

Responses to review of ANONYMOUS REVIEWER #1

Thank you for your comments and suggested edits which we address with revisions to the manuscript and also in our responses listed below. We list the reviewer comments and precede our responses with “RESPONSE”. A version of the revised manuscript with changes highlighted is also included.

REVIEWER: I have two major comments on the paper. First, I do not find the rationale for the two additional scenarios TEC and Trop-BAU. These two scenarios are highly unrealistic in the sense that they try to project as if things are really bad in tropical countries. This is based on the assumption that things can never get better in tropical countries which will be stuck in poverty forever and economies there would never transition from agriculture.

RESPONSE: We would argue that the RCPs are unrealistically optimistic, and so in order to bound what is likely to happen, we need to include more pessimistic scenarios. We do make assumptions about the future of LULCC in tropical countries, and globally, as is done for the RCPs. And we agree that the business-as-usual scenario is somewhat pessimistic. The reason that we introduce such a scenario is to increase the range of possible outcomes for the coming century with regard to LULCC. A range increase is justified because the RCPs all include reductions in deforestation rates relative to the present day census estimates from the FAO. In other words, all four RCPs (including 8.5) are optimistic with regard to deforestation in the 21st century. There are reasons to believe that deforestation rates could decrease this century – crop yield increases, national conservation policies, international policies like REDD, etc. However, we found in Ward et al. (2014) that deforestation rates in all RCPs were already too low in the tropics compared to 2000-2010 estimates from the FAO and only half the rates estimated from satellite over a similar period (e.g. Hansen et al., 2013). These points are illustrated in figure 5 from Ward et al. (2014) which we include in our responses (Fig. R1). In summary, it is good to be optimistic about the future for developing countries but it is also important to understand what will happen to global climate if present day activities are simply continued. In addition to further justification and text given in response to some following comments, we add text to explain the two non-RCP scenarios up front in the introduction:

Pg 1753, Line 8: “The two additional scenarios are added to bound the likely land use in the future because the RCPs scenarios tend to be very optimistic in their estimates of current and future land use conversion compared to current census and satellite based estimates (see Fig. 5 in Ward et al., 2014; FAO, 2010; Hansen et al., 2013; Kim et al., 2015).”

REVIEWER: This attempt at selective conclusion can be identified in the introduction: “Results for the year 2010 show substantial positive forcings from the direct modifications and agriculture sectors, particularly from India, China, and southeast Asia, and a smaller magnitude negative forcing response from wildfires.” I

suggest this sentence be removed in revision.

RESPONSE: We replaced “India, China and SE Asia” in the abstract with just “south and southeast Asia” as we agree that it is more appropriate for the abstract to describe regions instead of specific countries. We do, however, respectfully disagree that this is a case of selective conclusion. The major question this study asks is “where does the radiative forcing from anthropogenic land use and land cover change come from at present?” We think it is important to give the reader a brief mention of this basic result in the abstract.

REVIEWER: The emphasis on deforestation and specifically tropical deforestation is surprising because deforestation fluxes have gone down in the recent decades and RCP scenarios do have smaller LULCC forcings (Table 1) compared to fossil fuels (FF). The RF from tropical deforestation is artificially inflated in Fig. 5 which shows only RCP4.5 forcing from FF in all 6 panels (b-g). Why the FF forcing from corresponding scenarios are not shown? This figure should show RF from respective scenarios in corresponding panels.

RESPONSE: This is a good question. As we argue above, the RCPs are not capturing the tropical deforestation very accurately in the current time period, and assuming it will stay lower than current rates for the next century, which is a large assumption. The comparison to the FF from RCP4.5 is a good point. We derive the RCP4.5 non-LULCC (mostly fossil fuel burning) RFs from the difference between the total anthropogenic RF between 1850 and 2010 (or 2100) and the LULCC RF for the same period. Since we use RCP4.5 background anthropogenic emissions to determine all forcings and in this way truly isolate the LULCC contribution, we can only compute the non-LULCC RF for this RCP. To do the same computations for the other RCPs would require running all simulations again for each scenario and this is outside the scope of our study which is focused on LULCC-only. We have added text to the manuscript to clarify these points:

Pg 1756, Line 10: “Future RFs were computed against a background of non-LULCC anthropogenic emissions following RCP4.5 (Wise et al., 2009).”

Pg 1768, Line 4: “We are only able to compare the LULCC RFs against non-LULCC RFs from RCP4.5 for which fossil fuel burning emissions were used to compute background constituent concentrations in Ward et al. (2014). Note that the contribution of non-LULCC activities to global RF would be larger if RCP6.0 or RCP8.5 was shown.”

The latitudinal band RFs for all scenarios have not been artificially inflated or modified in any way but are the actual values that we computed according to the methods and assumptions laid out in the manuscript.

REVIEWER: My suggestion is that this paper should just focus on only the 4 RCP scenarios and remove all discussions relating to the 2 unrealistic future scenarios

with excessive and unrealistic tropical deforestation.

RESPONSE: We understand the reviewer's concerns since we did not give a substantial amount of justification for including the Trop-BAU scenario. We did consider the reviewer's suggestion to remove these two scenarios (the Trop-BAU and TEC) from the study and decided that they are too important to the main purpose of the study, defining costs of land use activities in terms of RF, so that we kept them in but understand the need to include better explanation for why the Trop-BAU scenario in particular is important to keep. We added the following text to the manuscript to communicate these points:

Pg 1759, Line 24: "Forest area projections for all four RCP scenarios assume reductions in the rate of global deforestation during the 21st century (Lawrence et al., 2012). It is also important to understand the impacts of LULCC and the sources of these impacts under a scenario in which current land use practices are continued. To address this knowledge gap we introduce a sixth projection in which tropical forest area changes for years 2010 to 2100 follow the year 2000 to 2010 rates published by the FAO (2010). Together with the RCPs, this creates a more comprehensive range in possible outcomes for the 21st century."

Pg 1760, Line 8 (last phrase added): "Recent studies suggest that deforestation rates are higher than reported in census data (Hansen et al., 2013, Margono et al., 2014), especially in the tropics (Kim et al., 2015)."

Expanding the set of future scenarios also augments our ability to define the climate costs of LULCC in RF terms by increasing the number of valid points for the statistical regression shown in Figure 9. These results would be substantially less robust if we only included the four RCP scenarios – not only because there would be fewer points but also because the range in future LULCC captured by the RCPs is so narrow.

REVIEWER: Second, the paper has too long a section on methods. It has 9 pages now. I suggest the authors briefly discuss the methods in 1-2 pages and move the elaborate details to supplemental online material. This should greatly improve the readability of the paper. Otherwise, the presentation is sound. I recommend publication only after my 2 major and the following specific comments are addressed.

RESPONSE:

We agree that the methods section reads as too long. We moved the description of the RF computations to an appendix since this is mainly a summary of previous work and might not be of interest to some readers. This reduces the length of the methods section by about 30%. We did consider the reviewer's suggestion to only include 1-2 pages of methods but decided that the text describing the methods of attributing the RF to different sectors and locations should remain in the main text. Our justification for this is that although we believe our attribution methodology to

be robust (see sensitivity tests in Ward and Mahowald, 2014 ERL), describing the several approximations that we make in the main text is important to help the reader understand the sources of uncertainty in our results. We also considered moving the explanation of the Trop-BAU scenario development to an appendix but again, there are several approximations in this process that we felt are better to explain up front. Also, this way we can more easily include some of the additional text in response to comment #1 in the main text.

REVIEWER: Specific comments: 1. In the abstract it would be clearer if the following message is explicitly mentioned:

Both in 2010 and in the future scenarios, the agriculture component of LULCC provides a positive RF and wildfires provide a negative RF. Direct modification provides the major contribution to positive RF.

RESPONSE: This is indeed a major point of the paper and we feel that this is better communicated in the revised sentences in the abstract: "Results for the year 2010 show substantial positive forcings from the direct modifications and agriculture sectors, particularly from south and southeast Asia, and a smaller magnitude negative forcing response from wildfires. The spatial distribution of future sources of LULCC RF is highly scenario-dependent, but we show that..."

REVIEWER: 2. In the abstract you have mentioned 3 regions: India, China and Southeast Asia as substantial contributors to positive RF due to direct modifications and agriculture. This point is not made clear in any part of the results section. I suggest removing this sentence.

RESPONSE: As noted above, we replaced "India, China and SE Asia" in the abstract with just "south and southeast Asia" as this may be more appropriate for the abstract to describe regions instead of specific countries. In the results section we do note that the US, India and China together contribute 70-80% of the RF in 2010 as well as in two of the future scenarios (Pg 1767, Line 18). We mention the US here because we are describing the continuity in RF contributions from present day to 2100 for major agricultural centers. In the abstract we are simply stating which regions the most RF is coming from which is clearly south and southeast Asia (see Fig. 5), so we do not mention the US here.

REVIEWER: 3. The methods section is lengthy. See my major comment. I suggest authors to prepare a flow chart for methods section in the main paper.

RESPONSE:

With the summary of forcing calculations from Ward et al. (2014) now moved to the appendix, we believe the methods section becomes much more readable. To improve the organization of this section from a reader's standpoint, and in lieu of a flow chart figure, we have added a paragraph of introduction to the beginning of Sect. 2 that outlines the sub-sections: "The methodology employed in this study is explained in this section in four steps. First, a brief summary is given of the

computation of global RFs due to LULCC from Ward et al. (2014) that are used in this study (Sect 2.1). This is followed by a description of the future LULCC scenarios used by Ward et al. (2014) and in this study, and also the development of an additional scenario (Sect. 2.2). In Sect. 2.3 the methods for attributing the global LULCC RFs for each scenario to three major sectors of land use activities are explained for the individual forcing agents. Finally, our approach for ascribing the sector and agent-specific RFs to individual source locations is described in Sect. 2.4.”

REVIEWER: 4. Page 1754 para 15: what do you mean by direct modification? Please define explicitly

RESPONSE: We have added in parentheses: “e.g. deforestation, reforestation, wood harvesting”

REVIEWER: 5. Page 1756, lines 2-5: “Forcing from changes . . .” I believe the definition of adjusted forcing takes care of these changes.

