Responses to the review of T. Gasser

REVIEWER:
This paper by Ward et al. presents an assessment of the climate forcing induced by past and future land-use and land-cover change. As far as I know, this paper is the most comprehensive assessment of climate forcing from LULCC, and thus it is worth publishing. I, however, have some questions/suggestions on the scientific aspect of the work, as well as strong concerns as to how the work is presented.

RESPONSE:
Thank you for your comments, which we found to be insightful and helpful for revising this manuscript. We have addressed all comments with major revisions to the manuscript including a revision of the overall organization of the text. Please see our responses to the comments below, preceded by "RESPONSE".

REVIEWER:
1 On the methods
1.1 Overall
In this paper, the authors use historical and future land-use and land-cover change data to estimate the RF induced by these activities and to compare it with the one induced by other anthropogenic activities (mainly fossil-fuel burning and industrial activities). Land-cover change, wood harvesting, agriculture and livestocks are the anthropogenic land-use-related activities considered in the study. The study then follows the "cause- effect chain" to go from anthropogenic activities to emissions of various compounds, to atmospheric burdens of GHGs and aerosols, and finally to the radiative forcing induced by these compounds.

The overall approach is scientifically sound. It appears to be a reasonable compromise between accuracy and efficiency, though it is subject to several shortcomings that, as long as they are explicitly identified and discussed, do not change the qualitative conclusions of the work. All these shortcomings and/or inconsistency have to be mentioned in the text (which is not always the case), maybe even in a specific sub-section of the methods section.

RESPONSE:
We address this comment specifically in our response to comment 1.2.2.

REVIEWER:
1.2 More specific comments
1.2.1
This paper is an attribution exercise, and I think it should clearly be presented as this by using the word "attribution" more often, especially in the abstract, introduction and conclusion.

RESPONSE:

We made an effort to use the word attribution more often in this manuscript and found several instances, particularly in the introduction, where using this terminology should be much more effective.

REVIEWER:
To this attribution exercise is associated an attribution method called the residual method, where the contribution of LULCC is deduced by substraction of two model realizations: one with all drivers (LULCC + non-LULCC) and one without LULCC (non-LULCC alone). This approach is carried out along the whole study, hence the authors implicitly define the contribution of LULCC as the difference between these two realizations (which raises some issues as to non-linearity, but this is not the point here).

This is at least what I understood. But it does not appear clearly in the text: there should be somewhere (introduction, methods section) a clear statement about this attribution method.

RESPONSE:
We agree that this basic approach (explained nicely here by the reviewer) was not explicit in the MS text and should be prominently explained. We add the following text to the "Overview of methods" section (first paragraph in Sect. 2) to explain this approach:

"For several forcing agents, including CO_2, we isolate the LULCC emissions by comparing global transient simulations of the terrestrial biosphere with LULCC to simulations without LULCC that are otherwise identical, and attribute the difference in emissions between the LULCC and no-LULCC simulations to LULCC. This general approach, attributing the differences between the LULCC and no-LULCC environment to the impacts of LULCC, also applies to our calculations of RFs."

REVIEWER:
Along with this comment, I am very very uncomfortable with the vocabulary used to discuss this attribution. Especially surrounding table 2, the authors usually refer to the contribution of LULCC as a "change", or they write that LULCC "increased" or "decreased" emissions of some compound in a given year. This is disturbing. All this should be rewritten, using a more dedicated vocabulary like: "contributions from LULCC", "attributed share", "LULCC-induced emissions". Words like "change", "increase" or "decrease" are misleading when comparing two realizations, i.e. two hypothetical worlds, and they should be reserved for temporal dynamics.

RESPONSE:
We have corrected all instances of this kind of language usage as suggested by the reviewer. The majority of the changes were needed in Section 2, often when referencing Table 2 as pointed out. There were several instances where we use similar language but to refer to changes in atmospheric concentrations of species or changes with emissions over time and in these cases we kept the original language.

REVIEWER:
1.2.2
There is an opposition (and somehow an inconsistency) between using a complex land model to deduce emissions of some coumpounds (CO2, Fire, SOA, Dust), and a simple rescaling for others. I am not asking to redo all the work, but the inconsistency and missing processes should be clearly acknowledged. For instance, a process-based representation of wetlands (both anthropogenic and natural) could significantly affect the quantitative conclusions of this study about CH4. Indeed, drying of wetlands in the past has likely decreased CH4 emissions from wet- lands. Also, if rice paddies were taken over natural wetlands, only the difference in CH4 emissions is attributable to the land-use activity (it is not done this way in the RCP). However, little is known about preindustrial wetlands extent, and given it is also affected by climate, it is understandable that it was not included in the study.

RESPONSE:
To address this comment we have added text and moved some existing text into two new paragraphs with the aim of being more comprehensive and organized about communicating the shortcomings and missing processes in this study. We found that we did include some of these inconsistencies in the original MS but they were often scattered throughout the text and not prominently placed. Most of these are now listed in the same place and combined with additional missing processes into the last paragraph of new Sect. 2.1 (LULCC activities):

"While we consider this list of activities to be highly inclusive, several LULCC activities and processes are not included in this study, either because they are difficult to properly model or represent as a forcing, or because of a poor level of current understanding of the process. We exclude the impacts of anthropogenic water use, mainly irrigation, on global water vapor concentrations and the associated RF (Boucher et al., 2004). Changes in water use and land use have numerous other implications for the hydrological cycle including impacts on evapotranspiration, runoff, and wetland extent (Sterling et al., 2013). Related to these effects, the impact of land surface albedo changes may be further moderated by changes in cloudiness (Lawrence and Chase, 2010), which we did not consider in this analysis. Also, emissions of CH4 are tied to the global extent of wetlands, which have likely changed since preindustrial times (Lehner and Doll, 2004), but the scale and distribution of the change is not yet known well enough to be included in our model setup. We assume that natural CH_4 emissions remain unchanged from 1850 through 2100 for all scenarios. Finally, there is a potentially major source of CO_2 from deforestation and forest degradation in tropical peat swamp forests that has only recently been recognized (Hergoualc'h and Verchot, 2011), although it is thought that contributions from this source to current global CO2 concentrations are small (Frolking et al, 2011)."

We are explicit about the lack of understanding of natural N2O emissions (new Sect. 2.3.2) and kept this in the original location in the text. The second paragraph

focuses on the shortcomings of the methodology we use to calculate the RFs. This is the last paragraph in new Sect. 2.4 (RF calculations), and part of this new text that is relevant to this comment is given here:

"For the calculation of the many forcing agents that we do consider, our approach is to treat each forcing separately, which could lead to differences in RFs between agents that are due partly to methodology. For example, land cover changes and agricultural emissions were developed jointly for each of the RCPs, but for use in terrestrial models, including CLM, the land cover change projections were altered (Di Vittorio et al., 2014). This leads to inconsistent storylines between future emissions computed by CLM (Sect. 2.2) and those taken directly from the RCP integrated assessment model output (Sect. 2.3.1). Therefore, it is important to view the future RFs computed here as comprising a broad range in possible outcomes, extended with the TEC, as opposed to precise results corresponding to specific storylines for the future."

We now suggest in the results section (new Sect. 3.1) that since our total anthropogenic RFs match previous estimates, methodology is robust even though there is no single method for computing the RFs of the many forcing agents. The aerosol forcings of course are highly model-dependent and that is why we make an exception for these and use the IPCC AR5 values instead.

REVIEWER:
Given that CLM includes an explicit N-cycle, I wonder why land-related N-fluxes (i.e. NOx, NH3, N2O) were not taken from the model, while the C-fluxes were. Again, it is alright if the authors are not confident enough to take the fluxes from their model, but it should be clearly stated.

RESPONSE:
This is a great question and the answer is, unfortunately, that these emissions are simply not simulated by CLM yet. We now note this in the first sentence of new Sect. 2.3.1 (Agricultural emissions):

"Agricultural emissions of important trace gas species, such as NH_3 and N_2O, are not simulated by CLM. Therefore, additional emissions from LULCC activities associated with agriculture were taken from the integrated assessment model emissions for the different RCPs (e.g. van Vuuren et al., 2011). "

REVIEWER:
It is unclear if changes in biogenic NMHCs emission induced by LCC (not by deforestation fires, but by changes in PFT fractions and LAI) are also added to anthropogenic emissions from RCP in the calculation of tropospheric O3 and change in CH4 lifetime. According to figure 2 it is not, but it could/should be.

RESPONSE:

Thank you for pointing this out - changes in these emissions attributed to LULCC are included in the CAM-chem simulations and we added an arrow to this figure to note that non-fire changes in NMHCs are also coming from CLM.

REVIEWER:
1.2.3
This study obviously took some time, and it looks like it begun a while ago, thus results are compared to the AR4. It seems to me that updating the paper with the AR5 would not be too difficult, as it does not require further simulations. Also, the AR5 reference year is 2011, which is closer to the year 2010 used in this study. This would be needed when comparison of results is done (figure 5), and for the rescaling of aerosols effects (which are not so much separated into direct and indirect in the AR5).

RESPONSE:
This is an excellent suggestion and we have done this. Using AR5 did not require any further simulations but it did require redoing most of the offline calculations since we scale our aerosol RFs to the IPCC central estimates (which are quite different in AR5 compared to AR4). Using AR5 makes this scaling of the aerosol RFs more justifiable as they now report effective RFs, which are what we calculate in this study. The text, tables and figures have been updated to reflect this change.

The change in total anthropogenic aerosol RFs (now scaled to AR5) did not change the LULCC RF from these forcings in a substantial way since they were small to begin with. It does, however, change the uncertainties and perhaps the biggest change is in the proportion of the total anthropogenic RF attributed to LULCC. Since the cooling aerosol RFs are now smaller in magnitude, the contribution to positive RF from fossil fuel burning is larger. The new LULCC portion of total anthropogenic RF is 40% +/- 15%.

REVIEWER:
By the way, if such an update is feasible in a reasonable amount of time, I also suggest to change the IRF used for CO2 with the one used in the AR5, chapter 8

RESPONSE:
This is also a good suggestion and we were aware of the Joos et al. (2013) work and made a decision to use the older IRF from Enting et al. because they include a scenario where CO2 concentrations are increasing, instead of only scenarios of either preindustrial or present day CO2 concentrations. We consider the older IRF to work better for understanding the airborne fraction of CO2 emitted into an transient atmosphere with respect to CO2 concentrations, such as the historical period and most future scenarios.

REVIEWER:
1.2.4
The way CO2 emissions from LULCC are estimated puzzles me (section 3.2.5). I do not think there should be any downward adjustment! The debate as to what should be

included in the CO2 LULCC flux is still open, and very unlikely to be settled any time soon (see doi:10.5194/esd-4-171-2013 and doi:10.5194/esd-5-177-2014). I'd rather see the authors of this paper choose an attribution method (see above) and stick to it, and not try to correct some biases that only exist for a specific definition of "emissions from land-use change".

RESPONSE:
This aspect of our study has now been clarified with references to the categories defined by Pongratz et al. (2014). The changes to the text are in new Sect. 2.2.4 (Co2 emissions). Our approach to computing the emissions with un-coupled terrestrial model simulations puts our net LULCC carbon flux into the "D3" category as defined by Pongratz et al. (2014), meaning we are missing the CO2-fertilization feedback. If we were not interested in attributing changes in atmospheric CO2 concentration to LULCC then we could report the emissions without adjustment from our model and it could be compared to previous D3 studies. However, to get the concentration change right we need to account for all carbon sinks associated with LULCC and therefore need to adjust for the CO2-fertilization feedback.

