward et al 2014, Ward and Mahowald 2015). Global radiative forcing values were computed at years 2010 and 2100, relative to a base
state of 1850, for changes in CO$_2$, CH$_4$, N$_2$O, O$_3$, halocarbons, aerosol (black carbon, organic carbon, sulfate, mineral dust) direct effects, aerosol indirect effects, aerosol impact on snow surface albedo, and land albedo change. Total anthropogenic aerosol radiative forcing calculated in our model was scaled to match best estimates from the last IPCC (Myhre et al 2013), since these forcings from aerosols were overestimated in our model similar to most models (Myhre et al 2013).

For this study, we computed the time-varying radiative forcing to show the evolution of the LULCC vs. non-LULCC contributions to radiative forcing and temperature. Interpolation between 1850 and 2010, and between 2010 and 2100, was done for the individual forcing agents by scaling the RF linearly with changes in the emissions of the agent or relevant precursor species, such as NO$_x$ for the O$_3$ forcing (Ward and Mahowald 2015). Uncertainties in the radiative forcing values, computed for the year 2010 by Ward et al (2014), were scaled by the same methodology.

Ward et al (2014) report future LULCC and non-LULCC radiative forcing estimates for each of the four RCP scenarios. In addition, we evaluated a non-RCP-based scenario, which assumes that tropical deforestation continues into the future at current rates (FAO 2010). This scenario was first presented in Ward and Mahowald (2015). We focused on the rates (FAO 2010). This scenario was first presented in Ward and Mahowald (2015). Uncertainties in the radiative forcing values, computed for the year 2010 by Ward et al (2014), were scaled by the same methodology.

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Figure 1. (a) Anthropogenic radiative forcing (Wm$^{-2}$) for the year 2010 relative to 1850 partitioned into LULCC and non-LULCC sources for different forcing agents, with uncertainty in the portion of total radiative forcing due to LULCC given by the error bars (adapted from Ward et al 2014). (b) Timeseries of anthropogenic radiative forcing (Wm$^{-2}$) for LULCC and non-LULCC sources with uncertainty represented by the shading.

The IPCC AR5 does not define a ‘best guess’, median equilibrium climate sensitivity so here we defined the gamma distribution median as 2.4 K, the value of the equilibrium climate sensitivity that lead to the best match between MAGICC6 and the observed global mean surface temperature anomaly (relative to preindustrial) for the period 1980–2010, determined by the least-squares method. We fit a gamma distribution with a shape parameter equal to 5 to the (Rogelj et al 2014) probability ranges, which, because of the low median equilibrium climate sensitivity relative to the possible range in equilibrium climate sensitivity values (0.5 K to 8.0 K), skews somewhat toward lower values of equilibrium climate sensitivity than estimated by the IPCC AR5.

3. Results

3.1. Cumulative carbon dioxide emissions relationship with temperature

In 2015, although only 10% of the current emissions of CO$_2$ derive from LULCC (Le Quéré et al 2016), 20% of the accumulated anthropogenic rise in CO$_2$ concentrations originates from LULCC (figure 1(a), Ward et al 2014). The enhanced impact of LULCC on anthropogenic CO$_2$ occurs because LULCC was a proportionally larger source of CO$_2$ emissions during the 20th century (Le Quéré et al 2016), there is still substantial contribution of previously emitted LULCC to atmospheric concentrations (figure 1(a)). Currently, although only 20% of the accumulated anthropogenic rise in carbon dioxide originates from LULCC, 40% of the net positive radiative forcing from human activities is attributable to LULCC sources (Ward et al 2014). The effective LULCC radiative forcing is enhanced by LULCC emissions of methane and nitrous oxide (figure 1(a)). The other anthropogenic greenhouse gas sources (non-LULCC) derive partially from fossil fuel CO$_2$, but include CO$_2$ from cement production and halocarbons. The impact of the radiative forcing of the non-LULCC emissions is partially offset through co-emissions of aerosols; these aerosols cause a net negative, or cooling, radiative forcing (Ward et al 2014) (figure 1(a)). While at present similar amounts of methane are emitted by LULCC and non-LULCC sources, co-emissions from non-LULCC sources enhance the oxidative capacity of the atmosphere and reduce the methane lifetime relative to the LULCC case, leading to a smaller methane RF attributed to non-LULCC emissions (Ward et al 2014).