RESPONSE:

The adjusted RF takes into account stratospheric temperature adjustment but, in its purest form, is computed without changes in sensible heat flux or clouds, i.e. with zero climate response. The recently coined “effective” RF does include some quick response effects especially those associated with cloud feedbacks. Ward et al. (2014) use the effective RF for aerosol forcings but do not compute adjusted RFs for the agents listed in this sentence, thus we retain the original text.

REVIEWER: 6. Page 1756, line 9: “reduce” should be “increase”?

RESPONSE:

Since nitrate aerosols are effective scatterers of incoming solar radiation, increases in their concentration, for example due to increased agricultural activities, will actually lead to a more negative (stronger cooling) radiative forcing. Often it is more clear to use the phrase “more negative” instead of “reduce” as we use here. However, in the context of this sentence in which we state that increases in nitrate aerosol would likely reduce an overall positive forcing from agriculture, we think this phrasing makes the most sense and decided to keep the original text with an additional explanatory phrase: “...by increasing scattering of solar radiation.”

REVIEWER: 7. Page 1757, lines 1-3: Can you briefly explain why the flux was adjusted downward?

RESPONSE: We have added the following text at this location in the manuscript (now in Appendix A): “The double-counting occurs in transient-CO₂ simulations when no LULCC is included but atmospheric CO₂ concentrations reflect the impact of LULCC, thereby artificially increasing CO₂ fertilization of vegetation.”

The entire explanation reads as follows: “The LULCC flux was adjusted downward to account for the CO₂ fertilization feedback (Strassmann et al., 2008), which leads to double-counting of CO₂ emissions in uncoupled terrestrial model simulations

(Pongratz et al., 2014; Arora and Boer, 2010). The double-counting occurs in transient-CO₂ simulations when no LULCC is included but atmospheric CO₂ concentrations reflect the impact of LULCC, thereby artificially increasing CO₂ fertilization of vegetation.”

REVIEWER: 8. Page 1762, line 17: change “compare the” to “compared with”?

RESPONSE:

We have made this correction.

REVIEWER: 9. Page 1764: line 2: “this method”? Which method?

RESPONSE:

We have re-written this sentence so that the method is explicitly described: “Ward and Mahowald (2014) show that ascribing RF from short-lived forcing agents to individual locations based on proportional emissions is reasonable for comparing the climate impacts of developed countries, as a group, to developing countries.”

REVIEWER: 10. Page 1765, line 5: “-0.20” should be “-0.17” to be consistent with the table.

RESPONSE:

Thank you for the attention to detail here. In fact, the numbers are different because there is a small positive forcing (+0.03 W/m²) that is a result of the climate change impacts on the carbon cycle from this sector’s emissions. This carbon cycle response is also included in the RF reported for CO₂ but in this sentence we were only referring to the forcing from N-deposition enhancing carbon uptake. The fact that we combine these two forcings into the CO₂ is mentioned only briefly in the methods and now even this is in the appendix. So to make this point more clear we modified the text at this same point to read: “...(part of the CO₂ RF from the agriculture sector in Table 1, along with a +0.03 Wm⁻² RF from the carbon cycle response to the forcing from this sector).”

REVIEWER: 11. Figures 5 and 6: Delete the bottom 2 panels since they represent unrealistic deforestation scenarios.

RESPONSE: In light of our response to the reviewer’s major comments we retain these figure panels.

REVIEWER: 12. Figures 7 and 8: What is the purpose of these figures? You have not shown the absolute values of total RF (Fossil fuels plus LULCC). By showing only the ratio of deforestation to FF fluxes, these figures have the potential to negatively portray tropical countries though their total emissions have been smaller so far. These figures again attempt to unrealistically show that things are bad in tropical countries. I suggest removing these figures or also show the total RF along with the ratios.

RESPONSE: We modified text in the manuscript explaining that these figures are included to show that in many countries LULCC is the main source of global RF and that this is true especially for many tropical countries.

Pg 1768, Line 8: “We plot the ratios of LULCC RF to total anthropogenic RF to illustrate that on an individual country level there is a substantial range in the proportion of total anthropogenic RF that can be ascribed to LULCC activities (Figs. 7, 8).”

There have been several assessments of country-level anthropogenic climate change contributions that show the differences the reviewer cites between developed and developing countries (e.g. Hohne et al., 2010; Matthews et al., 2014) including one using the same model setup described here (Ward and Mahowald, 2014). Rather than repeat the results of these studies and take away from the point being made here (not about the magnitude of forcing but about the composition) we instead twice reference the results of Ward and Mahowald (2014) in section 3.3 (3rd paragraph) to note which countries are important for total global anthropogenic RF and which are not.

It is important also to show the second panel in both figure 7 and 8 which includes greenhouse gases only. The impact of anthropogenic aerosols is to reduce the contribution to anthropogenic global RF from their source and since these are emitted in the greatest quantities from fossil fuel burning, aerosols reduce the proportional contribution to global RF from fossil fuels and highlights LULCC. Since major climate metrics, such as CO₂-equivalents, usually only include greenhouse gases, we need to show the fossil fuel/LULCC comparison without aerosols to better inform policy debates. We add the following text to support this point:

Pg 1768, Line 18: “Standard climate change metrics, such as CO₂-equivalents, often do not incorporate short-lived climate forcers (Ward and Mahowald, 2014).”

REVIEWER: 13. Page 1768, lines 10-15: Fossil fuel emission globally is now about 9 PgC/yr but LULCC emission is only about 1 PgC/yr. How do you justify that LULCC contribute more RF than fossil fuel emission? Please explain in detail.

RESPONSE: We added text to clarify this point (see below). It is true that fossil fuel burning contributes many more times the amount of CO₂ that is emitted from LULCC each year (in the present day) and that CO₂ is the largest single anthropogenic climate forcer. However, as shown by Ward et al. (2014), LULCC activities are the major contributors to non-CO₂ greenhouse gas forcing, such as from CH₄ and N₂O, and do not lead to a large negative forcing from aerosols. Non-LULCC activities do lead to a large negative aerosol forcing and, therefore, Ward et al. (2014) estimate that LULCC accounts for 40% of total anthropogenic RF in 2010. When this global number is broken down into a country-level analysis it might be easier to see how countries could have a greater LULCC contribution. We added the following text that summarizes this finding from Ward et al. (2014) and addresses

the reviewer's comment:

Pg 1756, Line 2: "They compute uncertainties for the RF from each forcing agent and find that LULCC account for 40% +/- 16% of year 2010 anthropogenic RF by a combination of substantial positive forcing from non-CO2 greenhouse gases and the absence of major negative forcing from aerosols. The forcings calculated by Ward et al. (2014) are within the uncertainty ranges in estimates of the total anthropogenic RF published in major assessments (e.g. Myhre et al., 2013; van Vuuren et al., 2011), suggesting that different approaches would likely achieve similar results."

Also, it is important to remember that the global forcing from LULCC and non-LULCC CO2 from Ward et al. (2014) that we use in this study contains the history of anthropogenic CO2 emissions since 1850, some fraction of which is still in the atmosphere today. So the CO2 RF alone does not only depend on present day emissions but also on the history of emissions. We made further note of this in the text:

Pg 1757, Line 7 (now in Appendix A): "In this way, the history of CO₂ emissions from different sectors of LULCC is accounted for in these calculations."

REVIEWER: 14. Page 1770, line 15: expand VOC, it is not defined before.

RESPONSE: This was a good catch; we replaced the acronym with the full phrase and a new acronym (BVOC).

REVIEWER: 15. In Figure 1, the direct modifications need to be defined more clearly (you have used land cover change which does not give a clear picture of what is to be conveyed)

RESPONSE: We add a definition for land cover change to the text at the point where figure 1 is first referenced and the direct modifications group is being defined:

Pg 1760, Line 15: "We define land cover changes as the replacement of a biome, such as grassland or forests, with a different biome by anthropogenic activity."

REVIEWER: 16. In all figures, the font size of the labels should be increased for better readability.

RESPONSE: We have increased the font size on all labels in all figures by between 2 to 4 points.

Responses to review of ANONYMOUS REVIEWER #2

Overview

The paper evaluates a wide range of mechanisms by which landuse change can affect climate. The data used is appropriate to the problem and it is well analysed. The results are important.

The two main revisions are to clarify what climate forcing data is used in the future simulations and to better explain the affect of LULCC in wildfire CO2 emissions.

RESPONSE: Thank you for your comments and suggested edits. We have addressed all comments in our responses below and with revisions to the text. Our responses are preceded by "RESPONSE".

REVIEWER: *Minor Revisions*

p1758 L25 – State how RF calculated from change in surface albedo. Is a radiative transfer model used? Is the surface downward shortwave flux somehow scaled?

RESPONSE: The following text was added to clarify the calculation of the albedo RF. This text was added at the line noted by the reviewer but note that this has been moved to Appendix A.

"The simulated changes in albedo alter the fraction of incident solar radiation that is reflected back into the atmosphere. The reflected solar radiation is multiplied by the fraction of outgoing radiation that reaches the top of the atmosphere at each grid point of a model climatology characteristic of the year 2000 in which clouds and aerosol scattering are implicit. The radiative forcing is then simply the difference in top-of-atmosphere net solar radiative flux caused by the changes in albedo."

REVIEWER: P1762 L14 – This assumption means that changes in soil carbon which could occur for a long time after a change in land cover are attributed to the direct category. It would be good to point out that these carbon fluxes due to "direct modifications," can occur for decades after the land cover change is imposed. Also, should harvest be included as a loss term along with burning and tillage.

RESPONSE: This is a good point and we had neglected to mention C emissions from disturbed and managed soils. These emissions are not captured in the Ward et al. (2014) simulations and therefore not included in this study. While changes in soil emissions due to land management are uncertain, there is evidence that they may be large (Lal, 2004). We note that we do not include anthropogenic changes to soil emissions in the text now:

Pg 1756, Line 2: "Carbon emissions from soils that are managed or disturbed by anthropogenic activities (Lal, 2004) were not included in this analysis."

We have included “harvesting” as a loss term in the referenced sentence.

REVIEWER: P1762 L21 – What errors do you expect from using 1948-1972 climate for the pre- industrial spin-up?