We have also slightly modified our approach to accounting for this feedback. Previously we reduced carbon emissions from LULCC by a constant PgC amount per year. In light of recent papers we find that it is more appropriate to reduce the carbon emissions by a percentage of the emissions, not a constant PgC amount. We use the same method as in the original MS to arrive at this percentage – 20%. The RF from LULCC-attributable CO2 is unchanged for 1850-2010 but has been reduced for all future scenarios 1850-2100. These changes in RFs are reflected in the tables, figures and text.

REVIEWER:
Actually, the strongest bias as to CO2 induced by the way the attribution is done is the inclusion of the loss of potential sink into the CO2 flux (again, see doi:10.5194/esd-4-171-2013 and doi:10.5194/esd-5-177-2014). But, again, it is only a matter a choice, and I only suggest to state it clearly somewhere in the text, but not to correct it.

RESPONSE:
The added references to Pongratz et al. (2014) make our methods in this regard more understandable, in our view. We do mention that we are accounting for changes in the terrestrial carbon sink attributable to LULCC in new Sect. 2.2.4 (CO2 emissions).

REVIEWER:
The third paragraph of section 3.4.5, discussing the "aerosol BGC effect", actually discusses the carbon-climate feedback. The author decided to complement the IRF approach for CO2 atmospheric concentration with a simple linear correction to account for this feedback. Although it is a bit crude, I think it is a not-so-bad approach. However, I believe this whole section should be put in the section discussing the atmospheric concentration of CO2.

RESPONSE:
We do agree that the C-climate feedback could also be included in the section on atmospheric CO2 changes (now in Appendix B1). However, since we compute the RF from the C-climate feedback separately from the RF from the LULCC CO2 emissions and fertilization feedback we have decided that it is most appropriate to keep this text in the section on BGC feedbacks (now Appendix B7). We have changed the title of this section to read "Biogeochemical and carbon-climate feedbacks" since the previous title referred specifically to aerosols and that may have been part of the reason why the carbon-climate feedback material seemed out of place.

REVIEWER:
2 On the outline
The paper is organized following the conventional introduction-methods-results-conclusion outline. Despite being quite complete, precise and accurate, it is rather tedious to read and sometimes repetitive. I believe the paper could greatly benefit from an overhaul! More specifcally, some details should be put in Appendix, to let only the strong message in the main text.

To me, the main results are: 1) the estimation of the contribution of LULCC to RF in present days and in the future; and 2) the use of CLM the derive some emissions that are not well accounted for in other studies. The creation of a WCS is also of interest given the low likelihood of the RCPs' land-use scenarios. Thence, I would recommend puting in Appendix everything else. There would be 3 main appendixes: the way WCS is created (along with figures 3 and 4), the details of the methods and models used (esp. about atmospheric burden and RF), the uncertainty treatment.
Repetitions could be avoided by organizing the paper per process/phenomenon. Currently, the paper first enumerates all the land-use-related phenomena in introduction, then it describes how they are accounted for in the methods section, and then in the results section the values and limits are discussed. This can lead to double/triple citation of phenomena and/or references that renders the paper heavy.

I recommend an outline like this:
1. Brief introduction (quick context, goal of the study, overview of methods: follow causal-chain from activities to RF).
2. Overview of methods
2.1. LULCC activities (should not include Fires)
2.2. Emissions deduced with CLM (should include Fires, one subsection per com- pound, should include brief discussion about table 2)
2.3. Emissions not by CLM (one subsection for N2O, and one for others)
3.4. Radiative forcing (one paragraph for GHGs, one for short-lived species, one for albedo effects; give details in Appendix)
4. Results
4.1. Individual contributions from compound/process (present-day only)
4.2. Overall contribution from LULCC (present-day, RCPs, WCS)

4.3. Enhancement factor
5. Conclusions
With a clear reorganization things like table 1 or introductive paragraph of section 3 could be removed.

RESPONSE:
We followed the reviewer's suggested outline and find that the manuscript is much improved in readability. We include a somewhat more expanded section on RF in the methods section (new Sect. 2.4) than was recommended in order to communicate the basics of the uncertainties and shortcomings of our approach.

REVIEWER:
3 Specific points
p.12170 l.4–20 To complete, one could add the change in VOCs emissions due to LCC (e.g. doi:10.1029/2005GL024164), and a reference to Arneth et al. (doi:10.1038/ngeo905) could be added as they give a comprehensive view of the feedbacks involving the land biosphere.

RESPONSE:
In shortening the introduction and moving to the new outline, as described above, we had deleted some of this text. However, we now reference Arneth et al. in our discussion of carbon-climate feedbacks.

REVIEWER:
p.12172 l.24–25 This is no longer true (yet not totally false) as for some compounds the AR5 gives the partition between fossil-fuel and land-use.

RESPONSE:
This is true and maybe a sign that there is building interest in sector-based studies of forcing and climate change.

REVIEWER:
p.12177 l.14 Unclear what happens between 2005 and 2010, as RCPs are not de- fined over this period.

RESPONSE:
Thank you for pointing this out, we now include in the text:

"We use historical agricultural emissions from ACCMIP (Lamarque et al., 2010), which covers the time period of 1850-2005 and extend the historical emissions with RCP2.6 projected emissions through year 2010 for computing LULCC RFs in the year 2010."

We now make a similar statement for the extension of the land cover change timeseries for computing RFs in 2010. Also, we had been comparing our calculated total anthropogenic RF in 2010 to van Vuuren et al. (2011) and using RCP2.6 for the

comparison (not much change between RCPs in 2010) but now compare to IPCC AR5 instead.

REVIEWER:
p.12178 l.4 Section 3.1.1. includes a description of environmental changes (CO2, climate) used with CLM. These are not stricto sensu "LULCC activities". They could be put in Appendix with the details of how CLM is used. By the way, I did not understand how the two different climate projections were used to assess uncertainties...

RESPONSE:
This paragraph has been moved to new Sect. 2.2 (LULCC emissions (computed from CLM)), a more appropriate point in the text as the reviewer points out. The use of two atmospheric forcing datasets that are very different from one another was simply used to create a range in future fire emissions that gives some idea for what the uncertainty in future fire might be, given a particular scenario. This is similar to how the RCPs are used to create a range in potential outcomes even though the uncertainty in future climate (as impacted by human activities) can be considered undefinable.

REVIEWER:
p.12178 l.16–26 This whole paragraph goes with the way WCS is created (in Appendix).

RESPONSE:
This paragraph has been moved to Appendix A (along with the WCS text).

REVIEWER:
p.12180 l.9 These are not explicit land-use activities in the study: only implicit as emission data are taken from the RCPs.

RESPONSE:
This is correct, we make this clear now in the first paragraph of the section on LULCC activities (new Sect. 2.1).

REVIEWER:
p.12181 l.5 Give the precision that N2O is treated separately because sectoral info is not available from RCPs.

RESPONSE:
We added the text "N_2O emissions are not reported by sector for the RCPs and we compute these separately (Sect. 2.3.2)." as the next sentence.

REVIEWER:
p.12182 l.9 "CAM" acronym is used without being defined.

RESPONSE:

This has now been defined.

REVIEWER:
p.12185 l.14 Davidson (doi:10.1038/ngeo608) did some things about N2O emissions by tropical forest soils. Although uncertainties are not assessed and are certainly high, it is at least an estimate. But this relate to my major comment 1.2.2.

RESPONSE:
Davidson (2009) does a really nice job estimating N2O emissions from manure and fertilizer but we still lack a good enough understanding of natural emissions to justify changing these emissions in the future.

REVIEWER:
p.12188 l.5 Again, this is an old IRF.

RESPONSE:
See our response to the previous comment on this subject.

REVIEWER:
p.12196 l.8–13 I would not mention at all the "uncertainty in policies": it is a very different and peculiar kind of uncertainty, not directly comparable with scientific uncertainty.

RESPONSE:
We have removed this text.

REVIEWER:
p.12199 l.14 I think there is a bias in estimating P and Fe deposition only from fires. More specifically, fossil-fuel burning also emits phosphorus, and I think continental dusts do bear iron as well. Actually, the uncertainty is so high in that field that I would suggest not to account for these two effects at all.

RESPONSE:
As suggested by the reviewer we have removed estimates of these forcings from the analysis and the reported RFs.

REVIEWER:
p.12202 l.1 The discussion relative to the enhancement factor should be extended, especially regarding the effect of accounting for uncommon land-use-related emissions (Dust, Fires, etc.). Would another model give significantly different enhancement factors? Are there still missing processes/compounds that could change the results, in one way or another?

RESPONSE:
We address these comments with an additional paragraph in the section on enhancement (new Sect. 3.3):

"The uncertainties in this factor (computed using the monte carlo method are described in Appendix C3) are large but suggest that the enhancement is unlikely to be less than 1.3 for the year 2010 or any of the given future scenarios. Values above 4.0 for the enhancement factor are within the uncertainty range for the RCP4.5, RCP8.5 and TEC scenarios. The large enhancement factors for the RCP8.5 and TEC scenarios result mainly from the substantial CH_4 RF relative to the CO_2 RF. For RCP4.5, this is a reflection of the low CO_2 RF attributed to LULCC and relatively high total RF with contributions from all other non-CO_2 greenhouse gases. The aerosol forcings play a minor role in the sum RF attributed to LULCC but impact the enhancement factor by reducing the non-LULCC forcing considerably. The aerosol ERFs are the source of much of the uncertainty surrounding the enhancement factor. Since the RF calculations presented here are within uncertainty estimates across many models and estimates (Fig. 3), it is likely that other models or approaches would obtain similar results if the same processes and activities were considered. We do not expect that the LULCC activities and biogeophysical forcings that we exclude from this study would have a substantial impact on the enhancement as these forcings have been shown to be small when considered on a global scale (Lawrence and Chase, 2010). Including model representation of LULCC impacts on soil carbon could increase the CO_2 and total RF attributed to LULCC (Levis et al., 2014) and lead to a small reduction in the enhancement factors compared to the values we report."

REVIEWER:
table 2 I suggest to add CO2 emissions (maybe cumulative) to this table. Also, see major comment 1.2.1. about vocabulary and the fact that it should be clear that the emissions presented here are the emissions attributed to LULCC following the chosen method.

RESPONSE:
We have changed the language used in the caption to be more responsive to reviewer comment 1.2.1. Here we decided not to include the cumulative CO2 emissions in the table since it would introduce a different timescale to the table (currently only showing emissions from one year) and might be confusing. Also, we do not refer to the cumulative emissions from CO2 in the text any more, preferring to note the change in CO2 concentrations attributed to LULCC given the many different ways net carbon emissions from LULCC can be defined.

REVIEWER:
table 5 Define AOD.

RESPONSE:
Corrected.

REVIEWER:

table 6 Given the importance – in the main message – of the enhancement factor, and given the authors assessed the uncertainty in the study, I strongly suggest to show uncertainty ranges of the factor in this table.

RESPONSE:
We applied the same montecarlo methodology used to estimate uncertainties in the proportion of anthropogenic RF attributable to LULCC to this question. The uncertainties surrounding the enhancement factors are large but this makes sense since we are looking at a ratio with a number in the denominator (CO2 RF) which can be quite small for LULCC within its own range of uncertainty. These uncertainties are reported in Table 5.

REVIEWER:
figures The figures are nice. But again, figures 3 and 4 could be put in Appendix.

RESPONSE:
These figures have been moved to the appendix as per the reviewer's suggestion.