LULCC was the dominant driver of positive anthropogenic radiative forcing until the 1980s (figure 1(b)), in part because of the considerable contribution of CO$_2$ emissions from this sector relative to other
sources during first half of the 20th century (Le Quéré et al. 2016). For the contemporary period, the overall net radiative forcing from LULCC (40%) is twice the proportion of the radiative forcing from CO₂ that can be attributed to be from LULCC (20%), indicating a two-fold enhancement of total radiative forcing (RF) relative to the CO₂ anomaly for LULCC compared with non-LULCC sources (figure 1) (Ward et al. 2014).

LULCC impacts on climate change are also likely to be significant into the future (Ward and Mahowald 2015, Ward et al. 2014, figure S1). The two-fold enhancement of total RF compared with RF from CO₂ for LULCC compared to non-LULCC is predicted for all the different RCPs used in the last IPCC at 2100 (van Vuuren et al. 2011, Ward and Mahowald 2015, Ward et al. 2014). Although these results are sensitive to assumptions regarding co-emissions of aerosols and non-CO₂ greenhouse gases, the forcing differences are surprisingly small across the various RCPs and historical estimates (Ward and Mahowald 2015, Ward et al. 2014). Because aerosol emissions in the RCPs are projected to decrease at a possibly unrealistic rate (Schindell et al. 2013), the non-LULCC contribution to overall temperature change may even be smaller than these estimates.

This suggests that while the linear relationship between cumulative carbon dioxide emissions and temperature may work well for the net impact anthropogenic activity over a variety of scenarios (Allen et al. 2009, Stocker et al. 2013), a different, steeper slope should be used when considering the influence of LULCC compared to non-LULCC (figure 2, 0.0030 K PgC⁻¹ vs. 0.0016 K PgC⁻¹). Until the 1970s, non-LULCC CO₂ emissions were associated with a zero net radiative forcing (figure 1), which results in a zero net impact on temperature, and then later the slope with respect to cumulative carbon emissions steepens, as the co-emitted species change (figure 2). The observed line (based on 1960–2010 observed temperatures) has a similar slope and intercept as to the non-LULCC CO₂ emission line (based on 1960–2100 predicted temperatures), as during this time period especially, there is a stronger contribution from non-LULCC to current warming (e.g. figure 1).

Effectively, the slopes ($m_{\text{LULCC}}$ and $m_{\text{non-LULCC}}$) in figure 2 represent the following processes:

$$m_{\text{LULCC}} = \frac{\Delta T}{\Delta RF} \frac{\text{RF}_{\text{CO₂}} + \text{RF}_\text{CH₄} + \text{RF}_\text{N₂O} + \text{RF}_{\text{aerosols}}}{\sum \text{Emis}_{\text{LULCC}} (\text{CO₂})}$$

$$m_{\text{non-LULCC}} = \frac{\Delta T}{\Delta RF} \frac{\text{RF}_{\text{CO₂}} + \text{RF}_\text{CH₄} + \text{RF}_\text{N₂O} + \text{RF}_{\text{aerosols}}}{\sum \text{Emis}_{\text{non-LULCC}} (\text{CO₂})}$$

(1)