RESPONSE: We expect that terrestrial C storage is more sensitive to other factors, such as atmospheric CO₂ and prescribed land cover, than it is to the period of reanalysis used to spinup the preindustrial land model. We add several supporting references to justify our use of this reanalysis:

Pg 1762, Line 18: “For these simulations we follow the same protocol as in Ward et al. (2014) and several previous studies (e.g. Kloster et al., 2010; 2012; Ward et al., 2012).”

REVIEWER: P1763 L16 – What climate forcing is used for the future? Do all simulations use RCP4.5 climate? Or does is each RCP landuse scenario used with the respective RCP climate?

RESPONSE: This is an excellent question and alerted us to the fact that we had not included this information. The following text was modified at the pg and line referenced by the reviewer:

“The future atmospheric forcing datasets,,produced by Kloster et al. (2012), are derived from the output of two coupled climate models each following the SRES A1B1 future scenario. The same atmospheric forcing is used for all future simulations regardless of the LULCC scenario and in this way the impacts of the LULCC can be isolated (Ward et al., 2014).”

REVIEWER: P1766 Section 3.2 - Does the vegetation distribution respond to wildfire activity?

RESPONSE: The vegetation is not dynamic in this model so fires do not change the existing plant functional types (PFTs). Although, PFT changes due to anthropogenic land cover change are prescribed. We added:

Pg 1763, Line 2: “Existing PFTs do not change type due to fires or climate in this version of CLM.”

REVIEWER: P1767 L5-7 – I don’t follow this argument, it needs more explanation. I think you need to state that fire activity is increasing during the historic and future simulations, and therefore reducing the burned area reduces the net loss of carbon from the land. It would also be good to add the reason why fire activity is increasing and whether this is a robust result.

If I understand correctly the argument is as follows: If it is assumed that wildfires are carbon-neutral then changing the burnt area by increasing crop area will have no affect on the net carbon flux caused by wildfires. For there to be a net effect on the terrestrial carbon sink wildfires can not be carbon neutral and therefore the

model must be simulating a period of trending global fire activity. In this case the trending fire activity must be an increase in fire CO₂ emissions.

In Figure 3 when there is no LULCC fires cause a small reduction in terrestrial carbon (blue lines), supporting the idea that it is a period of increasing fire activity. Yet including LULCC greatly increases the affect of fires on terrestrial carbon (difference in green lines compared to difference in blue lines), by much more than neglecting fires altogether in the no-LULCC case (blue lines). Does this mean that fire activity must be increasing a lot in some locations and decreasing a lot in other locations and that LULCC mostly occurs in locations of increasing fire activity?

RESPONSE: These ideas are complex and our original explanation was probably not sufficient to communicate them. We made major revisions to this section of the text, detailed below. We are considering only changes in terrestrial carbon emissions due to LULCC and the wildfire response to LULCC. These changes are isolated from trends in global fire activity due to climate changes and transient CO₂ since we are looking at the differences between simulations with and without fire, and simulations with and without LULCC. For this reason we do not mention or discuss historical or future trends in global fire activity, although we cite several papers that do (e.g. Kloster et al., 2010; 2012; Ward et al., 2012).

We believe that the confusion here comes at least partly from our too-brief explanation of an artifact of this methodology that we exclude from our calculations of atmospheric CO₂ concentration changes from these sources. This was compounded by our reference to a shaded region of Figure 3, which we mistakenly did not include in the actual figure. This has been corrected, and the paragraph containing the lines referenced by the reviewer has been expanded and largely rewritten to clarify these points, with more references to specific aspects of Figure 3. Please refer to the revised manuscript to view the changes.

REVIEWER: P1767 L9 - "About half of this..." I found this sentence confusing at first. Can you explicitly say that this component is included in the direct modifications sector, and can you remove the reference to figure 3.

RESPONSE: We have clarified this with the expanded and revised paragraph mentioned above.

REVIEWER: P1768 L4 – Why is RCP4.5 non-LULCC antropogenic forcing used for all future scenarios? It would be more informative and clearer to use the non-LULCC forcings from the respective futrue scenarios. I accept the point that the LULCC scenarios are not tightly linked to the CO₂ concentration scenarios, but it would still be useful to see the range of each.

RESPONSE: We did not compute non-LULCC anthropogenic RFs for the other RCP scenarios. This would require an additional set of Community Atmosphere Model (CAM) simulations and offline analyses (from Ward et al., 2014) for each scenario. We can show RCP4.5 because Ward et al. (2014) used non-LULCC emissions from

this scenario for background atmospheric composition to compute the LULCC forcings. We agree that ideally the LULCC RFs could be compared to non-LULCC RFs from the same scenario (although as the reviewer notes they are not always tightly linked) but this is not necessary to be able compare the magnitudes of the LULCC forcings alone which are the focus of this study. We added the following text to the manuscript to address this point:

Pg 1756, Line 10: "Future RFs were computed against a background of non-LULCC anthropogenic emissions following RCP4.5 (Wise et al., 2009)."

Pg 1768, Line 4: "We are only able to compare the LULCC RFs against non-LULCC RFs from RCP4.5 for which fossil fuel burning emissions were used to compute background constituent concentrations in Ward et al. (2014). Note that the contribution of non-LULCC activities to global RF would be larger if RCP6.0 or RCP8.5 was shown."

REVIEWER: P1768 L5 – this is only true of the TEC scenario and not of the Trop-BAU scenario.

RESPONSE: We agree and have removed the reference to Trop-BAU in this sentence.

REVIEWER: P1770 – It would be good to add something on the uncertainty in these results. If this study were repeated using different models would the aerosol indirect effect/fire/NPP responses be expected to be the same? Or is there evidence that this model represents these processes robustly?

RESPONSE: This is a good point. There is substantial discussion of the uncertainties in the global LULCC RFs for each forcing agent (which we use in the current study) and how they are calculated in Ward et al. (2014). Since the focus of this study was more on the proportions of the total LULCC RF contributed by different sectors/locations we had not thought to summarize this discussion in our manuscript here. However we agree that it is important for the reader to understand the level of uncertainty in the global RFs which are the starting point for all the work shown in this study. We add the following text to make sure this is put across:

"They compute uncertainties for the RF from each forcing agent and find that LULCC account for 40% +/- 16% of year 2010 anthropogenic RF by a combination of substantial positive forcing from non-CO2 greenhouse gases and the absence of major negative forcing from aerosols. The forcings calculated by Ward et al. (2014) are within the uncertainty ranges in estimates of the total anthropogenic RF published in major assessments (e.g. Myhre et al., 2013; van Vuuren et al., 2011), suggesting that different approaches would likely achieve similar results."

Also it is noted in the text that for most forcing agents the majority of relevant emissions/changes occurs in a single sector or are dominated by a single sector. This cuts down on uncertainty that is introduced by partitioning the total LULCC RF

into smaller categories.

Technical corrections/suggestions

P1753 L29 delete “seasonal”

RESPONSE: Removed “seasonally”

p1755 L24 change “and” to “however”

RESPONSE: Changed

p1757 L5 delete “at the year the RF”

RESPONSE: Changed to “at some future time”

p1757 L15 change “Rfs” to Rfs”

RESPONSE: Changed to “RFs”

p1758 L16 delete comma

RESPONSE: Changed (note this text is now in the appendix)

p1765 L8 change “2100 present day” to “2100”

RESPONSE: Changed

p1765 L25 add (1.65 W/m²) after “agricultural CH₄”

RESPONSE: Changed

p1770 L5 delete “, or, in the case of Ward et al. (2014), LULCC effects as a whole”

RESPONSE: Changed

p1770 L10 change “Therefore,” to something like “We find that these changes cancel out and that”

RESPONSE: Changed

p1771 L27 add “(Fig. 2)” after “in this study”

RESPONSE: This sentence had been removed already.

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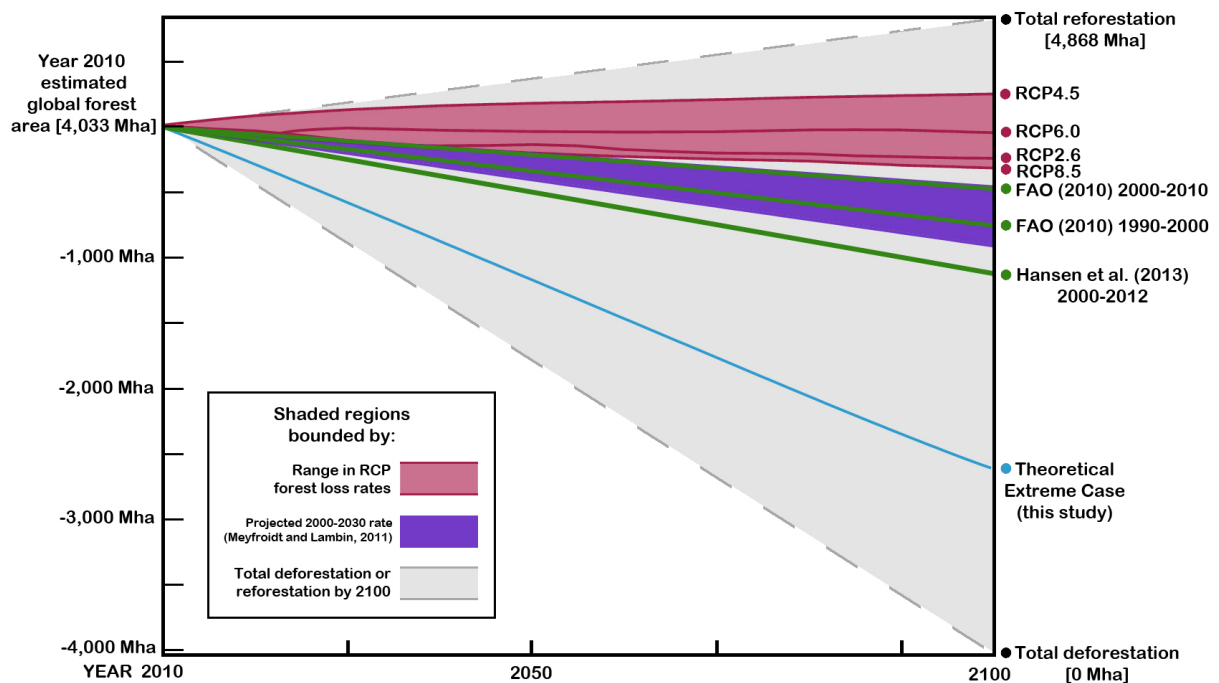
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Figure R1: Comparison of projected annual rates of forest area change. Colored lines and shading represent the change in global forest area between 2010 and 2100 for the Representative Concentration Pathways (red) and the theoretical extreme case (light blue). The grey shaded region is bounded by the annual rate of forest area change required to completely reforest to the estimated prehistoric forest area (Pongratz et al., 2008), or remove all forests by year 2100. Reported and projected forest area change from Meyfroidt and Lambin (2011) (purple) and FAO (2010) and Hansen et al. (2013) (green) are depicted as constant rates through year 2100 to show the result if these rates were sustained.