Responses to the review of A. Arneth

REVIEWER:
This is a v. nice paper that attempts to provide estimates for a range of climate effects arising from LULCC. By doing so, the authors rightly emphasise that human land management has plenty of impact on atmospheric composition, and climate, and hence we need to look beyond "only" CO2 (and more recently: the biophysical aspects of LULCC). As it seems, quite an amount of work has gone into the paper; it combines a range of simulation experiments done with a suite of global models with estimates that are more of a review -based nature, using previously published work. The individual numbers are thus the products of different levels of complexity, which reflects to some degree our current state of modelling, but should be a little more openly acknowledged (see also the review by Thomas). I have a number of fairly minor comments, mostly related to the methods:

RESPONSE:
Thank you for your thoughtful comments, we have addressed them with revisions to the text and in our responses included below. The manuscript has been rearranged and several parts have been re-written in response to the first reviewer. Our responses are preceded by "RESPONSE".

REVIEWER:
1) LULCC-C fluxes: Julia Pongratz made a nice comparison of how the exact "meaning" of this term varies between studies (depending on what fluxes are included), see her 2013 ESD paper. For clarity, could you specify, which of Julia's cases is closest/identical to your definition of LULCC CO2 flux

RESPONSE:
We have done this, referencing Pongratz et al. (2014) several times in the new Sect. 2.2.4 (CO2 emissions) and noting that our method falls into the "D3" category from her paper and that our adjustment for the CO2-fertilization feedback is an attempt to emulate an "E2" model setup.

REVIEWER:
2) Have I overlooked something – but could you clarify whether in 1850 you used natural land cover, or applied a constant anthropogenic cover fraction for 1850 in the spin up – and/or accounted in the spin-up already for C lost due to LULCC before that period ? (see e.g., Sentman et al, Earth Int., 2011). Using natural cover for spin-up would be incorrect, because of large vegetation removals before that period, legacy effects, the different turnover times of harvested C and so forth.

RESPONSE:
We apply a constant 1850 land cover during spinup but were not explicit about this in the text. We have added reference to this now in the new Sect. 2.2, first sentence of the second paragraph:

"Spin-up of CLM is carried out with year 1850 land cover, which includes some anthropogenic changes."

We now also reference Pongratz and Caldiera (2012) in which they note that almost 10% of historical anthropogenic global temperature change may be due to preindustrial LULCC which we do not capture in this study.

REVIEWER:
3) "Worst case scenario": While being rather academic, I actually quite like the idea of exploring a system's response to an extreme scenario case, especially since e.g., the most recent RCP LUC scenarios are limited in terms of their assumptions (and in the CMIP5 simulations were realised individually only by one IAM). The authors have put quite some effort into preparing this scenario. However, I had to ponder a bit as to why the "WCS" made me feel a little uneasy. And perhaps this is semantics, but to me the term "worst case" implies a scenario that is really, really bad – but not necessarily implausible. Yet I would argue that the total con- version of aerable land into crop and pasture indeed is implausible (hence disagreeing with your statement on page 12201, line 5) – based on the hypothesis that well before such a conversion was complete humanity would run into serious issues with local and regional hydrology (floods vs. water shortage), water pollution through fertilisers, desertification and related dust pollution, etc. Social, economic and political pressure would not allow this worst case to be reached. So I like the idea of a (as the authors call as well) theoretical case. But I would like to see it re-labelled, e.g., "theoretical extreme case" ("TEC") scenario, which would have the implausibility already clearer in the title.

RESPONSE:
This makes sense to us, and we have rephrased the sentence on pg. 12201 to no longer include the word "plausible". We have changed the WCS to TEC in the text, tables, and figures.

REVIEWER:
And: perhaps I have missed an important point, but possibly the authors would have saved themselves quite a bit of work by using the projections of the agro-ecological zones from FAO. I am sure there are differences in the methodology, but the same principle applies, namely to assess crop potentials based on soil and climate to yield potential crop areas for present-day and future. How different are the areas identified suitable in the AEZs from the areas used in your paper?

RESPONSE:
We did consider using the FAO AEZ dataset but our impression was that it would be difficult to extract estimates for pasture expansion from this dataset, even though it is much more detailed and comprehensive with crop potential, including a set of different crops and yields. Also the simplicity of the Ramankutty approach was appealing with the results of the analysis being the fraction of the gridcell supporting crops/pasture regardless of yield, which was ideal for creating the dynamic PFT timeseries.

The difference in crop area between the AEZs and our estimates for total arable land appears to be small in most regions. They can be compared by looking at panel 'b' in new Figure A2 in our manuscript and comparing to the FAO panel for suitability for rain-fed crops. This is from the 2002 dataset:
http://webarchive.iiasa.ac.at/Research/LUC/SAEZ/plates/gif/plate46.gif

The Ramankutty approach seems to underestimate crop area in northern Europe and in central Africa in comparison but the quantities being compared are not exactly the same.

REVIEWER:
And just for curiosity: what's the main reason for your parameter values in (2) - (5) being different from Ramankutty?

RESPONSE:
Good question - we follow the same procedure as Ramankutty et al. (2002) but use updated datasets. So where they use 1970-2000 climate data, we were using 1980-2010, and we were using updated soil and crop area data as well.

REVIEWER:
Finally: a very recent review of existing potentially available cropland estimates also can help to place the "WCS" into context (accepted manuscript, online): Eitelberg et al., GCB, 10.1111/gcb.12733

RESPONSE:
Thank you for pointing us to this paper, we now cite this in our discussion of our estimate of the potential crop area (4180 Mha) and note that it is near the high end of the range of published estimates, but not the highest. This part of the text is now in Appendix A.

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These comparisons are highly uncertain in part because reports of historical CO_2 emissions from LULCC cover a wide range of values and are computed with several different methodologies (Houghton et al., 2012; Brovkin et al., 2013). Houghton (2010) estimates that 156 PgC has been emitted by historical LULCC from 1850 to 2005, using an inventory-based method (Houghton et al., 1983; 1999). This approach does not account for the feedback between increasing atmospheric CO_2 and LULCC C emissions, also known as the fertilization feedback (Arora and Boer, 2010), or for the diminished capacity of deforested land to act as a CO_2 sink as atmospheric CO_2 concentrations increase (Strassmann et al., 2008). Alternatively, LULCC C emissions are estimated with model simulations of the terrestrial biosphere with and without LULCC after assessing the difference in C stocks between the two simulations. With this approach the effects of CO_2 fertilization on LULCC C emissions can be accounted for, although there is as yet no consistent method for including feedbacks without using a fully-coupled carbon cycle model (Arora and Boer, 2010). Gasser and Ciais (2013) propose a framework by which some of these studies may be compared. The results of several studies that calculate a LULCC C flux are summarized by Houghton (2010) and Pongratz et al. (2009). They report a range of previously published C emission estimates for LULCC of 138 PgC to 294 PgC for years 1700 to 2000, including results from the modeling studies of Strassmann et al. (2008) and Shevliakova et al.

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Strassmann et al. (2008) account for the impact of CO_2 fertilization and estimate that this negative feedback on C emissions amounts to roughly 25% of the LULCC C flux. More recently, Lawrence et al. (2012) calculated a net LULCC C flux of 128 PgC for 1850 to 2005, and Ciais et al. (2013) suggested a range of 180 ±80 PgC for the time period 1750 to 2011. Arora and Boer (2010) estimate a substantially smaller historical LULCC C flux between 40 and 77 PgC using a coupled climate-carbon cycle model. Although, the representation of nitrogen-limitation on plant growth, not included in Arora and Boer (2010), may lead to a greater LULCC C flux in otherwise similar model experiments (Arora et al., 2013).

Model estimates of C emissions from soils that have been disrupted by land use are poorly constrained (Houghton, 2010) and introduce major uncertainty into estimates of the LULCC C

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In a review of field studies, Guo and Gifford (2002) conclude that soil C is increased for most conversions of natural land to pasture, and decreased for conversions to cropland.

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In addition, there is a potentially major source of CO_2 from deforestation and forest degradation in tropical peat swamp forests that has only recently been recognized (Hergoualc'h and Verchot, 2011).

Previous studies have shown that land cover change also modifies climate by biogeophysical effects such as changes to surface latent and sensible heat fluxes and to the hydrological cycle

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(DeFries et al., 2002; Feddema et al., 2005; Brovkin et al., 2006; Pitman et al.,

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(DeFries et al., 2002; Feddema et al., 2005; Brovkin et al., 2006; Pitman et al.,

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Of these biogeophysical effects of LULCC, land albedo change is recognized as the dominant forcing globally (Betts et al., 2007; Pongratz et al., 2009). The surface underlying a forest may have a different albedo than the canopy that is revealed following forest removal. In high latitude forests, clear-cut areas may become snow-covered in the winter and therefore, highly reflective. Many estimates of the global RF of land albedo change have been published, derived from modeling experiments (e.g. Brovkin et al., 1999; Betts, 2001; Defries et al., 2002; Brovkin et al., 2004; Betts et al., 2007; Davin et al., 2007; Pongratz et al., 2009; Skeie et al., 2011; Lawrence et al., 2012; Avila et al., 2012) and from satellite retrievals (Myrhe et al., 2005). In all these studies, a representation of the present day land albedo, whether simulated or observed by satellite, is compared to the land surface albedo with preindustrial vegetation, or the potential

vegetation. Estimates for the global albedo change RF range from -0.10 Wm^{-2} (Skeie et al., 2011) to -0.28 Wm^{-2} (Lawrence et al., 2012), with a central estimate from the IPCC of -0.20 Wm^{-2} (Forster et al., 2007). The

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inhomogeneous distribution of forcing from surface albedo changes and short-lived trace gas and aerosol species could lead to non-additive (A. Jones et al., 2013), and highly variable local climate responses (Lawrence et al., 2012). Therefore, we use the RF for our assessment of global-scale climate impacts and acknowledge the limits of the RF concept for predicting the diverse and

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local impacts of land use (Betts, 2008; Runyan et al., 2012).

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local impacts of land use (Betts, 2008; Runyan et al., 2012).

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local impacts of land use (Betts, 2008; Runyan et al., 2012).

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local impacts of land use (Betts, 2008; Runyan et al., 2012).

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2 Methods: Crop suitability calculations for worst case scenario

To estimate the maximum extent of crop and pasture for the worst case

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future scenario requires criteria that measure the potential of a land area to support agriculture. We follow the methodology of Ramankutty et al. (2002) to define the suitability of the climate and soil properties at model grid point locations for crops or pasture. In that study the authors define suitability based on the growing degree days, moisture index, soil organic carbon content, and soil pH that are characteristic of present day agricultural areas. Areas with a long enough growing season and sufficient water resources to support present day crops, absent irrigation (which is not included in their analysis), are considered suitable based on climate. For both soil organic carbon content and soil pH the authors find an ideal range of values that support agriculture and categorize areas that meet the criteria as suitable based on the soil. We repeat their analysis with temperature and precipitation data from the Climatic Research Unit TS3.10 dataset (Harris et al., 2014), soil data from the International Soil Reference and Information Centre – World Soil Information database (Batjes, 2005) and a simplified moisture index (Willmott and Feddema, 1992).

In this approach, sigmoidal functions are fit to probability density functions of gridbox fractional crop area and four environmental factors; growing degree days (GDD),

moisture index, soil pH and soil organic carbon density. These functions describe where crops grow in today's world and how well they grow there. The functions are then applied to current global climate and soil datasets to identify areas that could support crops but have yet to, and also some areas where crops outdo their potential based on the local climate and soil, usually due to irrigation.

We use the Ramankutty et al.

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(2002) definitions for soil pH, soil carbon, defined as the mass of C

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per meter squared in the top 30 cm of the non-gravel soil, and for GDD, defined as the number of ˚C by which daily mean temperature exceeds 5 ˚C.