Where ($\Delta T/\Delta RF$) is the change in temperature per change in RF (called the climate sensitivity, and the colored areas around the points represent the spread due to uncertainties in the climate sensitivity, as described in section 2), and $\sum \text{Emis}$ (CO₂) is the cumulative carbon emissions, from either LULCC or non-LULCC processes up until different times (Stocker et al. 2013). Strong positive and negative contributions are indicated in bold and put inside square brackets, respectively. Weak contributions are shown in black or not included (relative contributions for each
forcing agent are shown in figure 1(a)). Uncertainties in these slopes originate from uncertainties in our understanding of the climate sensitivity, the magnitude of forcing associated with individual processes, and the response of global mean temperature to a particular radiative forcing (Stocker et al. 2013). Since most of the positive RF from methane and nitrous oxide come from LULCC, and most of the negative RF from aerosols comes from non-LULCC (figure 1(a)), the non-LULCC cumulative carbon relationship with temperature at different times has a lower slope. The LULCC and non-LULCC slopes are much more similar, of course, if instead of considering cumulative carbon dioxide emissions, we consider equivalent carbon dioxide emissions (figure S2). Note also, that if deforestation rates were stabilized, but agriculture or pasture usage caused continued increases in methane or nitrous oxide emissions, the carbon dioxide emissions would be zero, but there would be a non-zero climate response, forcing the slope to be even higher (infinite).

3.2. Future climate sensitivity to deforestation rates

The Climate Model Intercomparison Project (CMIP) simulations used in the IPCC are based on the RCPs projections of future land use change or deforestation rates. Most contemporary deforestation is focused in tropics, and so we focus our discussion here on that region (FAO 2010). The combined historical and RCP scenario estimates used in Earth system models estimates of current deforestation rates in the tropics are less than those observed during the past two decades (figure 3) based on Food and Agriculture Organization (FAO) estimates (FAO 2010, Huru et al. 2011, Meyfroidt and Lambin 2011, Ward et al. 2014), although carbon emissions in the simulations presented here during 2000–2010 are similar to other model and observationally-based estimates within the large uncertainties (Le Quéré et al. 2016, Ward et al. 2014). The future scenarios generated by the IAMs for the RCPs used to drive the CMIP5 earth system models in the most recent IPCC all simulate the same or lower rates of tropical deforestation than estimated today by FAO (figure 3). If we assume for simplicity that the IAMs are correct in projecting that the pressure for land conversion will remain the same as what is observed today, and we use observations to set the baseline rate during 2000–2010, we can estimate the influence of TBAU LULCC impacts on climate (Ward and Mahowald 2015).

Assuming all other anthropogenic emissions cease in 2015, the TBAU LULCC impacts will likely cause temperatures to increase more than 1.5 °C and potentially even more than 2 °C, relative to the pre-industrial era, by 2100 (figure 4(a)). This future-LULCC forced rise in temperature adds about 1 °C to the rise in temperature already in the pipeline from emissions that occurred prior to 2015 to produce the 1.5 °C warming (Hansen et al. 2005) (figures 4(b) and (c)). At 2100 TBAU LULCC impacts can be as large as RCP4.5 non-LULCC climate impacts (figure 4(c); case ii vs. iii). The difference at 2100 between RCP4.5 and RCP8.5 non-LULCC is more than 1K (figure 5; v vs. vi) and is likely to grow larger after 2100. Our results are consistent with previous studies that emphasize climate change policy should focus on reducing CO2 emissions from non-LULCC sources. However, about 1 °C rise in temperatures is associated solely with LULCC-TBAU, even with a moderate emission scenario for fossil fuels and other anthropogenic emissions, such as RCP4.5 (figure 4(c); case iii vs. v).
Figure 4. (a) Change in global mean surface temperature relative to an 1880–1900 average for a scenario including TBAU LULCC forcing and non-LULCC emissions that are set to zero after the year 2015. Quantiles are computed from the MAGICC6 simulation ensemble, and the observed global mean temperature is plotted as a solid line between 1985 and 2015 (GISS). (b) Decadal average net anthropogenic radiative forcing from the LULCC and non-LULCC scenarios used to determine the temperature in panel (a). The radiative forcing terms are calculated in Ward and Mahowald 2015, Ward et al 2014) for LULCC and other sources (labeled non-LULCC here). The interquartile range is determined from the MAGICC6 ensemble. Note that the gray bands represent a consistent temperature change between panels (a) and figure 5.