REVISED MANUSCRIPT TEXT

Abstract

Identifying and quantifying the sources of climate impacts from land use and land cover change (LULCC) is necessary to optimize policies regarding LULCC for climate change mitigation. These climate impacts are typically defined relative to emissions of CO₂, or sometimes emissions of other long-lived greenhouse gases. Here we use previously published estimates of the radiative forcing (RF) of LULCC that include the short-lived forcing agents O₃ and aerosols, in addition to long-lived greenhouse gases and land albedo change, for six projections of LULCC as a metric for quantifying climate impacts. The LULCC RF is attributed to three categories of LULCC activities: direct modifications to land cover, agriculture, and wildfire response, and sources of the forcing are ascribed to individual grid points for each sector. Results for the year 2010 show substantial positive forcings from the direct modifications and agriculture sectors, particularly from India, China, south and southeast Asia, and a smaller magnitude negative forcing response from wildfires. ~~The RF from direct modifications, mainly deforestation activities, exhibits a large range in future outcomes for the standard future scenarios implying that these activities, and not agricultural emissions (which lead to more consistent RFs between scenarios), will drive the LULCC RF in the future. The spatial distribution of future sources of LULCC RF is highly scenario-dependent, but we~~ show that future forest area change can be used as a predictor of the future RF from direct modification activities, especially in the tropics, suggesting that deforestation-prevention policies that value land based on its carbon-content may be particularly effective at mitigating climate forcing originating in the tropics from this sector. Although, the response of wildfire RF to tropical land cover changes is not as easily scalable and yet

imposes a non-trivial feedback onto the total LULCC RF.

1. Introduction

Global land use and land cover change (LULCC) is recognized as an important element of past and future anthropogenic climate changes (Feddema et al., 2005; van der Werf and Peterson, 2009; Foley et al., 2011). Decision makers are faced with the major challenge of meeting increasing global demands for food products (Godfray et al., 2010) while simultaneously minimizing the climate costs of expanding or intensifying agriculture. The Reducing Emissions from Deforestation and Forest Degradation (REDD) program is a one such effort that seeks to lower anthropogenic greenhouse gas emissions from deforestation using financial incentives to maintain or increase forest area (Lubowski and Rose, 2013).

Estimating the costs to climate from LULCC activities is necessary for developing policies like REDD, yet these costs are difficult to define. The total CO₂ emitted is sometimes used for this purpose (e.g. Mendelsohn and Dinar, 2009), or global warming potentials and CO₂ equivalents are used to include the effects of other long-lived greenhouse gases (e.g. van der Werf and Peterson, 2009; Cherubini et al., 2012; Reisinger and Ledgard, 2013). However, changes in forest area also modify the land surface biophysics (such as albedo) and emissions of short-lived species: aerosols and precursors to ozone formation. Several studies have shown that when other forcing agents besides CO₂ are considered, the contribution of LULCC to global climate change can be highly dependent on the location of the LULCC (Claussen et al., 2001; Brovkin et al., 2004; Bala et al., 2007). For example, clear-cutting of extra-tropical forest emits

CO₂ but also reveals the land surface underlying the forest canopy that, ~~if seasonally~~when snow-covered, is highly reflective. The cooling impact of the albedo change can compensate for the warming of the emitted CO₂, and has even been shown to dominate at high latitudes (Claussen et al., 2001; Matthews et al., 2004). Patterns of wildfire activity also change as a result of land management (Houghton et al., 1999; Kloster et al., 2012), with feedbacks onto the global carbon cycle, and emissions of carbonaceous aerosols and trace gases. Finally, the impacts of LULCC include the agricultural activities that often follow deforestation (Foley et al., 2005) and lead to emissions of CH₄, N₂O, NH₃, NO_x, and dust (Ward et al., 2014; Ginoux et al., 2012).

The general approach to identifying sources of anthropogenic impacts on climate has been to divide the impacts by forcing agent (e.g. Forster et al., 2007; Myhre et al., 2013). However, as pointed out by Unger et al. (2010), it is more useful for policy making to break impacts down into contributions by economic sectors. Specific sectors can be regulated more easily than an individual forcing agent, such as CH₄, that has many sources both from industry and from land use. Given the large role of LULCC in present day anthropogenic climate forcing (Ward et al., 2014), there is a need to know what activities are driving this forcing and to address whether the majority of climate forcing from LULCC activities results from deforestation, agricultural emissions, or from wildfire feedbacks. Further questions regarding where contributions from LULCC to climate change originate geographically are important on country-level and smaller scales for assessments of individual country responsibilities for climate change and potential for mitigation (den Elzen et al., 2013; Matthews et al., 2014).

In this study, we use previously compiled estimates of the global LULCC

radiative forcing for six future scenarios (five from Ward et al., 2014, and one described in this study), including the four Representative Concentration Pathways (RCPs; Moss et al., 2010), and compute the contributions of three major LULCC sectors to the total RF: agriculture, direct modifications to the land surface ([e.g. deforestation, reforestation, wood harvesting](#)), and the wildfire feedback. [The two additional scenarios are added to bound the likely land use in the future because the RCPs tend to be very optimistic in their estimates of current and future land use conversions compared to current census and satellite based estimates \(see Fig. 5 in Ward et al., 2014; FAO, 2010; Hansen et al., 2013; Kim et al., 2015\).](#) The global total and sector-specific forcings are ascribed to their source locations on a latitude/longitude grid basis for historical LULCC and for the projected LULCC of the future scenarios. With these methods our objectives are to 1) identify where the RF of specific LULCC activities will likely come from in the future, and, based on this information, 2) to assess the relative importance of land use location and type of activity for future mitigation of global RF.

2. Methods

[The methodology employed in this study is explained in this section in four steps. First, a brief summary is given of the computation of global RFs due to LULCC from Ward et al. \(2014\) that are used in this study \(Sect 2.1\). This is followed by a description of the future LULCC scenarios used by Ward et al. \(2014\) and in this study, and also the development of an additional scenario \(Sect. 2.2\). In Sect. 2.3 the methods for attributing the global LULCC RFs for each scenario to three major sectors of land use activities are explained for the individual forcing agents. Finally, our approach for ascribing the](#)

sector and agent-specific RFs to individual source locations is described in Sect. 2.4.

2.1 Use and calculation of global RFs

We use the adjusted radiative forcing (RF), as defined by Forster et al. (2007), and relative to a preindustrial state (year 1850), to measure the impacts of LULCC activities. RF has several advantages as a metric for this kind of study in which different forcing agents are assessed together. The RF is defined the same way for short-lived and long-lived forcing agents allowing for their direct comparison. Also, this metric is used in many studies, including the Intergovernmental Panel on Climate Change assessment reports, to compute the total anthropogenic contribution to climate change, providing substantial context within which to place our results (Forster et al., 2007; Myhre et al., 2013).

It has been demonstrated that the biophysical effects of LULCC have a different climate sensitivity compared to identical forcing from CO₂ (e.g. Davin et al., 2007; Pongratz et al., 2008), and that the biochemical and biophysical RFs of LULCC are not strictly additive when it comes to surface temperature response (Jones et al., 2013). However, estimates of the efficacy of LULCC biophysical effects, which account for varying climate responses among forcing agents, range from 0.3 to 5 depending on model assumptions (Hansen et al., 2005; Davin et al., 2007; Cherubini et al., 2012) and, being defined by the global climate response, may not apply equally to specific source locations. Therefore we adopt RF as an assessment metric and acknowledge the uncertainty regarding the climate response to the different forcing agents, and the limits of the RF concept for predicting the diverse climate impacts of land use (Betts, 2008;

Runyan et al., 2012). Pongratz and Caldeira (2012) show that preindustrial LULCC, which we do not consider in our study, accounts for less than 10% of historical anthropogenic climate change (measured as global surface temperature change), but can alter the proportional contributions of individual countries to climate change in important ways. They find that including preindustrial LULCC emissions enhances the contribution of developing countries, particularly in south Asia, however and we are not able to capture this enhancement in our study.

The RFs attributed to LULCC by Ward et al. (2014) from changes to greenhouse gas concentrations, including CO₂, N₂O, CH₄, and O₃, aerosol direct and indirect effects, including biogeochemical feedbacks, and surface albedo are used in this study. Their analysis includes deforestation, afforestation and other land cover changes, deforestation fires, wood harvesting, agricultural emissions from livestock, fertilizer and waste burning, and changes to wildfires caused by land cover change. They compute uncertainties for the RF from each forcing agent and find that LULCC account for 40% +/- 16% of year 2010 anthropogenic RF by a combination of substantial positive forcing from non-CO₂ greenhouse gases and the absence of major negative forcing from aerosols. The forcings calculated by Ward et al. (2014) are within the uncertainty ranges for estimates of the total anthropogenic RF published in major assessments (e.g. Myhre et al., 2013; van Vuuren et al., 2011), suggesting that different approaches would likely achieve similar results. Carbon emissions from soils that are managed or disturbed by anthropogenic activities (Lal, 2004) were not included in this analysis. Forcing from changes to evapotranspiration, sensible heat flux, and associated changes to cloud cover (van der Molen et al., 2011), are difficult to define with the RF metric and are excluded

from the Ward et al. (2014) calculations. They also did not consider changes to fluvial C fluxes (Moore et al., 2013), changes to natural CH₄ and N₂O emissions from LULCC (Lehner and Doll, 2004), or irrigation (Boucher et al., 2004). Direct radiative effects of nitrate aerosols were not included. Nitrate aerosol concentrations can be enhanced by emissions from fertilizer and livestock and act to reduce the RF from these agricultural sectors by increasing scattering of solar radiation (Unger et al., 2010). Future RFs were computed against a background of non-LULCC anthropogenic emissions following RCP4.5 (Wise et al., 2009). A more detailed summary of the methodology of Ward et al. (2014) is given in Appendix A.