For the moisture index we use the Climate Moisture Index (CMI) (Willmott and Feddema, 1992) which is defined using precipitation, P, and potential evaporation, PE, data as:

$$\begin{aligned} CMI &= 1 - PE/P \quad when \quad P \geq PE \\ CMI &= P/PE - 1 \quad when \quad P < PE \\ CMI &= 0 \quad when \quad P = PE = 0 \end{aligned}$$ (

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We use 1979-2009 averages for climate variables and year 2000 crop area data (Ramankutty et al., 2008). For fitting the individual sigmoidal curves, we restrict the data to only those points that are otherwise optimal for crops, as in Ramankutty et al. (2002). For example, when fitting the CMI data, we restrict the crop area data to regions where the GDD, soil

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This isolates grid points that could be CMI limited.

Following Ramankutty et al. (2002), we fit a single sigmoidal curve to the GDD data, and the CMI data, a double sigmoidal curve to the soil

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C data and explicitly define a pH limit function.

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The expressions for these functions from Ramankutty et al. (2002) are given below with new coefficients computed for our study:

$$f_1(GDD) = \frac{1}{\left[1 + e^{a(b-GDD)}\right]} \quad (2)$$

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$$f_2(\alpha) = \frac{1}{\left[1 + e^{c(d-\alpha)}\right]} \quad (3)$$

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Where a=0.0037, b=1502, c=10.16, and d=0.3544.

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$$g_1(C_{soil}) = \frac{a}{\left[1 + e^{b(c-C_{soil})}\right]} \frac{a}{\left[1 + e^{d(h-C_{soil})}\right]} \quad (4)$$

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Where a=22.09, b=3.759, c=1.839, d=0.0564, and h=106.5.

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$$g_2(pH_{soil}) = \begin{cases} -1.64 + 0.41 pH_{soil} & if \quad pH_{soil} \le 6.5 \\ 1 & if \quad 6.5 < pH_{soil} < 8 \\ 1 - 2(pH_{soil} - 8) & if \quad pH_{soil} \ge 8 \end{cases} \quad (5)$$

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These functions are multiplied together to create suitability indices: the product of the *f* functions gives the climate suitability index and the product of the *g* functions gives the soil suitability index. Natural land that is "suitable" for crops based on these criteria is converted to cropland (on a linear year-to-year basis) between years 2006-2100. We assume area that is suitable for crops based on climate, but not soil characteristics, can support grass and is used for pasturing animals. This assumption leads to the replacing of most tropical forests by crops or grasslands. The global potential crop area computed here for present day climate is 4,180 Mha and the potential pasture area is 3,110 Mha, compared to reported year 2010 utilized areas of 1,570 Mha for crops and 2,030 Mha for pasture (Hurtt et al., 2011).

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Since the potential crop area depends on climate, it is likely to change in the future. One estimate, using a business-as-usual greenhouse gas emissions scenario, yields a 16% increase of the 1961-1990 potential crop area by 2070-2099, mainly in high latitudes (Ramankutty et al., 2002). We did not include climate-dependent trends in potential crop area in this study but note here that doing so may increase the year 2100 RF of the

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worst case scenario LULCC. Further information on how the potential crop and pasture area is translated into LULCC is given in Section 3.1.1. As discussed below, emissions of CH_4 and N_2O from agriculture in the worst case scenario are based on emissions of these gases per area of crop/pasture in the RCP8.5 scenario and scaled by the differences in crop and pasture area between RCP8.5 and the worst case scenario. We do not consider possible future changes in natural emissions of CH_4 and N_2O. Other calculations are done similarly to the RCPs, as discussed below in Sect. 3.

3. Methods: Radiative forcing calculations

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Here we describe the methods for computing the various RFs, organized in four sections, corresponding to the rows in Fig. 2:

First the *LULCC activities* included in the analysis are outlined (Sect. 3.1)

This is followed by an explanation of the sources of the *emissions* data (Sect. 3.2)

Then the methods and models used to *compute concentration changes* are described (Sect. 3.3).

Next, the methods for *calculating the RFs* are explained (Sect. 3.4)

Finally we describe our approach to estimating uncertainties in Sect. 3.5. An outline of Sect. 3 is provided in Table 1.

3.1 LULCC Activities

3.1.1 Land cover change and wood harvesting

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Crop area is increased linearly starting in year 2006 at the expense of grassland first, then shrubs, then forest area. Pasture is increased at the expense of shrubs, then forest area. Different PFTs within those general categories are lost or gained in proportion to their year 2006 fractions. In this scenario, global crop area increases 200% with substantial expansion into tropical Africa and South America, and southeast Asia (Fig.

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). The expansion of crops and pasture into the tropics occurs at the expense of forests, which have virtually disappeared from the tropics by the year 2100 (Fig.

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3.1.3 Agricultural activities

Additional emissions from LULCC activities associated with agriculture were taken from the integrated assessment model emissions for the different RCPs (e.g. van Vuuren et al., 2011) and are estimated based on RCP8.5 for the worst case scenario, as described below. These activities are fertilizer application, soil modification, livestock pasturage, rice cultivation and agricultural waste burning.

3.2 Emissions

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2). For non-LULCC related emissions (such as those from fossil fuel burning) we use the emission inventories from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) (Lamarque et al., 2010) for historical time periods, with future emissions from RCP4.5 (Wise et al., 2009). These datasets include emissions of non-methane hydrocarbons (NMHCs), NO, NH_3, SO_2, and organic carbon (OC) and black carbon (BC) aerosols.

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2011) (fire emissions are discussed in Section 3.2.2, and agricultural emissions of N_2O are discussed in Section 3.2.6).

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The four Integrated Assessment Models (IAMs) associated with the RCPs for the fifth IPCC assessment report simulate the expansion and contraction of agriculture driven by the demand for food and projected land use policies, such as carbon credits for reforestation or support of expanded biofuel crops (van Vuuren et al., 2011). The area

under cultivation and type of agricultural activities jointly determine the future distribution of agricultural emissions for each projection (van Vuuren et al., 2007; Wise et al., 2009; Fujino et al., 2006; Riahi et al., 2007).

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We use historical agricultural emissions from ACCMIP (Lamarque et al., 2010).

For the worst case scenario

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, agricultural emissions are derived by scaling the RCP8.5 emissions by the difference in cultivated area between the two scenarios in year 2100. First, three latitude band average (-90˚ to -30˚, -30˚ to 30˚, and 30˚ to 90˚ latitude) values of emissions of each species per unit cultivated area are computed for RCP8.5, year 2100.

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Next, the latitude band averages are applied to the worst case scenario cultivated area in the year 2100. This requires making the assumption that the practices and intensity of agriculture in the worst case scenario are the same as in RCP8.5, only the cultivated area changes. We also assume that natural CH_4 emissions remain unchanged from 1850 through 2100 for all scenarios.

3.2.2 Fire emissions

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Next, the latitude band averages are applied to the worst case scenario cultivated area in the year 2100. This requires making the assumption that the practices and intensity of agriculture in the worst case scenario are the same as in RCP8.5, only the cultivated area changes. We also assume that natural CH_4 emissions remain unchanged from 1850 through 2100 for all scenarios.

3.2.2 Fire emissions

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3.2.2 Fire emissions

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3.2.2 Fire emissions

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3.2.2 Fire emissions

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3.2.2 Fire emissions

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3.2.2 Fire emissions

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3.2.2 Fire emissions

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3.3 Concentration changes

3.3.1 Tropospheric O_3 concentration

To model changes in O_3 concentrations from LULCC we use the Community Atmosphere Model version 4 (CAM4)

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(Hurrell et al., 2013; Gent et al., 2011) with online chemistry from the Model for Ozone and Related chemical Tracers (MOZART) (Emmons et al., 2010) which simulates all major processes in the photochemical production and loss of O_3.

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Our model setup also includes changes in O_3 deposition rate due to LULCC impacts on LAI through the vegetation dependence of the dry deposition rate.

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In all cases CAM4 is setup with horizontal grid spacing of 1.9 degrees latitude by 2.5

degrees longitude with 26 vertical levels and a timestep of 30 minutes. Each simulation is branched from a two-year spinup using year 2000 climate conditions (air temperature, sea surface temperature, solar forcing, etc.). Model setup is identical for all simulations except for trace gas emissions, and CH_4 concentrations, which are specific to the case (LULCC vs. no-LULCC, year 2010 vs. year 2100). In these simulations the tropospheric chemistry evolves differently depending on the initial emissions but does not interact with the model radiation. Therefore the CAM4 model climate is identical for all simulations and the RF of the changes in chemistry can be isolated. A one-year post-spinup CAM4 integration is used for analysis of the RF.

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To compute direct (through emissions) and indirect (through altered chemical lifetime) changes in CH_4 concentrations (due to LULCC and other anthropogenic activites) we treat them as separate perturbations to observed (year 2010) and projected (year 2100) concentrations. We compare the concentration with all anthropogenic CH_4 sources/influences to the concentration with either LULCC or other anthropogenic sources/influences removed to compute the change in concentration for each case. The lifetime of CH_4 in the atmosphere (~9 years) means our simulations are too short to directly simulate the changes in CH_4 concentration. Instead we use approximations based on the known emissions of CH_4 and changes in the quick-adjusting main chemical sink for CH_4 – the hydroxyl radical (OH).

If we remove direct emissions of CH_4 from a particular source such as LULCC, a new steady state concentration can be approximated using the following expression from Ward et al. (2012):

$$\Delta[CH_4] = F * \Delta E / E_O * [CH_4]_O \qquad (1)$$

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such that a percentage change in CH_4 emissions, E, leads to a percentage change in concentration, $[CH_4]$, times the ratio of the perturbation lifetime to the initial lifetime, F.

We do not calculate F from our simulations but use $F = 1.4$ as recommended by the IPCC (Prather et al., 2001).

Changes in global OH concentration can be used to approximate the change in CH_4 lifetime caused by a change in emissions (Naik et al., 2005). Here we use the OH concentrations predicted in the CAM4 simulations for each case. The impact of non-LULCC emissions on CH_4 lifetime is taken as the difference between the year 2010 or 2100, and year 1850 CH_4 lifetime in the simulations with no LULCC emissions. Estimated this way, the CH_4 lifetime decreases by more than two years between 1850 and 2010 and by one and a half years between 1850 and 2100.

We compute the change in concentration due to the change in CH_4 lifetime, τ, with respect to reaction with OH using this expression (Naik et al., 2005):

$$\Delta[CH_4] = F * [CH_4]_O * \frac{\Delta\tau}{\tau_O} \qquad (\text{}$$

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Here we also use F = 1.4 to account for the positive feedback between CH_4 and OH (Naik et al., 2005).

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CO_2 is chemically inert in the atmosphere but, over time, the airborne fraction of emitted CO_2 decreases as ocean and land uptake of carbon occurs. Therefore, the most recent CO_2 emissions will have the highest airborne fraction. We apply a CO_2 pulse response function (Enting et al., 1994) to compute the airborne fraction of the yearly pulse emissions at the year 2010 or 2100, following previously used methods (e.g. Randerson et al., 2006; Ward et al., 2012). This weighting is especially important for non-LULCC emissions, which have been largest over the most recent decades.