Figure 5. Temperature anomaly in 2100 relative to the 1880–1900 average (GISS) (with one standard deviation uncertainty bands) for five different cases, all of which include the estimated historical forcing until 2015: (i) all non-LULCC emissions cease after 2015 (2015-off) and LULCC stopped at 2015 (2015-off); (ii) all non-LULCC emissions cease after 2015 (2015-off), but LULCC continues at tropical business as usual (TBAU); (iii) RCP4.5 non-LULCC emissions with LULCC stopped at 2015 (2015-off); (iv) RCP4.5 non-LULCC emissions with LULCC using RCP4.5; (v) RCP4.5 non-LULCC emissions with LULCC using TBAU; (vi) RCP8.5 non-LULCC emissions with LULCC using TBAU. The radiative forcing terms are calculated in Ward and Mahowald 2015, Ward et al 2014) for LULCC and other sources (labeled non-LULCC here). The interquartile range is determined from the MAGICC6 ensemble. Note that the gray bands represent a consistent temperature change between figures 4(a) and 5.

4. Discussion and conclusions

Here we show that the slope of the cumulative carbon dioxide emissions and temperature relationship is twice as high for LULCC than for non-LULCC processes (figure 2). This implies that carbon dioxide emissions from LULCC is associated with twice the impact on climate as carbon dioxide emissions from non-LULCC processes, at least until 2100. This is due to the larger contributions of the warming greenhouse gases methane and nitrous oxide from LULCC to global RF relative to LULCC carbon dioxide emissions, and
the larger cooling from co-emitted aerosols from non-LULCC per unit emission of carbon dioxide (figure 1(a); Ward et al 2014). The impact of these emissions in future scenarios on climate will be very sensitive to the assumptions about the emissions of aerosols (from non-LULCC) and methane and nitrous oxide from LULCC sources (figure 1(a)), but these results are surprisingly robust across the multiple IAMs used for the RCPs (Ward et al 2014). They may also underestimate the effect of aerosols into the future, as all of the RCPs assume very strong cuts in aerosol emissions in the short term (Van Vuuren et al 2011, Shindell et al 2013). While the use of the linear relationship between temperature response and cumulative carbon dioxide emissions is helpful in contrasting very high CO₂ and low CO₂ future scenarios, for medium to low CO₂ scenarios, using metrics which include other green house gases and aerosols is important (e.g. Allen et al 2016).

Additionally, the LULCC contribution to future warming may be of greater importance than is currently thought because it is likely that the land use scenarios used in the IPCC are underestimating the current land use conversion rate. FAO estimates are higher than those used to derive future warming in the IPCC (FAO 2010, Hurr et al 2011, Meyfroidt and Lambin 2011, Ward et al 2014) (figure 3) and recent observationally-based estimates of deforestation suggest that deforestation now may be larger than estimated from FAO (Achard et al 2014, Hansen et al 2013) (figure 3). It is difficult to derive deforestation rates, however, from Landsat satellite observations because some changes in forest area are not caused by deforestation or other forms of land management, but by natural processes. Indeed there can also be shifting cultivation or wood harvesting areas, allowing regrowth. This suggests that we can only use the observational estimates as upper bounds on deforestation rates (Achard et al 2014, Hansen et al 2013), but these observational estimates and FAO estimates are larger than the forcing datasets used in the IPCC. Thus, our TBAU estimates may be considered a reasonable upper bound on future rates of change, but require further refinement.

Loss of tropical forest cover also weakens the response of the terrestrial biosphere to accumulate carbon in response to rising levels of atmospheric CO₂ (Gitz and Ciais 2003, Mahowald et al 2017). This considerably weakens the carbon-concentration feedback, accelerating climate warming (Mahowald et al 2017).