~~The anthropogenic RF of an atmospheric constituent is computed from the change in the concentration of that constituent due to anthropogenic activities over a reference time period, often a preindustrial date to the present. Therefore, computing RFs is, for most forcing agents, a three step process beginning with assembling of the emissions dataset of interest, using the emissions to calculate a change in concentration of the forcing agent, and finally assessing the RF from the concentration change. Forcing agents with different atmospheric lifetimes, for example N₂O (>100 years) compared to aerosols (days to weeks), require different methods for determining concentration changes. In the remainder of this section we provide a summary of the different methodologies used to compute the RFs from LULCC for all forcing agents in Ward et al. (2014). The order of forcing agents in this summary is CO₂, N₂O, CH₄, O₃, aerosol effects, land albedo change, and biogeochemical feedbacks onto CO₂ concentrations.~~

~~Global CO₂ emissions from LULCC are considered uncertain. Model inter-comparison studies produce a large range in values for this quantity (Brovkin et al., 2013)~~

and even differences in terminology play a role in the uncertainty (Pongratz et al., 2014). Using a modified Community Land Model version 3.5 (CLM; Oleson et al., 2008; Thornton et al., 2009), Ward et al. (2014) compute the net LULCC carbon flux from 1850 through the year 2100 as the difference in terrestrial carbon storage between simulations with land cover change and land use, and a reference simulation with preindustrial land cover (year 1850). The LULCC flux was adjusted downward to account for the CO₂ fertilization feedback (Strassmann et al., 2008), which leads to double counting of CO₂ emissions in uncoupled terrestrial model simulations (Pongratz et al., 2014; Arora and Boer, 2010). The airborne fraction of CO₂ emissions, that is the portion of emitted CO₂ remaining in the atmosphere at the year the RF, was derived from a pulse response function characteristic of rising CO₂ concentrations (following the methodology of Randerson et al., 2006 and O'Halloran et al., 2012). From the change in CO₂ concentration, the RF of CO₂ emitted by LULCC activities was calculated with the simple expression from Ramaswamy et al. (2001).

Nitrous oxide is emitted by livestock and by the application of fertilizer onto crops. LULCC also has a minor impact on N₂O concentrations by modifying wildfire emissions. N₂O has a long lifetime in the troposphere (greater than 100 years (Meinshausen et al., 2011)) and its chemistry can be treated with a simple box model approach. Ward et al. (2014) used the Kroeze et al. (1999) box model to calculate the change in N₂O concentrations resulting from the emissions associated with LULCC. RFs were calculated with the simple expression recommended by Ramaswamy et al. (2001).

Methane concentrations are modified directly by emission of CH₄ from LULCC activities, and indirectly by changes to the oxidation capacity of the troposphere that

impacts CH_4 lifetime. Emissions of CH_4 from LULCC have been compiled for the historical time period (Lamarque et al., 2010) and for the RCP scenarios (van Vuuren et al., 2007; Wise et al., 2009; Fujino et al., 2006; Riahi et al., 2007). In addition, small changes in CH_4 emissions from wildfires are caused by LULCC and were simulated by CLM for these calculations (Ward et al., 2014). A box model approach from Ward et al. (2012) was used to determine the direct modifications to CH_4 concentrations from LULCC. To determine changes to the CH_4 lifetime, Ward et al. (2014) simulated atmospheric chemistry within the Community Atmosphere Model version 4 (Hurrell et al., 2013; Gent et al., 2011; Emmons et al., 2010) with LULCC emissions of non-methane hydrocarbons (NMHC) and NO_x , and without these emissions. The different emissions lead to changes in global hydroxyl radical, OH , concentrations. The CH_4 lifetime can be computed from the new OH concentration (Naik et al., 2005; Ward et al., 2012) and the changes to CH_4 concentration from LULCC activities were adjusted according to the new lifetime (Ward et al., 2014). The RF is calculated using the simple expression recommended by Ramaswamy et al. (2001) for CH_4 :

LULCC impacts tropospheric O_3 concentrations by emitting NO_x (such as from fertilizer application) and by modifying emissions of NMHCs from vegetation and from fires. The response of O_3 concentrations to the changes in these emissions cannot be represented with a simple model approach but involves a complex set of chemical reactions. Ward et al. (2014) calculated the LULCC contribution to tropospheric O_3 with the same set of CAM4 simulations used to assess the CH_4 lifetime. The radiative impact of the changes in O_3 was determined with the Parallel Offline Radiative Transfer (PORT) tool (Conley et al., 2013) for both shortwave and longwave interactions. The response of

~~O₂ on long time scales to changes in CH₄ concentrations, known as the primary mode response, was included in the LULCC O₂ RF calculation following Prather et al. (2001).~~

~~Emissions of several aerosol species are impacted by land use and land cover change. Ward et al. (2014) considered changes in biogenic, secondary organic aerosol from modified leaf area index, changes in dust emissions from cultivation, and changes in fire emissions of black carbon (BC), organic carbon (OC) and sulfate aerosols from LULCC. Changes in aerosol concentrations were computed with a set of CAM version 5 simulations with the modal aerosol model (MAM3) (Liu et al., 2012), with and without the LULCC emissions. Radiative effects of the aerosols, both direct effects and indirect effects on clouds, were diagnosed online, giving values for effective radiative forcings (ERF) for the LULCC aerosol emissions.~~

~~Changes to the land surface albedo from land cover change were derived directly from the CLM simulations in Ward et al. (2014). Additional forcing from modified albedo following fires was also included, for the change in fires due to LULCC, following the offline analysis of Ward et al. (2012). Feedbacks of nitrogen deposition by aerosols and feedbacks of climate change onto the carbon cycle have been identified and quantified by Mahowald (2011). The magnitudes of these feedbacks for LULCC were estimated by Ward et al. (2014) and included in the total CO₂ RF.~~

2.2 Future scenarios

RFs were estimated by Ward et al. (2014) for the year 2100 (relative to 1850) given historical LULCC (Hurtt et al., 2011) and five projections of future LULCC including four developed as part of the Coupled Model Intercomparison Project phase 5

(CMIP5) (Taylor et al., 2012) corresponding to each of the four Representative Concentration Pathways (RCP2.6, RCP 4.5, RCP 6.0, RCP 8.5) (Hurtt et al., 2011; Lawrence et al., 2012). The fifth projection represents a theoretical extreme case (TEC) in which all arable land is converted to crops at a linear rate between years 2010 and 2100, and remaining pasturable land (defined as land for which the climate would support crops but where the soil is too nutrient-poor) is converted to grasses (Ward et al., 2014). The TEC leads to a near complete deforestation of the tropics and more than 2.5 times the present day crop area. Since the land use included in the RCPs is thought to be smaller than is likely in reality based on historical land use change (e.g. Ward et al., 2014), the TEC allows us to have a higher than likely estimate in order to bound the probable impacts of land use on climate.

All projections represent LULCC as changes in plant functional type (PFT) coverage over time, with redistribution of carbon by wood harvesting also included (Lawrence et al., 2012). Recent work has demonstrated that changing agricultural practices, even something as simple as improving livestock feeding, can also reduce greenhouse gas emissions (Bryan et al., 2012). Here we assume changes in agricultural practices are consistent with the LULCC projections created to accompany the Representative Concentration Pathways.

Forest area projections for all four RCP scenarios assume reductions in the rate of global deforestation during the 21st century (Lawrence et al., 2012). It is also important to understand the impacts of LULCC and the sources of these impacts under a scenario in which current land use practices are continued. To address this knowledge gap we We introduce a sixth projection in which tropical forest area changes for years 2010 to 2100

follow the year 2000 to 2010 rates published by the FAO (2010). Together with the RCPs, this creates a more comprehensive range in possible outcomes for the 21st century.

In this tropical business-as-usual (Trop-BAU) scenario the forest area change reported for each country is gridded. Only grid points with past forest area loss were allowed to experience future loss, although in the case of completely deforested grid points the forest loss spilled into adjacent points. Forest PFTs are converted to cropland and pasture (grasses) at proportions of 80% and 20% respectively, as reported by Houghton (2012) for the tropics. Global wood harvesting rates and extra-tropical land cover changes in the Trop-BAU scenario are from RCP8.5. Some reforestation was reported in Southeast Asia between 2000 and 2010 (FAO, 2010) but we assume only tropical forest area loss in Trop-BAU, citing an increase in net forest loss in this region between 2005 and 2010 (FAO, 2010). Recent studies suggest that deforestation rates in some tropical countries are higher than reported in census data (Hansen et al., 2013, Margono et al., 2014), especially in the tropics (Kim et al., 2015). Therefore, the Trop-BAU scenario may underestimate global forest area loss if current rates were to continue during this century.

2.3 Assigning RF to sectors

We divide RFs attributed to LULCC into three groups of anthropogenic activities and feedbacks (Fig. 1). The first group, direct modifications, includes land cover changes with associated deforestation fires, and wood harvesting. We define land cover changes as the replacement of a biome, such as grassland or forests, with a different biome by anthropogenic activity. The agricultural emissions group contains N₂O and CH₄ emissions from livestock and fertilizer application, dust emissions from cultivation, and

waste burning. It is important to emphasize the distinction we make between fires that are associated with different activities. We include fires associated with the act of deforestation in the direct modifications category, while yearly burning of agricultural waste falls into the agriculture category. Finally, changes in wildfire activity that result from land cover changes comprise the third category.