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N_2O concentration

Nitrous oxide is a long-lived greenhouse gas with a lifetime in the troposphere of over 100 years. Therefore, we use a simple atmospheric box model that can be run quickly for many model years to diagnose changes in N_2O concentration that result from LULCC and other anthropogenic emissions. The box model uses an expression of N_2O mass balance to predict changing concentrations, C, with time given yearly emissions, E, and a dynamic N_2O lifetime, τ (Kroeze et al., 1999):

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

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Here, S is a conversion factor (4.8 Tg N $ppbv^{-1}$) and t is time (years). The N_2O lifetime is dependent on its own concentration, which we account for here following Meinshausen et al. (2011b) and using a year 2000 reference state:

$$\tau = \tau_O \left(\frac{C}{C_O} \right)^{-0.05} \qquad (2$$

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We run the box model from simulation year 1850 through 2100 with natural and anthropogenic emissions, but with emissions from the source of interest, either LULCC or other anthropogenic activities, removed. We assume that the decrease in natural N_2O emissions (Syakila and Kroeze, 2011) is attributable to LULCC. This decreases the net LULCC emissions of N_2O.

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Unfortunately chemistry was not yet available in CAM5 at the time of this study, so that different versions of the model had to be run for chemistry and aerosols. Since we use CAM4 and CAM5 to model concentration changes for separate forcing agents (trace gases in CAM4 and aerosols in CAM5), differences in physics between the two models

do not affect our results. CAM5 is setup with horizontal grid spacing of 1.9 degrees latitude by 2.5 degrees longitude with 26 vertical levels and a timestep of 30 minutes. Each simulation is branched from a two-year spinup using year 2000 climate conditions (air temperature, sea surface temperature, solar forcing, etc.). Model setup is identical for all simulations except for aerosol emissions, which are specific to the case (LULCC vs. no-LULCC, year 2010 vs. year 2100). In CAM5, aerosols are both radiatively and microphysically active. This enables simulation of aerosol indirect effects but leads to different model climates for different initial aerosol emissions. To isolate the impacts of aerosols on the RF we integrate CAM5 for four years post-spinup and use the annual average for analysis. This smooths out the interannual variability in the model climate state to minimize its impact on the RF (Wang et al., 2011).

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3.4 RF calculations

We note here that all future LULCC RFs are calculated assuming background concentrations of trace gases and aerosols that are characteristic of RCP4.5.

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Our model setup also includes changes in O_3 deposition rate due to LULCC impacts on LAI through the vegetation dependence of the dry deposition rate.

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To assess the global mean RF of O_3 from the changes in emission of short-lived precursors and deposition, we compute radiative fluxes at the tropopause with the CAM4 output three-dimensional O_3 fields included, and also with tropospheric O_3 removed. This is accomplished by running the CAM4 radiation package offline with the Parallel Offline Radiative Transfer (PORT) tool (Conley et al., 2013). The difference in net radiative flux at the tropopause caused by removing O_3 gives the total RF of tropospheric O_3 in each case. The difference in O_3 RF between cases with LULCC and the corresponding case without LULCC is equivalent to the contribution from LULCC to the RF. The contribution of other anthropogenic activities is estimated by computing the difference between the year 2010 or 2100 simulations without LULCC, and the 1850 simulation without LULCC.

The short-lived O_3 RF estimated here is an instantaneous forcing since we do not allow for stratospheric temperature adjustment. Hansen et al. (2005) estimate a ratio of adjusted RF to instantaneous RF of approximately 0.8 in global simulations for the period between 1880 to 2000. We multiply the instantaneous RFs for O_3 by 0.8 to account for the stratospheric adjustment and report adjusted RFs.

Tropospheric O_3 acts as a source for OH. Therefore, changes to O_3 concentrations lead to a response in CH_4 and, as a consequence, a response in peroxy radical concentrations (Naik et al., 2005). The changes in peroxy radical concentrations, an end result of the changes in emissions of O_3 precursors caused by LULCC or other anthropogenic activities, feeds back onto O_3, a response which is approximated with the following expression (Naik et al., 2005):

$$\left(\Delta O_3\right)_{primary} = \frac{\Delta\left[CH_4\right]}{\left[CH_4\right]} * 6.4DU \qquad (\text{}$$

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We use a value of 0.032 +/- 0.006 W m^{-2} DU^{-1} (Forster et al., 2007) to compute the additional RF of O_3 caused by this process, known as the primary mode response.

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3.4.2 CO_2, CH_4, N_2O

After changes in the long-lived greenhouse gas concentrations

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due to LULCC or other anthropogenic emissions are calculated, simple expressions from the IPCC TAR (Ramaswamy et al., 2001) can be used to estimate the adjusted radiative forcing (ΔF).

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For CO_2:

$$\Delta F = 5.35 * \ln\left(\frac{C}{C_O}\right) \quad (11)$$

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Here C_o is the atmospheric CO_2 concentration in the unperturbed state (with no LULCC emissions, or no emissions from other anthropogenic activities) and C is the perturbed atmospheric CO_2 concentration containing both all anthropogenic contributions. In this way the CO_2 saturation effect of the different perturbed CO_2 concentrations on the RF is taken into account.

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Likewise, the adjusted RF for the changes in CH_4 and N_2O concentrations

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can be computed with the following expressions (Ramaswamy et al., 2001):

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$$\Delta F = 0.036\left(\sqrt{M} - \sqrt{M_O}\right) - \left[f\left(M, N_O\right) - f\left(M_O, N_O\right)\right] \quad (12)$$

$$\Delta F = 0.12\left(\sqrt{N} - \sqrt{N_O}\right) - \left[f\left(M_O, N\right) - f\left(M_O, N_O\right)\right] \quad (13)$$

$$f\left(M, N\right) = 0.47 * \ln\left[1 + 2.01\times10^{-5}\left(M * N\right)^{0.75} + 5.31\times10^{-15} M\left(M * N\right)^{1.52}\right] \quad (14)$$

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using the average tropospheric concentrations of CH_4 (ppb) and N_2O (ppb) in the perturbed state with LULCC or other anthropogenic emissions removed (M and N, respectively), and in the unperturbed, reference state (M_o and N_o, respectively).

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Eq. 12 corresponds to CH_4 and Eq. 13 corresponds to N_2O.

3.4.3

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Aerosols impact radiative transfer directly by scattering and absorbing shortwave and some longwave radiation, and also indirectly by their effects on clouds. We compute the direct effect of changes in aerosols from LULCC by running the CAM5 radiation online in a diagnostic mode separately from the prognostic radiation in the model. The radiation package is run at every timestep through the model atmosphere with all aerosols and again with aerosols removed from interactions with radiation. The difference in top-of-atmosphere net radiative flux when aerosols are removed is the all-sky direct radiative effect. We compute this effect for shortwave and longwave interactions.

Indirect effects are defined here as the change in total cloud forcing between the simulations with and without LULCC (referenced to 1850), where total cloud forcing is the sum of the longwave and shortwave cloud forcing. This quantity is assessed after the direct effects of aerosols have been removed with the online diagnostics. Therefore, the sum of the direct effects and indirect effects of aerosols is equal to the total radiative change caused by aerosols in the CAM5 simulations.

In CAM5, the indirect effects of aerosols on clouds includes the first indirect effect by which aerosols, acting as cloud condensation nuclei, lead to changes in cloud droplet size and, as a consequence, cloud albedo. CAM5 also simulates aerosol/cloud interactions that are considered secondary indirect effects. These include aerosol impacts on stratiform cloud lifetime and height, and the semi-direct effect. The semi-direct effect refers to the change in cloud fraction that results from the warming of an air layer by

aerosol absorption of shortwave radiation (Lohmann and Feichter, 2005). Aerosol impacts on convective clouds are not included in our simulations.

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These aspects of the CAM5 microphysics may lead to bias in our RF calculations when compared to the model consensus RFs from the IPCC AR4 (Forster et al., 2007). The IPCC

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These aspects of the CAM5 microphysics may lead to bias in our RF calculations when compared to the model consensus RFs from the IPCC AR4 (Forster et al., 2007). The IPCC

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These aspects of the CAM5 microphysics may lead to bias in our RF calculations when compared to the model consensus RFs from the IPCC AR4 (Forster et al., 2007). The IPCC

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For this reason, and because models generally disagree on the magnitude of the aerosol effects (Forster et al.,

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2007), we use the IPCC AR4 central estimate aerosol direct and indirect effects for calculating

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IPCC AR5 report total -0.9 Wm^{-2} (Myhre et al., 2013). Our calculations

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LULCC RFs would be nearly unchanged if we used

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the proportion of total anthropogenic RF

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In addition to these effects in the atmosphere, light-absorbing aerosols, particularly BC and dust, can decrease the albedo of the Earth's surface when they are deposited onto snow and ice surfaces. The Snow, Ice, and Aerosol Radiative (SNICAR) model (Flanner and Zender, 2006) is run online with CAM5 to simulate this process and estimate the RF. For all cases the RF of aerosol deposition onto snow and ice surfaces is between 0 and

0.03 W m^{-2}. Note that we only capture aerosol deposition on snow and ice covering land and not over sea. This will reduce our estimates of the RF compared to estimates including sea-ice, although the RF from aerosol deposition onto sea-ice is thought to be less important than deposition onto land-covering snow and ice (Flanner et al., 2007).

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The albedo changes, apart from those caused by fires, are simulated by CLM.

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For albedo changes from wildfire activity, post-fire albedo response curves (Ward et al., 2012) are applied to the difference in burned area with LULCC and without LULCC at each grid point. Fires lead to negative (cooling) RF from albedo changes on a global average (Ward et al., 2012). Since historical and projected LULCC reduced burned area in CLM, the result was a small but positive RF in all cases, acting in the opposite direction of the overall negative LULCC albedo change RF.

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The importance of aerosol biogeochemical feedbacks onto CO_2 concentrations is beginning to be recognized and known impacts have recently been quantified (Mahowald, 2011).

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We consider changes to terrestrial uptake of carbon by the addition of nutrients (N, phosphorous (P), and iron (Fe)) transported by aerosols, and also by modifications of climate.

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N deposition from anthropogenic sources fertilizes vegetation growth and increases the drawdown of CO_2, causing a present day RF of -0.12 to -0.35 W m^{-2}. We multiply this forcing by the ratio of N emissions (NH_3, NO_x) from LULCC or other anthropogenic activities for each case to year 2010 total anthropogenic N emissions.

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Fertilization can also be enhanced by deposition of P and Fe from fire emissions. Changes in Amazonian fire activity have led to an estimated -0.12 to 0 W m^{-2} RF from increased CO_2 drawdown due to fertilization by P. Deposition of fire-emitted Fe to the oceans could be responsible for a RF of -0.02 +/- 0.02 W m^{-2} (Ward et al., 2012). We scaled these RFs by the changes in fire activity due to LULCC in the Amazon (for P) and globally (for Fe) for all cases. These result in small RFs (less than +/- 0.05 W m^{-2}) such that N dominates these biogeochemical feedbacks.

Finally, changes in global surface temperature caused by the previously described RFs of LULCC and non-LULCC activities lead to a response in carbon uptake by the terrestrial biosphere and the ocean (Mahowald, 2011).

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Moreover, aerosols affect vegetation by redistributing precipitation and changing the ratio of diffuse to direct radiation incident on the surface. While not very well understood, these biogeochemical feedbacks can be estimated by coupled carbon-climate models that suggest a roughly linear response of between 0 and 40 ppm CO_2 for a RF of 1.4 W m^{-2} (Mahowald et al., 2011). We sum the total RF of LULCC for all cases from greenhouse gases, aerosol effects and albedo changes, to estimate the impact of the potential changes in climate on atmospheric CO_2. In all cases, since the total RF from LULCC is positive, the RF of the feedback onto CO_2 concentrations is also positive.

The total RFs of these biogeochemical feedbacks are included with the CO_2 RF in the tables and figures since they impact climate through changing CO_2 concentrations.