Estimates suggest the rates in Amazonian deforestation in Brazil have been increasing again, showing the vulnerability of tropical forests to the demand for land expansion (Tollefsen 2016). The future scenarios generated by the IAMs and used in the CMIP5 Earth system models used in the most recent IPCC simulate the same or lower rates of tropical deforestation than estimated today by the FAO (figure 3). Of course, future land conversion is difficult to project. While future crop yield projections are sensitive to assumptions about the ability of humans to innovate both management methods and genetic attributes (Fischer et al 2005), some evidence suggests that yield improvements may already be decreasing (Ray et al 2012) and that agricultural crops may be more sensitive to temperature than previously estimated (Lobell et al 2011). Thus we may require more land in the future for the same food production. Recent studies highlight the potential dangers of foreign land acquisition in many poorer countries, as rapidly developing countries try to purchase available land and ‘outsource’ their LULCC (Rulli et al 2013), which may also drive additional deforestation. In addition, most of the emission projections that stay at or below the 2°C warming target require substantial negative emissions, often using land-based biofuels and carbon sequestration (Smith et al 2016). Thus, there is a potentially large, systematic low bias in future projections of LULCC deforestation and land conversion rates, and the resulting impact on climate (Ward et al 2014). Taken together, these recent developments suggest that reductions in land use conversion, especially of forests in tropical countries, as assumed in the RCPs, may not occur without considerable international effort. Using a more realistic estimate of tropical-business-as-usual conversion of forests, we estimate about 1°C rise in temperature will result by 2100 solely due to LULCC, with a substantial probability of exceeding 2°C warming relative to preindustrial temperatures even without non-LULCC emissions (figure 4). Since both the deforestation itself, as well as the land management emissions from agriculture or pasture usage contribute roughly equally to the LULCC radiative forcing (Ward and Mahowald 2015), policy measures targeted at LULCC should address both deforestation rates, as well as agricultural emissions (Foley et al 2011, Kauppi et al 2006, Lambin and Meyfroidt 2011, Chabbi et al 2017). Policy tools can provide incentives for farmers to reduce emissions from fertilizer use, rice cultivation and livestock, for example (Foley et al 2011, Kauppi et al 2006, Lambin and Meyfroidt 2011, Chabbi et al 2017).

Fundamentally, LULCC is driven by the need for food and shelter. We can use land more efficiently with less environmental impacts (Foley et al 2011, Kauppi et al 2006, Lambin and Meyfroidt 2011, Chabbi et al 2017), but land-based agriculture requires arable land. Although humans have recently been successful at obtaining more food from the oceans (FAO 2016), this may be difficult in the future as these ecosystems are also heavily exploited (Watson et al 2013). In contrast, at least theoretically, there are methods for producing sustainable energy without producing carbon dioxide (IPCC 2014). Thus in some ways LULCC emissions may be just as difficult or more difficult to mitigate than energy (Lambin and Meyfroidt 2011). More realistic consideration of LULCC is needed in IAM projections used for IPCC assessments (e.g. Riahi et al 2017), so that the many policy choices and tools
for LULCC are more fully considered (e.g. Foley et al. 2011, Chabbi et al. 2017). While reducing fossil fuel emissions of carbon dioxide must remain a priority for climate change policy (figure 5), policies addressing LULCC, especially tropical deforestation and other agricultural emissions, must be included in the agreements if we want to achieve low temperature targets, such as 2 °C warming such as pledged as part of the Paris agreements.

Acknowledgments

We would like to acknowledge the support from grants NSF-ATM1049033, NSF-CCF-1522054, NSF-AGS-1048827 and DOE-SC0016362, DOE Office of Science Biogeochemical Cycles Feedbacks and ACME Science Focus Areas as well as assistance from the Atkinson Center for a Sustainable Future, and three reviewers. We would like to acknowledge high-performance computing support from Yellowstone (ark:/85065/d7wd3hc) provided by NCAR’s Computational and Information Systems Laboratory, sponsored by the National Science Foundation.

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