We take a simple approach to apportioning the global LULCC RF into these three categories. Forcing is assigned to a category in proportion to the fraction of global LULCC emissions of the forcing agent, or agent precursor gases, that are associated with the category. For example, roughly 90% of LULCC NO_x emissions were from agricultural activities in the year 2010, with the remainder associated with deforestation fires. The same percentage of forcing due to tropospheric O_3 , roughly 90%, is attributed to the agriculture sector. A global reduction in wildfire emissions from land cover change leads to a 15% decrease in total LULCC NO_x emissions and we attribute 15% of the total LULCC O_3 RF of the opposite sign to the wildfire forcing category. For short-lived species like O_3 , forcing efficiency (global mean forcing per unit emission) can depend on the location and timing of the emissions (Shindell and Faluvegi, 2009; Streets et al., 2013). We have defined the three LULCC categories such that, in general, emissions of a particular forcing agent are dominated by one category, which will minimize the errors introduced by this effect on the short-lived forcings.

As above-mentioned, apportioning of the O_3 forcing is based on NO_x emissions. NO_x emissions are also used to apportion the forcing of indirect changes to CH_4 , while the forcing from direct changes to CH_4 can be assigned to categories based on CH_4 emissions. To properly divide the direct aerosol effect between categories we need to

treat different aerosol species separately. The magnitude and even the sign of the effective RF of aerosols depend on the properties of the different aerosol species. Sulfate and OC aerosols scatter shortwave radiation while BC absorbs shortwave radiation and can be a source of heat in the troposphere. Ward et al. (2014) diagnose the direct effect of all LULCC aerosols, and for five different aerosol species: BC, OC, sulfate, mineral dust and secondary organic aerosol (SOA), from the CAM5 simulations. In these online diagnostics, the radiative transfer scheme is passed through several times, each time with a different aerosol species removed. The resulting direct effect forcing for individual aerosol species is approximate since water uptake onto aerosols is unaffected by the removal of aerosols in the radiative transfer passes.

With these forcings for individual aerosol species estimated, the direct ERF attributed to LULCC is apportioned into sectors by the relative emissions of each of the five species listed above. The indirect ERF attributed to LULCC is apportioned according to the fraction of aerosol number concentration emissions originating from each sector.

N₂O emissions, similar to emissions of NO_x, are dominated by activities associated with the agriculture sector, but deforestation fires and wildfires also change N₂O concentrations. The forcing from LULCC N₂O cannot be divided into sectors based on contemporaneous emissions of N₂O because its long lifetime in the atmosphere requires that emission history be taken into account. Therefore, we apply the box model technique of Kroeze et al. (1999) and used by Ward et al. (2012; 2014) to emissions of N₂O from each individual sector to determine the contribution of each sector to the total LULCC N₂O RF for each year from 1850 to 2100, and for each future scenario. The box

model simulates changes in N₂O concentration with time, dC/dt , as a result of yearly emissions, E . We also include a variable N₂O lifetime, τ , that is a function of its own concentration, following Meinshausen et al. (2011):

$$\frac{dC}{dt} = \frac{E}{S} - \frac{C}{\tau} \quad (1)$$

$$\tau = \tau_o \left(\frac{C}{C_o} \right)^{-0.05} \quad (2)$$

In Eq. 1, S is a conversion factor, 4.8 Tg N ppbv⁻¹, and t is time in years.

Apportioning the CO₂ RF into sectors presents a similar challenge because of its long residence time in the atmosphere. We assume that agricultural activities are carbon neutral, sequestering the same amount of carbon in plant regrowth that is lost through waste burning, ~~and~~ tillage and harvesting. Then, we separate the carbon emissions from land cover changes and wood harvesting from LULCC-modified wildfire emissions using a set of CLM simulations in which fires are turned off. The terrestrial carbon storage in these simulations is compared with the reference state carbon storage from the Ward et al. (2014) CLM simulations with and without LULCC, but all including wildfires. For these simulations we follow the same protocol as in Ward et al. (2014) and several previous studies (e.g. Kloster et al., 2010; 2012; Ward et al., 2012). The land model is forced from 1850 to 2004 with reanalysis atmospheric forcing from Qian et al. (2006). The reanalysis temperature, precipitation, wind, solar forcing, and humidity from 1948 to 1972 is used to force the model during preindustrial spinup and from 1850 to 1948, followed by the 1948 to 2004 reanalysis to force CLM in the corresponding years. CLM is coupled to a process based fire model (Kloster et al., 2010). Fire area burned is

predicted based on the probability of ignition by lightning or human activities, the fuel moisture, and the available biomass in a grid cell. In this scheme, different PFTs exhibit different mortality rates and combustion completeness. The combustion completeness of crop PFTs is set to zero. Existing PFTs do not change type due to fires or climate in this version of CLM.

Deforestation fires occur separately from wildfires in the Kloster et al. (2010) model. In this scheme, after deforestation, vegetation carbon that is normally lost to the atmosphere through decomposition may be converted to atmospheric CO₂ and other trace gas species immediately through fire if a low soil moisture condition is met. In the Kloster et al. (2010) fire model used here, deforestation fires do not impact the amount of carbon removed from the terrestrial biosphere by land cover change, but do impact the timing of the carbon loss. The more relevant impact of deforestation fires in this scheme is in the additional emissions of trace gases and aerosol species when carbon is burned, rather than lost through decomposition.

We perform two historical simulations from 1850 to 2004 with CLM, one with LULCC and one without LULCC, and both without wildfires, branched from a preindustrial spinup without fires (year 1850 land cover). This is followed by 14 future simulations without wildfires, including two simulations for each future scenario (six LULCC scenarios and the no-LULCC case), one for each of two sets of future atmospheric forcing. The future atmospheric forcing datasets, ~~were produced by Kloster et al. (2012)~~, produced by Kloster et al. (2012), are derived from the output of two coupled climate models each following the SRES A1B1 future scenario. The same atmospheric forcing is used for all future simulations regardless of the LULCC scenario

and in this way the impacts of the LULCC can be isolated (Ward et al., 2014). ~~and used by Ward et al. (2012).~~

2.4 Ascribing RF to the grid

To ascribe the global RF to each point on a 1.9 degree latitude by 2.5 degree longitude grid we assume that the contribution to the global RF from a grid point is proportional to its share of the global emissions of the forcing agent in question (or emissions of NO_x for the O_3 and indirect CH_4 forcings). This assumption holds well for globally well-mixed forcing agents such as CO_2 . A kg of CO_2 emitted from the extratropics carries similar weight, in RF terms, as a kg of CO_2 emitted from the tropics. However, Bowman and Henze (2012) showed that for the short-lived greenhouse gas, O_3 , tropical emissions lead to an enhanced RF relative to extratropical emissions. This is also potentially important for aerosols, including direct effects, due to latitudinal changes in solar insolation, and indirect effects, due to regional differences in cloud regimes (Chuang et al., 2002). Ward and Mahowald (2014) show that ascribing RF from short-lived forcing agents to individual locations based on proportional emissions is reasonable for comparing the climate impacts of developed countries, as a group, to developing countries. Although, on smaller spatial scales there are likely to be differences in the radiative forcing efficiency of short-lived forcing agents, especially aerosols, emitted from different locations (Streets et al., 2013). Here we weight all aerosol emissions equally, regardless of the source location, and note that the aerosol ERFs attributed to LULCC activities are small compared to other forcings (Ward et al., 2014).

3. Results

3.1 Land use RF by sector

In the year 2010, the LULCC RF consists of two large positive contributions from direct modifications to the land cover and from agricultural activities, and a smaller negative contribution from changes to wildfire activity (Table 1; Fig. 2). The major source of positive forcing from direct modifications to the land cover is from CO₂ emissions, with a minor negative forcing from albedo change and small contributions from aerosols and non-CO₂ greenhouse gases. In contrast, forcing from the agriculture sector is comprised mainly of positive forcings from non-CO₂ greenhouse gases. These two sectors combined account for more than 1 Wm⁻² of forcing. Global reductions in wildfire activity due to increased land management since the preindustrial time period enhance the terrestrial carbon sink, leading to a negative forcing from this sector (Fig. 2).

The future scenarios show considerable variation in the breakdown of forcing between LULCC sectors (Table 1). The RCP2.6 scenario is characterized by widespread proliferation of biofuel crops, largely at the expense of forests (van Vuuren et al., 2007; Hurtt et al., 2011). This storyline is expressed in the RF as high positive forcing from direct modifications to land cover (0.94 Wm⁻²), mainly CO₂ emissions from deforestation, but only a small contribution from agricultural activities (0.27 Wm⁻²). Due to the expansion of crop land in RCP2.6, fertilizer emissions of nitrogen-containing species increases dramatically by the year 2100. This leads to a forcing from N₂O of 0.26 Wm⁻², but also a massive drawdown of CO₂ from increased N deposition, a forcing of -0.20 Wm⁻² (included in part of the CO₂ RF from the agriculture sector in Table 1, along with a +0.03 Wm⁻² RF from the carbon cycle response to the forcing from this sector).

Previous studies have also shown that N emissions from agriculture may have a near neutral RF because of these competing effects (Zaehle et al., 2011; Ward et al., 2014). Livestock emissions of CH₄ in RCP2.6 decrease from present day to 2100 ~~present day~~ (van Vuuren et al., 2011), so the contribution from methane RF is small compared to the other scenarios.

While RCP2.6 projects proliferation of biofuels, RCP4.5 includes widespread afforestation in response to a global carbon tax policy. The afforestation is reflected in the RF of direct modifications to land cover for RCP4.5, which is the only scenario that leads to a decrease in the RF from this sector between 2010 and 2100 (Fig. 2). Wildfire emissions of CO₂ decrease due to LULCC in RCP4.5, despite the afforestation in this scenario. The decrease in fires results mainly from continued increases in tropical wood harvesting (Lawrence et al., 2012). For the remaining realistic future scenarios, the total RF attributed to LULCC is progressively higher going from the RCP6.0, to the RCP8.5, to the Trop-BAU. ~~While both direct modifications and agriculture sector RFs are also increased along this progression, the direct modifications RF dominates the growth in total LULCC RF, ranging from 0.88 Wm⁻² in the RCP6.0 scenario to 1.78 Wm⁻² in the Trop-BAU.~~ The positive contributions to RF from direct modifications and agriculture in the TEC case are similar in magnitude, both above 2 Wm⁻². While the CO₂ forcing from direct modifications is large in the TEC (2.28 Wm⁻²), the extreme expansion of pasture leads to a contribution from agricultural CH₄ (1.65 Wm⁻²) that is nearly three times the same forcing for RCP8.5 LULCC. In addition, increased NO_x emissions from agricultural activity enhance the short-lived O₃ forcing from this sector.