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3), and a transfer of C from the terrestrial biosphere into the atmosphere. We estimate a cumulative C flux from land cover change of 131 PgC between 1850 and 2000, and 140 PgC between 1850 and 2010. This falls near the center of the range in values compiled for 1850 to 2000 by Houghton (2010) and Pongratz et al. (2009) from previous studies using inventory-based or carbon cycle model estimates (108 PgC to 188 PgC). Our estimate also lies within the large range in values reported from the CMIP5 model experiments (Fig. 2 in C. Jones et al., 2013). Note that the methods used to calculate the C flux are not consistent across these studies and our method of adjusting for the fertilization feedback is unique to this study.

Most studies that calculate the LULCC C flux also calculate the contribution of historical LULCC to present day CO_2 concentrations (e.g. Matthews et al., 2004; Brovkin et al., 2004; Strassman et al., 2008; Arora and Boer, 2010). These

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We introduce the worst case scenario to place an upper bound on the potential LULCC RF for this century. The worst case scenario

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Our CLM3 experiment resulted in negligible soil C change globally, even after applying the drastic forest

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Summary outline of Sect. 3.

Section	Topic	Summary
3.1	**LULCC Activities**	-
3.1.1	LCC and wood harvesting	These processes simulated in CLM3 (LCC: land cover change)
3.1.2	Fires	Changes in global fires from LULCC simulated by CLM3
3.1.3	Agricultural activities	Fertilizer, soil modification, livestock, rice cultivation and waste burning
3.2	**Emissions**	Non-LULCC emissions from ACCMIP and van Vuuren et al. (2011)
3.2.1	Agricultural emissions	Historical emissions from ACCMIP, RCPs from van Vuuren et al. (2011)
3.2.2	Fire emissions	Emissions factors applied to changes in fire activity from CLM3
3.2.3	Dust emissions	Cultivated area used to modify soil erodibility and resulting dust emissions
3.2.4	SOA emissions	Computed offline with MEGAN using LULCC leaf area changes from CLM3
3.2.5	CO_2 emissions	Difference in terrestrial C storage in CLM3 with and without LULCC
3.2.6	N_2O emissions	Emissions scaled by changes in crop and pasture area
3.3	**Concentration changes**	-
3.3.1	Tropospheric O_3 conc.	Concentration changes simulated by CAM4 with year 2000 climate
3.3.2	CH_4 concentration	Direct and indirect changes computed using methods of Ward et al. (2012)
3.3.3	CO_2 concentration	Pulse response function with approximated fertilization feedback included
3.3.4	N_2O concentration	Box model approach from Kroeze et al. (1999)
3.3.5	Aerosols concentrations	Simulated by CAM5 with MAM3, four year simulations (post-spinup)
3.4	**RF calculations**	Future LULCC RFs are computed against a RCP4.5 background atmosphere
3.4.1	Tropospheric O_3 RF	Computed offline with the Parallel Offline Radiative Transfer (PORT) tool
3.4.2	CO_2, CH_4, N_2O RFs	Computed with simple expressions from Ramaswamy et al. (2001)
3.4.3	Aerosol effects	Simulated by CAM5 and scaled to the estimates of Forster et al. (2007)
3.4.4	Land surface albedo	Computed from albedo change simulated by CLM3 for LULCC
3.4.5	Aerosol bgc feedbacks	Changes to CO2 conc. from biogeochemical feedbacks (Mahowald, 2011)
3.5	**Uncertainty**	See Appendix A for details of uncertainty calculations

Table 2. Changes in emissions

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2012), and the worst case scenario (WCS; green).

Fig. 4. Percent of gridbox area consisting of (a) year 2010 crops, (b) potential crops based on climate and soil suitability, (c) year 2010 forests, and (d) year 2100 forests in the worst case scenario.

Fig. 5.

Potential climate forcing of land use and land cover change

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Abstract

Pressure on land resources is expected to increase as global population continues to climb and the world becomes more affluent, swelling the demand for food. Changing climate may exert additional pressures on natural lands as present day productive regions may shift, or soil quality may degrade, and the recent rise in demand for biofuels increases competition with edible crops for arable land. Given these projected trends there is a need to understand the global climate impacts of land use and land cover change (LULCC). Here we quantify the climate impacts of global LULCC in terms of modifications to the balance between incoming and outgoing radiation at the top of the atmosphere (radiative forcing; RF) that are caused by changes in long-lived and short-lived greenhouse gas concentrations, aerosol effects and land surface albedo. We attribute historical changes to terrestrial carbon storage, global fire emissions, secondary organic aerosol emissions, and surface albedo to LULCC using simulations with the Community Land Model version 3.5. These LULCC emissions are combined with estimates of agricultural emissions of important trace gases and mineral dust in two sets of Community Atmosphere Model simulations to calculate the RF of changes in atmospheric chemistry and aerosol concentrations attributed to LULCC. With all forcing agents considered together, we show that 40% (+/- 16%) of the present-day anthropogenic RF can be attributed to LULCC. Changes in the emission of non-CO_2 greenhouse gases and aerosols from LULCC enhance the total LULCC RF by a factor of 2 to 3 with respect to the LULCC RF from CO_2 alone. This enhancement factor also applies to projected LULCC RF, which we compute for four future scenarios associated with the Representative Concentration Pathways. We attribute total RFs between 0.9 to 1.9 Wm^{-2} to LULCC for the year 2100 (relative to a preindustrial state). To place an upper bound on the potential of LULCC to alter the global radiation budget we include a fifth scenario in which all arable land is cultivated by 2100. This theoretical extreme case leads to a LULCC RF of 3.9 Wm^{-2} (±0.9 Wm^{-2}), suggesting that not only energy policy but land policy is necessary to minimize future increases in RF and associated climate changes.

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1 Introduction

More than half of the Earth's land surface has been affected by land use and land cover change (LULCC) activities over the last 300 years, largely from the expansion of agriculture (Hurtt et al., 2011), leading to numerous climate impacts (Foley et al., 2005). Conversion of land from natural vegetation to agriculture or pasturage releases carbon from vegetation and soils into the atmosphere (Houghton et al, 1983), often quickly through fires, which emit carbon dioxide (CO_2), methane (CH_4), ozone (O_3)-producing compounds and aerosols (Randerson et al., 2006). Deforested areas have a diminished capacity to act as a CO_2 sink as atmospheric CO_2 concentrations increase (Arora and Boer, 2010; Strassmann et al., 2008). Furthermore, agriculture and pasturage emits CH_4 and nitrous oxide (N_2O), accelerates soil carbon loss (Lal, 2004), and changes aerosol emissions (Foley et al., 2011). For instance, land management can enhance mineral dust aerosol emission by modifying surface sediments and soil moisture (Ginoux et al., 2012), but reduces fire aerosol emissions (Kloster et al., 2012) and emissions of low-volatility products of oxidized biogenic organic compounds that condense to form secondary organic aerosols (SOA; Heald et al., 2008). Changes in the abundance of these atmospheric constituents generate forcings onto the climate system (Fig. 1), quantified in this study as radiative forcings (RF).

The global RF and associated climate response attributable to LULCC are often portrayed as a balance between cooling biogeophysical effects (changes in surface energy and water balance) and the warming biogeochemical effect of increases in atmospheric CO_2 (e.g. Claussen et al., 2001; Brovkin et al., 2004; Foley et al., 2005; Bala et al., 2007; Cherubini et al., 2012). Claussen et al. (2001) found that the cooling from biogeophysical effects of land cover change dominated over the warming from associated CO_2 emissions in high-latitude regions where the land may be snow covered for part of the year, whereas tropical LULCC leads to a warming due to a weaker albedo forcing. This regional contrast in the dominant forcing from deforestation also applies to natural forest disturbances (O'Halloran et al., 2011). On a global scale, model estimates have shown both canceling climate responses to historical land cover change biogeophysical effects and CO_2 emissions (Brovkin et al., 2004; Sitch et al., 2005) and a net warming (0.15˚C) from the same effects (Matthews et al., 2004).

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Additional LULCC forcings are often grouped together with fossil fuel burning and other activities for assessment of the total anthropogenic RF (e.g. Forster et al., 2007; Myhre et al., 2013). Nevertheless, there is some recognition of the importance of evaluating emissions of non-CO_2 greenhouse gases attributable to LULCC separately from fossil fuel emissions for targeting emission reduction policies (Tubiello et al., 2013). Less attention is given to forcings from short-lived atmospheric species that are affected by LULCC. Foley et al. (2005) acknowledge that changes in the concentrations of short-lived species, aerosols and O_3, attributable to LULCC are important for air quality assessment but do not estimate the impacts of these species on climate. Unger et al. (2010) partition sources of global, anthropogenic RF into economic sectors, including agriculture. They consider non-CO_2 greenhouse gas and aerosol forcing agents but only for present day land use emissions and they do not include land cover change. The full contribution of LULCC to global RF compared to the contribution from other anthropogenic activities remains unquantified.

Here we compute the CO_2 and albedo RF attributable to global LULCC and compare to previous estimates of these values, but we also compute the forcings from non-CO_2 greenhouse gases (CH_4, N_2O, O_3), and aerosol effects (direct, indirect, deposition on snow and ice surfaces). Individual forcings are computed from the results of terrestrial model simulations forced with historical land cover changes and wood harvesting, and projected land cover changes from five future scenarios. Because the land model used here includes a carbon model, fire module and emissions of volatile organic compounds, we can uniquely account for the complicated interplay between land use and fire (e.g. Marlon et al., 2008, Kloster et al., 2010; Ward et al., 2012). Four of the future scenarios of land cover change correspond to the four Representative Concentration Pathways (RCP) that were developed for the Climate Model Intercomparison Project in preparation for the IPCC 5th assessment report (AR5) (Lawrence et al., 2012; Hurtt et al., 2011; van Vuuren et al., 2011). The low emissions scenario, RCP2.6, includes widespread proliferation of bioenergy crops (van Vuuren et al., 2007), while RCP4.5 is characterized by global reforestation as a result of carbon credit trading and emission penalties (Wise et al., 2009). The higher emissions scenarios include expansion of crop area at the expense of existing grasslands (RCP6.0; Fujino et al., 2006) or forests (RCP8.5; Riahl et al., 2007) (Hurtt et al., 2011). We introduce a fifth, more extreme scenario, in which all arable and pasturable land is converted to agricultural land, either for crops or pasture, by the year 2100. This scenario, hereafter referred to as the theoretical extreme case (TEC), was not developed within an integrated modeling framework and, therefore, its likelihood

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of occurrence given economical and additional environmental constraints is difficult to judge. Instead, this scenario gives a theoretical upper bound on LULCC impacts over this century. The range in outcomes for the RF attributable to LULCC based on these five projections strengthens our understanding of the role that LULCC decision-making will play in future climate.

2 Overview of methods

Our approach for computing the RFs begins with estimating emissions of trace gases and aerosols from a diverse set of LULCC activities, many of which are illustrated schematically in Fig. 1. For several forcing agents, including CO_2, we isolate the LULCC emissions by comparing global transient simulations of the terrestrial biosphere including LULCC to simulations without LULCC that are otherwise identical, and attribute the difference in emissions between these simulations to LULCC. This general approach, attributing the differences between the LULCC and no-LULCC environment to the

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impacts of LULCC, also applies to our calculations of RFs. Our methods for computing these and other emissions from LULCC activities, as well as the calculations of changes in atmospheric constituent concentrations and RFs are summarized in this section and schematically in Fig. 2.

2.1 LULCC activities

We model the following LULCC activities with a global terrestrial model; wood harvesting, land cover change, and changes in fire activity, including deforestation fires. Changes in the terrestrial model carbon cycle driven by the historical and projected LULCC are used to derive the RF of surface albedo change, and emissions of CO_2, SOA, smoke, and mineral dust from LULCC (Fig. 2). We assemble emissions from additional LULCC activities; agricultural waste burning, rice cultivation, fertilizer applications, and livestock pasturage, from available datasets corresponding to the RCP LULCC projections.