While agricultural emissions and land cover change projections for each RCP

were developed jointly by an Integrated Assessment Model (IAM), the land cover change projections were modified during harmonization for terrestrial model use (Di Vittorio et al., 2014). This means that the sector RFs calculated in this study may be in conflict with the original LULCC storylines of the IAMs, and, therefore, it may be more informative to consider the RF from each sector as a range of possible outcomes, separately from their respective RCPs.

3.2 Fire-LULCC interactions

Non-deforestation fires are often considered carbon-neutral, meaning the carbon sequestered during post-fire regrowth roughly balances the carbon emitted. But this is not the case for periods of trending global fire activity, as during rapid climate change (Prentice et al., 2011) or ecosystem shifts (Runyan et al., 2012), when the fire carbon source and sink are out of balance and atmospheric CO₂ concentrations are affected on a long term basis (Ward et al., 2012). Anthropogenic changes to land cover can also alter wildfire area burned and emissions (Harrison et al., 2010; Marlon et al., 2008). However, it is difficult to isolate the impact of LULCC on global fire activity from the other important drivers such as climate (Pechony and Shindell, 2011). Perhaps for this reason, interactions between LULCC and wildfire have not been explored in detail on a global scale. Previous studies have generally concluded that, globally, fires have been reduced by increases in land management over the 20th century (Houghton et al., 1999; Marlon et al., 2008; Kloster et al., 2012; Yang et al., 2014). However, local and regional scale research show vastly different fire responses to land cover change and land management in different ecosystems (Cochrane and Barber, 2009; Archibald et al., 2009; Runyan et

al., 2012). Satellite observations of African savannah show that a portion of the decrease in fires that occurred over the first decade of the 21st century resulted from conversion of savannah to croplands (Andela and van der Werf, 2014). While in the Amazon region of South America wildfires probably increase in occurrence and area burned following landscape fragmentation, especially from deforestation (Nepstad et al., 1999; 2006; Aragao and Shimabukuro, 2010; Chen et al., 2013).

Local effects such as those that occur in the Amazon are generally not well represented by global scale fire models that do not capture ecosystem edge effects or ~~simulate~~ small-scale variations in surface hydrology. Area burned by fires in the Kloster et al. (2010) model used here responds to changes in biomass availability, meaning a decrease in vegetation, such as that following deforestation, leads to a decrease in area burned. Therefore, global scale conversion of forests to grassland or crops, a ~~carbon~~ source of carbon to the atmosphere, ~~triggers-leads to~~ a decrease in fire, ~~-enhancing the~~ terrestrial carbon sink emissions of carbon to the atmosphere. From 1850 to 2004, fires were responsible for a greater than 50 PgC decrease in total carbon emissions from LULCC (Fig. 3, difference between dashed and solid green lines). About half of this decrease can be attributed to an artifact of our experimental setup that results from the removal of fires from the CLM simulations. Fires are a substantial loss term for terrestrial carbon and when they are excluded from the CLM simulations, terrestrial carbon storage increases everywhere fires normally occur (Ward et al., 2012). As a result, in the “no-fire” simulations ~~reduction in~~ carbon emissions from land cover conversions are enhanced because there is more aboveground carbon available to be released (Fig. 3). We calculate the difference in carbon emissions from land cover

conversions in the simulations with and without fire and plot this as the shaded area in Fig. 3. We do not include this reduction in terrestrial carbon emissions from fires when computing the CO₂ RF from the wildfire response to LULCC. We do consider the remaining reduction in carbon emissions shown in Fig. 3 (space between shading and solid green line), which results from an increase in the terrestrial carbon sink as fires are reduced globally by land cover changes. Strictly LULCC-caused changes in fire activity are included here and using our methodology these are isolated from changes due to trends in global climate or atmospheric CO₂. ~~The other half is attributable to the increase in the terrestrial carbon sink when fire emissions are reduced. For computing the CO₂ RF from the wildfire response to LULCC we only include the change in carbon flux due to changes in the terrestrial carbon sink.~~ An even larger reduction in carbon emissions from the wildfire response is projected for RCP8.5 LULCC, whereas global carbon emissions are not affected greatly by the LULCC associated with RCP4.5 (Fig. 4).

3.3 Land use RF by source location

The sources of the LULCC sector RFs are spatially heterogeneous and depend strongly on the LULCC projection (Fig. 5). Major present-day agricultural regions that are projected to remain productive during this century, in particular India, eastern China, and the central United States (Hurtt et al., 2011), contribute 70-80% of the global LULCC RF in 2100 as well as in the RCP4.5 and RCP6.0 scenarios (Fig. 5). In contrast, the remaining scenarios all exhibit a substantial tropical source of positive RF from LULCC. Direct modifications to land cover dominate the RF from the tropics, although there are subtropical areas where agriculture contributes the most of all sectors, especially

for RCP8.5 LULCC (Fig. 6). Similarly, in 2010, direct modification to land cover is the dominant tropical source of RF (Fig. 6). In all cases there are regions of negative forcing from LULCC, particularly in northern China and Mongolia, although these are smaller in magnitude than the positive forcings.

Comparing the latitudinally averaged total RF from LULCC to the RF from other anthropogenic activities, mainly fossil fuel burning, demonstrates the role of LULCC as the major tropical source of positive anthropogenic forcing both in 2010 and in the future projections (~~fossil fuel forcing from RCP4.5~~). We are only able to compare the LULCC RFs against non-LULCC RFs from RCP4.5 for which fossil fuel burning emissions were used to compute background constituent concentrations in Ward et al. (2014). Note that the contribution of non-LULCC activities to global RF would be larger if RCP6.0 or RCP8.5 was shown. In ~~the extreme scenarios, Trop-BAU and~~ the TEC, the tropical RF from LULCC nearly surpasses the northern hemisphere extra-tropical RF from other anthropogenic activities (RCP4.5), largely due to direct modifications of the land cover (Fig. 5, Fig. 6).

We plot the ratios of LULCC RF to total anthropogenic RF to illustrate that on an individual country level there is a substantial range in the proportion of total anthropogenic RF that can be ascribed to LULCC activities (Figs. 7, 8). ~~On an individual country level there is a substantial range in the proportion of total anthropogenic RF that can be ascribed to LULCC activities (Fig. 7a).~~ The forcing from developed countries, including the United States, Canada, Japan and the European Union countries, is dominated by fossil fuel burning in the year 2010 (Fig. 7a). This is also true for many African countries where the total anthropogenic RF is small (Ward and Mahowald,

[2014](#)). The important developing countries for global, anthropogenic climate change: China, India, Brazil and Indonesia (Ward and Mahowald, 2014), all contribute more LULCC RF than fossil fuel burning RF. These differences in the source of RF between developed and developing countries were noted by Pongratz and Caldeira (2012) for LULCC CO₂ emissions. Here we show that the same is true when non-CO₂ greenhouse gas and aerosol forcings are included in the analysis. [Standard climate change metrics, such as CO₂ equivalents, often do not incorporate short-lived climate forcers \(Ward and Mahowald, 2014\)](#). If only greenhouse gas forcing agents are included in the comparison, China is more evenly split between LULCC and fossil fuel sources of RF (Fig. 7b). Tropical countries are more consistently dominated by LULCC without the contributions of aerosols, which are often negative. Similar differences between country groups are projected to persist in the RCP4.5 scenario, although fossil fuel RF plays a larger role in general (Fig. 8).

3.4 Future RF of land use activities

~~Pattern scaling of anthropogenic impacts on climate can be used to compliment complex IAM realizations of potential futures and fill in the gaps in the range of simulated socio-economic pathways.~~ In this section, we address whether [this a simple linear regression](#) approach could be used to estimate the RF of future changes in forest and crop area. We have calculated the RF from different LULCC sectors for six possible future scenarios, providing six data points per grid cell in the tropics to test this approach (in the extra-tropics there are only 5 data points since the Trop-BAU and RCP8.5 emissions are the same). Here we regress the RF from the year 2100, referenced against

the year 2010, onto forest area change over the same period for the direct modification and wildfire sectors (increases in forest area are given a positive sign), and onto crop area change for the agriculture sector (increases in crop area are given a positive sign) for each country, using a 1.9 degree latitude by 2.5 degree longitude grid.

The regression coefficients for the agriculture sector are generally positive, indicating that an increase in crop area leads to a positive RF from that sector. The magnitudes of the regression coefficients are high in tropical countries but also in northern hemisphere extratropical countries with major agricultural sectors. The relationship is significant at a 95% confidence level (two-tailed test), using the Spearman rank correlation coefficient, for most countries (Fig. 9a). Most countries also have a statistically significant regression between direct modification RF and the change in forest area, using the same significance test (Fig. 9b). Here deforestation always leads to positive RF, including in the high latitudes where negative forcings from land albedo change play a larger role. The relationship is particularly strong in tropical countries and appears to be linked to the terrestrial carbon storage such that the impact of deforestation on RF is greatest for the high carbon-storage regions of the Amazon and central African rain forests. The regression of the wildfire sector RF onto forest area change does not produce as many statistically significant regression coefficients, but does result in a positive relationship in the deep tropics of South America and Africa and a weak relationship in several subtropical and extra-tropical countries (Fig. 9c). As forest area is reduced, the wildfire emissions simulated by CLM in deforested areas are also reduced.
 ~~##~~—Notably in Brazil and Bolivia the positive relationship between RF and forest area change through the wildfire feedback is almost as strong as the negative relationship

through direct modification of the land cover (Fig. 9b, 9c; note the different scales on these two figure panels). This result warrants further study given the possible shortcomings of the fire model used in this study for simulating LULCC-fire interactions in the Amazon (Sect. 3.2).

4. Discussion

Discussions of the climate impacts of LULCC activities are often limited to the effects of deforestation (e.g. Brovkin et al., 2013; Boysen et al., 2014; Bala et al., 2007), ~~or, in the case of Ward et al. (2014), LULCC effects as a whole.~~ Here we find a substantial contribution to anthropogenic climate forcing from agricultural activities in 2010 and in most of the future projections. Fertilizer application drives both a positive forcing, as N₂O emissions, and a negative forcing, by fertilizing natural vegetation after transport and deposition of N and drawing down CO₂ from the atmosphere. ~~Therefore We find that these forcings partially cancel each other and,~~ the differences in the agricultural RF between future scenarios are mainly driven by emissions of CH₄ from livestock and rice cultivation.