Future land cover changes and wood harvesting rates projections have been developed as part of the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012) with projections corresponding to each of the four RCP scenarios (Hurtt et al., 2011; van Vuuren et al., 2011). These projections have since been joined to historical reconstructions of land use (Hurtt et al., 2011) and expressed as changes in fractional plant functional types (PFTs) which we use in this study with recently amended wood harvesting rates for RCP6.0 and RCP8.5 (Lawrence et al., 2012). Global forest area decreases in all projections between 2010 and 2100 except for RCP4.5, which projects large reforestation efforts (Fig. A1). The loss in forests is accompanied by increases in global crop area in all scenarios except RCP4.5 in which crop area decreases to a level not seen since the 1930s (Fig. A1). Development of PFT changes for the TEC is described in Appendix A.

While we consider this list of activities to be highly inclusive, several LULCC activities and processes are not included in this study, either because they are difficult to properly model or represent as a forcing, or because of a poor level of current understanding of the process. We exclude the impacts of anthropogenic water use, mainly irrigation, on global water vapor concentrations and the associated RF (Boucher et al., 2004). Changes in water use and land use have numerous other implications for the hydrological cycle including impacts on evapotranspiration, runoff, and wetland extent (Sterling et al.,

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2013). Related to these effects, the impact of land surface albedo changes may be further moderated by changes in cloudiness (Lawrence and Chase, 2010), which we did not consider in this analysis. Also, emissions of CH_4 are tied to the global extent of wetlands, which have likely changed since preindustrial times (Lehner and Doll, 2004), but the scale and distribution of the change is not yet known well enough to be included in our model setup. We assume that natural CH_4 emissions remain unchanged from 1850 through 2100 for all scenarios. Finally, there is a source of CO_2 from deforestation and forest degradation in tropical peat swamp forests that has only recently been widely recognized (Hergoualc'h and Verchot, 2011), although it is thought that contributions from this source to current global CO_2 concentrations are small (Frolking et al, 2011).

2.2 LULCC emissions (computed from CLM)

Changes in terrestrial carbon storage, fire activity and biogenic trace gas emissions due to dynamic land cover are simulated using version 3.5 of the Community Land Model (CLM) (Oleson et al., 2008; Stockli et al., 2008) with active carbon and nitrogen cycles (CN) (Thornton et al., 2009) coupled to a process-based fire model (Kloster et al., 2010). This configuration of CLM simulates the complicated interplay between land use, land use change, fires, land carbon uptake and loss, and emissions of volatile organic compounds (Thornton et al., 2009; Kloster et al., 2010; Guenther et al., 2006). To isolate the impacts of LULCC we perform separate simulations for each of the LULCC dynamic PFT scenarios and compare it to an identical simulation with no PFT changes. All CLM simulations use 1.9-degree latitude by 2.5-degree longitude spatial resolution and a 30 minute timestep.

Spin-up of CLM is carried out with year 1850 land cover, which includes some anthropogenic changes. Simulations of historical LULCC run from year 1850 to 2005 and future simulations from year 2006 to 2100. We compute forcings in the year 2010 assuming historical LULCC was extended to 2010 with RCP2.6 land cover changes. We follow the methods of Kloster et al. (2012) for historical and future atmospheric forcing, including meteorology, CO_2 concentrations and N deposition. Twelve future CLM simulations are run, two for each future LULCC scenario (RCP2.6, RCP4.5, RCP6.0, RCP8.5, theoretical extreme case, and No-LULCC) forced from the atmosphere with temperature, precipitation, wind, specific humidity, air pressure, and solar radiation data from the results of two fully-coupled CMIP3 simulations. The two sets of atmospheric forcing were selected for their divergent predictions of

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future temperature and precipitation (Kloster et al., 2012).

2.2.1 Fires

Fire area burned in CLM is controlled by available biomass, fuel moisture and ignition events, all expressed as probabilities, and adjusted by surface wind speeds (Kloster et al., 2010). Fire emissions from the area burned are contingent upon the available biomass and are partly determined by PFT-dependent combustion completeness. In addition to wildfires, deforestation fires occur in the model and are represented as an immediate release of a portion of the carbon lost during deforestation. In our analysis, deforestation fires do not impact the overall CO_2 RF but do speed up the timing of the release of carbon that would otherwise occur by decomposition. Deforestation fires do, however, contribute small amounts of CH_4, N_2O, O_3 precursor gases, and aerosols to the atmosphere that would not have been released through decomposition.

We attribute a reduction in global burned area, both historically and in the future, to LULCC in our simulations (for RCP4.5, which includes large scale reforestation, the reduction is only a few percent). This result matches our current understanding of the impact of LULCC on wildfires (Kloster et al., 2012; Marlon et al., 2008).

Emissions of trace gases and aerosols by wildfires and deforestation fires are derived from the CLM simulations of global fire activity. We use ten-year annual average fire carbon emission output from CLM, corresponding to each analysis year (1850, 2010, 2100) to reduce the influence of interannual variability in fires. Emission factors are applied to the carbon emissions from fires to determine the contribution of fires to the various chemical species (see Fig. 2) including NMHCs, CH_4, N_2O, NH_3, BC, OC, and SO_2 (Kloster et al., 2010; Ward et al., 2012). The LULCC contribution to global fire emissions of BC and OC is negative in the year 2010 (-13%), in the year 2100 for all scenarios except for RCP4.5, compared to the no-LULCC CLM realization (Table 1).

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2.2.2 Dust emissions

Agricultural activities have been linked to increased wind erosion of soils and greater dust emission in semi-arid regions (Ginoux et al., 2012). To address the impact of LULCC on dust emissions we introduce a modified soil erodibility dataset for each scenario into simulations with the Community Atmosphere Model (CAM) version 5 (Liu et al., 2011). The model protocol for these simulations is identical to that used to compute the aerosol forcings (see Appendix B5). For each model grid box, a new soil erodibility value is set equal to the sum of the original soil erodibility and the fraction of the grid box that is cultivated land. We then introduce a parameter that weights the cultivated fraction in the soil erodibility computation such that the fraction of the dust flux resulting from cultivation in the year 2000 for eight regions (N. America, S. America, N. Africa, S. Africa, W. Asia, C. Asia, E. Asia, and Australia) is comparable to recently reported, satellite-derived values for each region (Ginoux et al., 2012). The weighting parameter for cultivated land was tuned with three iterations of four-year global atmospheric model simulations (again using the model setup described in Appendix B5), comparing the results for the tuned and un-tuned soil erodibility to the Ginoux et al. (2012) estimates for each region after each iteration. From this tuning we estimate reasonable weighting parameters for the cultivated fraction of land in each of the eight regions. The weighting parameters are applied to the timeseries of historical and projected crop area to create timeseries of soil erodibility that are modified by cultivation.

Ginoux et al. (2012) estimate that 25% of present day, global dust emissions are caused by anthropogenic activities. We attribute about 20% of global dust emissions to historical LULCC (Table 1). Once these relationships between land use and dust are developed in the current climate, the natural dust source, along with changes in vegetation and climate are allowed to interact with the prognostic dust scheme to predict changes in dust concentrations (Mahowald et al., 2006; Albani et al., 2014). The extreme expansion of crop and pasture area in the TEC leads to more than a tripling of global dust emissions, from natural and human-impacted sources, by the year 2100 using this methodology (Table 1).

2.2.3 SOA emissions

Biogenic emissions of isoprene, monoterpenes, carbon monoxide (CO) and methanol depend on leaf

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area index (LAI) and, therefore, also on LULCC. We compute biogenic trace gas emissions using an offline version of the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006) with a forced diurnal cycle for temperature and solar radiation (Ashworth et al., 2010). The monthly average LAI output from CLM are used for each scenario to produce the biogenic emissions with LAI scaled globally such that predicted year 2000 isoprene emissions match present day global estimates from Heald et al. (2008).

Some biogenic NMHCs, notably monoterpenes and isoprene, can undergo gas to particle phase transitions in the atmosphere after oxidation (Heald et al., 2008) and contribute to changes in aerosol concentrations. The rate of secondary aerosol production depends on the concentrations of the gas precursors, but also the oxidation capacity of the troposphere (Shindell et al., 2009). Both criteria are predicted in our atmospheric chemistry model simulations, described in Appendix B2. On a global average, we estimate a negligible LULCC attributed share of biogenic SOA precursors (mainly isoprene) in the year 2010 and attribute larger reductions to projected changes in land cover for the future RCP between 6 to 16% (Table 1), similar to the results of Wu et al. (2012) for isoprene plus monoterpene emissions (~10% lower with LULCC) between 2000 and 2100 using the IPCC A1B future emissions scenario.

2.2.4 CO_2 emissions

The anthropogenic contribution to the concentration of atmospheric CO_2, used to compute the RF at years 2010 and 2100, depends on the history of anthropogenic CO_2 emissions up to that point. We estimate yearly LULCC emissions to the atmosphere as being equivalent to the global annual change in terrestrial carbon storage due to LULCC. Therefore, sources as well as changes to sinks of CO_2 associated with LULCC are accounted for in the CO_2 emissions. This approach is most similar to the "D3" group of studies as defined by Pongratz et al. (2014) in which simulations with and without LULCC are conducted with identical meteorological and atmospheric CO_2 forcing.

As noted in previous studies (e.g. Strassmann et al., 2008; Arora and Boer, 2010; Pongratz et al., 2009; 2014), this methodology does not account for the CO_2-fertilization feedback in which the CO_2 attributed to LULCC leads to greater fertilization of natural and managed vegetation and an enhanced terrestrial

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carbon sink. Arora and Boer (2010) show that excluding the CO_2-fertilization feedback leads to a form of "double-counting" land carbon storage and can cause overestimates of 20th century LULCC net carbon flux by about 50%. A review of the few studies estimating this feedback gives a range for the overestimate of the net carbon flux from LULCC of 25 to 50% (Pongratz et al., 2014). However, a recent model intercomparison study suggested that including nitrogen (N)-limitation dramatically reduces terrestrial carbon pool sensitivity to changes in CO_2 concentration (Arora et al., 2013). Land carbon uptake in coupled models using the CN version of CLM was only 40% as sensitive to changes in CO_2 concentration and surface temperature increases (known as the climate change feedback) compared to the model used by Arora and Boer (2010). Therefore we adjusted the yearly LULCC net carbon flux downward by 20% to account for the CO_2 fertilization feedback and make our calculations of CO_2 concentration increases attributed to LULCC more consistent with the "E2" group of studies as defined by Pongratz et al. (2014), including Arora and Boer (2010), Strassmann et al. (2008) and Pongratz et al. (2009).

Other model parameters, including aerosol and biogenic NHMC fluxes, depend on LAI, which would also be impacted by the different CO_2 fertilization. However, due to the non-linearity of the aerosol and ozone response we do not apply an adjustment to these RFs but note here that the magnitude of the year 2010 aerosol, O_3 and indirect CH_4 RFs may be small overestimates.

Our simulated net carbon flux from LULCC does not include the impacts of cultivation on soil carbon amounts. Model estimates of carbon emissions from soils that have been disrupted by land use are poorly constrained (Houghton, 2010) and introduce major uncertainty into estimates of the net LULCC carbon flux (House et al., 2002). In a review of field studies, Guo and Gifford (2002) conclude that soil carbon is increased following most conversions of natural land to pasture, and decreased following conversions to cropland. Lal (2004) estimates that cultivation has caused the loss of 78 ±12 PgC from soils since 1850. Modeling studies suggest that LULCC can contribute a net loss of soil carbon globally, from ~13% of total LULCC carbon emitted (Strassmann et al., 2008) to ~37% (Shevliakova et al., 2009), or a net gain as in Arora and Boer (2010). Recently, Levis et al. (2014) implemented a cultivation parameterization that includes impacts on soil carbon and found an additional global flux of 0.4 PgC yr^{-1} from soils due to crop management in recent decades.