There is now recognition of the importance of atmospheric chemistry for determining the sum forcing of LULCC (e.g. Heald et al., 2008; Ganzeveld et al., 2010). Unger (2014) found a global RF of -0.11 +/- 0.17 Wm⁻² from the modified biogenic volatile organic compound emissions that resulted from historical LULCC. Here we attribute most of the important atmospheric chemistry changes, including O₃ production and loss, and CH₄ lifetime, to modified wildfire activity, although we also simulate biogenic volatile organic compound (BVOC) ~~VOC~~ emissions and their impacts on

chemistry. While previous studies have assessed the response of fire C emissions to LULCC on a global scale (Houghton et al., 1999; Marlon et al., 2008; Kloster et al., 2012), we quantify this response as a RF, including a range of forcing agents in addition to CO₂. Both in 2010 and in the future scenarios, the wildfire response to LULCC leads to a negative forcing, in most cases a result of reduced CO₂ emissions from fires. However, this response is complex and, as in the wildfire response to RCP4.5 land use and land cover change, can depend on the chemistry of fire emissions that affects non-CO₂ greenhouse gases as much as it depends on changes in terrestrial CO₂ sources and sinks. The RF of the wildfire response is not generally predictable by a simple linear regression with forest area change. Yet, fire-LULCC interactions could be associated with a considerable global forcing that acts to reduce the total LULCC RF (Fig. 2). This demonstrates the importance of accounting for these interactions in global carbon cycle models and working toward better model representation of fire responses to land cover change.

When interpreting these results it is important to note that while the set of forcing agents considered in this study is nearly comprehensive, feedbacks of LULCC onto the hydrological cycle and clouds were not included in this study. These feedbacks could lead to a net cooling of global surface temperatures from deforestation even when accounting for increased CO₂ from forest removal (Bala et al., 2007). Although, Davin and Noblet-Ducoudre (2010) show that the non-radiative biogeophysical forcings of land cover change, associated with evapotranspiration and surface roughness, could be a net warming. A study using CLM in a fully coupled climate model suggests that the total forcing of biophysical effects, including cloud cover feedbacks, associated with historical

land cover change are probably small compared to the forcing from greenhouse gases emitted by the same activities (Lawrence and Chase, 2010). These forcings and feedbacks are not easily quantified with the RF metric (Pielke et al., 2002). A different approach to our stated aim of identifying the sources of climate impacts from LULCC could use global surface temperature change as a metric, instead of radiative forcing. With this approach the various biogeochemical and biogeophysical effects could be combined.

However, by attributing forcing from LULCC activities to specific sectors and locations, given the set of forcing agents included in this study, we gain a better understanding of where efforts to mitigate anthropogenic climate changes could focus. ~~The range in projected RF from direct modifications to land cover is much larger than that of agriculture or the wildfire response, and has the greater potential to increase in the future, following the six scenarios considered in this study.~~ The forcing from direct modifications is the most effectively scalable to changes in land cover, namely forest area changes (Fig. 9). The potential importance and scalability of RF from the direct modifications sector lends support to the REDD strategy of valuing land based on the potential C emissions from deforestation (Lubowski and Rose, 2013). This strategy could be particularly effective in the tropics, although related changes in wildfire activity complicate the overall LULCC contribution to global RF.

Appendix A

Summary of RF computations

In the remainder of this section we provide a summary of the different methodologies used to compute the RFs from LULCC for all forcing agents in Ward et al. (2014). The order of forcing agents in this summary is CO₂, N₂O, CH₄, O₃, aerosol effects, land albedo change, and biogeochemical feedbacks onto CO₂ concentrations. The anthropogenic RF of an atmospheric constituent is computed from the change in the concentration of that constituent due to anthropogenic activities over a reference time period, often a preindustrial date to the present. Therefore, computing RFs is, for most forcing agents, a three step process beginning with assembling of the emissions dataset of interest, using the emissions to calculate a change in concentration of the forcing agent, and finally assessing the RF from the concentration change. Forcing agents with different atmospheric lifetimes, for example N₂O (>100 years) compared to aerosols (days to weeks), require different methods for determining concentration changes. In the remainder of this section we provide a summary of the different methodologies used to compute the RFs from LULCC for all forcing agents in Ward et al. (2014). The order of forcing agents in this summary is CO₂, N₂O, CH₄, O₃, aerosol effects, land albedo change, and biogeochemical feedbacks onto CO₂ concentrations.

Global CO₂ emissions from LULCC are considered to be uncertain. Model inter-comparison studies produce a large range in values for this quantity (Brovkin et al., 2013) and even differences in terminology play a role in the uncertainty (Pongratz et al., 2014). Using a modified Community Land Model version 3.5 (CLM; Oleson et al., 2008; Thornton et al., 2009), Ward et al. (2014) compute the net LULCC carbon flux from 1850 through the year 2100 as the difference in terrestrial carbon storage between simulations with land cover change and land use, and a reference simulation with

preindustrial land cover (year 1850). The LULCC flux was adjusted downward to account for the CO₂ fertilization feedback (Strassmann et al., 2008), which leads to double-counting of CO₂ emissions in uncoupled terrestrial model simulations (Pongratz et al., 2014; Arora and Boer, 2010). The double-counting occurs in transient-CO₂ simulations when no LULCC is included but atmospheric CO₂ concentrations reflect the impact of LULCC, thereby artificially increasing CO₂ fertilization of vegetation. The airborne fraction of CO₂ emissions, that is the portion of emitted CO₂ remaining in the atmosphere at the year the RF at some future time, was derived from a pulse response function characteristic of rising CO₂ concentrations (following the methodology of Randerson et al., 2006 and O'Halloran et al., 2012). In this way, the history of CO₂ emissions from different sectors of LULCC is accounted for in these calculations. From the change in CO₂ concentration, the RF of CO₂ emitted by LULCC activities was calculated with the simple expression from Ramaswamy et al. (2001).

Nitrous oxide is emitted by livestock and by the application of fertilizer onto crops. LULCC also has a minor impact on N₂O concentrations by modifying wildfire emissions. N₂O has a long lifetime in the troposphere (greater than 100 years (Meinshausen et al., 2011)) and its chemistry can be treated with a simple box model approach. Ward et al. (2014) used the Kroeze et al. (1999) box model to calculate the change in N₂O concentrations resulting from the emissions associated with LULCC. RFs were calculated with the simple expression recommended by Ramaswamy et al. (2001).

Methane concentrations are modified directly by emission of CH₄ from LULCC activities, and indirectly by changes to the oxidation capacity of the troposphere that impacts CH₄ lifetime. Emissions of CH₄ from LULCC have been compiled for the

historical time period (Lamarque et al., 2010) and for the RCP scenarios (van Vuuren et al., 2007; Wise et al., 2009; Fujino et al., 2006; Riahi et al., 2007). In addition, small changes in CH₄ emissions from wildfires are caused by LULCC and were simulated by CLM for these calculations (Ward et al., 2014). A box model approach from Ward et al. (2012) was used to determine the direct modifications to CH₄ concentrations from LULCC. To determine changes to the CH₄ lifetime, Ward et al. (2014) simulated atmospheric chemistry within the Community Atmosphere Model version 4 (Hurrell et al., 2013; Gent et al., 2011; Emmons et al., 2010) with LULCC emissions of non-methane hydrocarbons (NMHC) and NO_x, and without these emissions. The different emissions lead to changes in global hydroxyl radical, OH, concentrations. The CH₄ lifetime can be computed from the new OH concentration (Naik et al., 2005; Ward et al., 2012) and the changes to CH₄ concentration from LULCC activities were adjusted according to the new lifetime (Ward et al., 2014). The RF is calculated using the simple expression recommended by Ramaswamy et al. (2001) for CH₄.

LULCC impacts tropospheric O₃ concentrations by emitting NO_x (such as from fertilizer application) and by modifying emissions of NMHCs from vegetation and from fires. The response of O₃ concentrations to the changes in these emissions cannot be represented with a simple model approach but involves a complex set of chemical reactions. Ward et al. (2014) calculated the LULCC contribution to tropospheric O₃ with the same set of CAM4 simulations used to assess the CH₄ lifetime. The radiative impact of the changes in O₃ was determined with the Parallel Offline Radiative Transfer (PORT) tool (Conley et al., 2013) for both shortwave and longwave interactions. The response of O₃ on long time scales to changes in CH₄ concentrations, known as the primary mode

response, was included in the LULCC O₃ RF calculation following Prather et al. (2001).

Emissions of several aerosol species are impacted by land use and land cover change. Ward et al. (2014) considered changes in biogenic, secondary organic aerosol from modified leaf area index, changes in dust emissions from cultivation, and changes in fire emissions of black carbon (BC), organic carbon (OC) and sulfate aerosols from LULCC. Changes in aerosol concentrations were computed with a set of CAM version 5 simulations with the modal aerosol model (MAM3) (Liu et al., 2012), with and without the LULCC emissions. Radiative effects of the aerosols, both direct effects and indirect effects on clouds, were diagnosed online, giving values for effective radiative forcings (ERF) for the LULCC aerosol emissions.

Changes to the land surface albedo from land cover change were derived directly from the CLM simulations in Ward et al. (2014). The simulated changes in albedo alter the fraction of incident solar radiation that is reflected back into the atmosphere. The reflected solar radiation is multiplied by the fraction of outgoing radiation that reaches the top of the atmosphere at each grid point of a model climatology characteristic of the year 2000 in which clouds and aerosol scattering are implicit. The radiative forcing is then simply the difference in top-of-atmosphere net solar radiative flux caused by the changes in albedo. Additional forcing from modified albedo following fires was also included, for the change in fires due to LULCC, following the offline analysis of Ward et al. (2012). Feedbacks of nitrogen deposition by aerosols and feedbacks of climate change onto the carbon cycle have been identified and quantified by Mahowald (2011). The magnitudes of these feedbacks for LULCC were estimated by Ward et al. (2014) and included in the total CO₂ RF.