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2.3 LULCC emissions (not computed from CLM)

This section describes the sources and accompanying computations for LULCC emissions of all relevant trace gas and aerosol species not derived from the CLM simulations in this study (Fig. 2). For non-LULCC related emissions (such as those from fossil fuel burning) we use the emission inventories from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) (Lamarque et al., 2010) for historical time periods, with future emissions from RCP4.5 (Wise et al., 2009). These datasets include emissions of non-methane hydrocarbons (NMHCs), NO, NH_3, SO_2, and organic carbon (OC) and black carbon (BC) aerosols.

2.3.1 Agricultural emissions

Agricultural emissions of important trace gas species, such as NH_3 and N_2O, are not simulated by CLM. Therefore, additional emissions from LULCC activities associated with agriculture were taken from the integrated assessment model emissions for the different RCPs (e.g. van Vuuren et al., 2011). These activities are fertilizer application, soil modification, livestock pasturage, rice cultivation and agricultural waste burning, and we include global, emissions of NHMCs, NO_x, CH_4, NH_3, BC, OC, and SO_2 from LULCC sources are from these activities. N_2O emissions are not reported by sector for the RCPs and we compute these separately (Sect. 2.3.2). The four Integrated Assessment Models (IAMs) associated with the RCPs for the fifth IPCC assessment report simulate the expansion and contraction of agriculture driven by the demand for food and projected land use policies, such as carbon credits for reforestation or support of expanded biofuel crops (van Vuuren et al., 2011). The area under cultivation and type of agricultural activities jointly determine the future distribution of agricultural emissions for each projection (van Vuuren et al., 2007; Wise et al., 2009; Fujino et al., 2006; Riahi et al., 2007). We use historical agricultural emissions from ACCMIP (Lamarque et al., 2010), which covers the time period of 1850-2005 and extend the historical emissions with RCP2.6 projected emissions through year 2010 for computing LULCC RFs in the year 2010.

For the TEC, agricultural emissions are derived by scaling the RCP8.5 emissions by the difference in cultivated area between the two scenarios in year 2100. First, three latitude band average (-90˚ to -30˚, -30˚ to 30˚, and 30˚ to 90˚ latitude) values of emissions of each species per unit cultivated area are

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computed for RCP8.5, year 2100. Next, the latitude band averages are applied to the theoretical extreme case cultivated area in the year 2100, requiring the assumption that the practices and intensity of agriculture in the TEC are the same as in RCP8.5, and only the cultivated area changes.

2.3.2 N_2O emissions

N_2O has both industrial and agricultural sources, in addition to a large natural source from soils and oceans. Total anthropogenic N_2O emissions have been estimated for the historical time period and projected for RCP4.5 (Meinshausen et al., 2011a). Additional information regarding natural emissions and also agricultural emissions are needed to partition the anthropogenic N_2O emissions into LULCC and non-LULCC components and estimate the associated RFs. We follow the methodology of Meinshausen et al. (2011b) in which the N_2O budget is balanced for a historical time period to extract the natural emissions from the total anthropogenic emissions. Natural emissions of N_2O decrease from about 11 to 9 TgN (N_2O) yr^{-1} using this method between the years 1850 and 2000. We maintain the year 2000 emissions, 9 TgN (N_2O) yr^{-1}, for the years 2000 to 2100. Future land cover change, particularly the theoretical extreme case, could lead to further reductions in natural N_2O emissions through the year 2100. However, not enough is known about global natural N_2O emissions to justify changing the future emission rate for this analysis (Syakila and Kroeze, 2011).

Anthropogenic emissions of N_2O have been partitioned into agricultural (LULCC) and other anthropogenic (primarily fossil fuel) sources, which have been further partitioned into animal production and cultivation sources for years prior to 2006 (Syakila and Kroeze, 2011). We compute the global N_2O emitted per area covered by crop or pasture in the year 2000 using these estimates. Our estimate for year 2010 N_2O emissions from agriculture, 4.3 $TgN(N_2O)yr^{-1}$, is at the lower end of previously reported values compiled by Reay et al. (2012), ranging from 4.2 to 7 $TgN(N_2O)yr^{-1}$. The year 2000 ratios of emission per area are applied to future changes in crop or pasture area to compute future LULCC N_2O emissions for all scenarios. This assumes no future trends in the rates per cultivated land area of the major agricultural N sources: N fertilizer application and animal waste management (Syakila and Kroeze, 2011). Our approach results in increased N_2O emissions from agriculture between years 2010 and 2100 for RCP2.6, RCP8.5, and the theoretical extreme case (Table 1). Emissions decrease during the 21st century in the RCP4.5 scenario and are about the same in 2100 as in 2010 for RCP6.0.

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2.4 Radiative forcing calculations

Radiative forcing (RF) is the change in energy balance at the top of the atmosphere due to a change in a forcing agent, such as an atmospheric greenhouse gas. It is a commonly used metric for comparison of a diverse set of climate forcings and can be used to approximate a global surface temperature response (Forster et al., 2007).

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The different atmospheric lifetimes of the relevant trace gas and aerosol species (listed in Fig. 2) means that a single model approach cannot easily capture changes in all the forcing agents (Unger et al., 2010) and, therefore, a combination of models and methodologies are used here (Fig. 2). Here we summarize the different methodologies for computing the RFs, while detailed descriptions are given in Appendix B.

We adopt the IPCC AR5 (Myhre et al., 2013) definitions of adjusted RF and effective RF (ERF) and calculate the adjusted RFs for each forcing agent (ERFs for aerosol forcings), relative to a preindustrial state (year 1850), with modeled radiative transfer or previously published expressions. Our choice of preindustrial reference year is constrained by the available land cover change datasets, which start in 1850. However, large-scale anthropogenic land cover change began centuries before 1850, and preindustrial changes could have an additional impact on present day climate, perhaps accounting for nearly 10% of historical anthropogenic global surface temperature change (Pongratz and Caldiera, 2012). In our study, the RF of LULCC relative to the year 1850 is then compared to the RFs of other anthropogenic activities, dominated by fossil fuel burning. RFs due to non-LULCC activities are calculated in this study for RCP4.5 non-LULCC emissions with identical methodology to that used for LULCC emissions. All future LULCC RFs are calculated assuming background concentrations of trace gases and aerosols characteristic of RCP4.5. With this approach we can examine the impacts of the range in projected LULCC on RF independent of other anthropogenic activities. Although we are not able to report, for example, the RF of projected LULCC from the RCP8.5 scenario in the context of RCP8.5 fossil fuel emissions. Using a different projection to provide the background concentrations would modify the resulting LULCC RFs.

The RFs of greenhouse gases from LULCC are easily computed from changes in their atmospheric concentrations since the preindustrial period. Time-dependent changes in CO_2 and N_2O concentrations, which are long-lived in the atmosphere, are calculated with simple, pulse-response function and box-model approaches, respectively. To model changes in O_3 concentrations from LULCC, which has a relatively short atmospheric lifetime, we use the CAM version 4 (Hurrell et al., 2013; Gent et al., 2011)

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with online chemistry from the Model for Ozone and Related chemical Tracers (MOZART) (Emmons et al., 2010) which simulates all major processes in the photochemical production and loss of O_3. Our model setup also includes changes in O_3 deposition rate due to LULCC impacts on LAI through the vegetation dependence of the dry deposition rate.

Results from these simulations also determine changes in the lifetime of CH_4 due to LULCC emissions of NMHCs and NO_x.

Aerosol chemistry and dynamics are simulated on a global scale using CAM version 5 (Liu et al., 2011) with the three-mode Modal Aerosol Model (MAM3) (Liu et al., 2012), including the two-moment microphysical scheme (Morrison and Gettelman, 2008) and aerosol/cloud interactions for stratiform clouds. Since models generally disagree on the magnitude of the aerosol effects,

we use the IPCC-AR5 central estimate aerosol direct and indirect ERFs for the year 2011 to estimate the total anthropogenic aerosol forcing in the year 2010 and use our model results to determine the proportion of the total anthropogenic aerosols effects due to LULCC. We then apply the same scaling to the aerosol effects in all future scenarios. The impacts of the LULCC aerosol emissions, both direct

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effects and indirect effects on clouds, are diagnosed online within CAM5. We do not attempt to isolate the RF of aerosols from quick-responding cloud feedbacks within the model and the computed forcings that include these feedbacks are more appropriately referred to as effective radiative forcings (ERF). For computing a total forcing from LULCC we include the aerosol ERFs with the RFs of the remaining forcing agents.

LULCC activities change vegetation cover and type, affect forest canopy coverage, and alter wildfire activity, all of which impact land surface albedo. We compute these impacts using output from the CLM simulations with and without LULCC (Sect. 2.2). Monthly averages for solar radiation incident upon the surface (after accounting for attenuation by monthly average cloud cover) are multiplied by the surface albedo with LULCC and without LULCC for each model grid point. The RF equals the global annual average difference between the outgoing solar radiation with LULCC and without LULCC.

2.4

1 Uncertainty

The uncertainty in these RF estimates arises largely from the uncertainty in modeling the effects of aerosols and modeling the impacts of climate, CO_2 changes, and LULCC on the carbon cycle. Our model predicts less uptake of anthropogenic carbon in natural land ecosystems compared to other land models, and thus could be underestimating the impact of land use on these regions (C. Jones et al., 2013.

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We compute the uncertainty in the total anthropogenic RF for each forcing agent with additional uncertainty associated with the partitioning of each RF into LULCC and other anthropogenic contributions, and with future fire emissions (Appendix C). For emissions from the theoretical extreme case we assume that our scaling assumptions (Sect. 2.3.1) are valid and do not introduce additional uncertainty, although the level of understanding of how emissions would scale under such an extreme scenario is low.

In addition to the uncertainties, there are a few shortcomings inherent in our approach. We do not include many biogeophysical effects of LULCC, such as changes to surface latent and sensible heat fluxes and to the hydrological cycle, that impact climate (DeFries et al., 2002; Feddema et al., 2005; Brovkin et al., 2006; Pitman et al., 2009; Lawrence and Chase, 2010). In general, while important for local or regional climate especially in the tropics (Strengers et al., 2010), these effects are considered minor on a global scale (Lawrence and Chase, 2010) and are difficult to quantify using the RF concept (Pielke et al., 2002). For the calculation of the many forcing agents that we do consider, our approach is to treat each forcing separately, which could lead to differences in RFs between agents that are due partly to methodology. For example, land cover changes and agricultural emissions were developed jointly for each of the RCPs, but for use in terrestrial models, including CLM, the land cover change projections were altered (Di Vittorio et al., 2014). This leads to inconsistent storylines between future emissions computed by CLM (Sect. 2.2) and those taken directly from the RCP integrated assessment model output (Sect. 2.3.1). Therefore, it is important to view the future RFs computed here as comprising a broad range in possible outcomes, extended with the TEC, as opposed to precise results corresponding to specific storylines for the future. Finally, the inhomogeneous distribution of forcing from surface albedo changes and short-lived trace gas and aerosol species could lead to non-additive (A. Jones et al., 2013), and highly variable local climate responses (Lawrence et al., 2012). Therefore, we use the RF for our assessment of global-scale climate impacts and acknowledge the limits of the RF concept for predicting the diverse and often local impacts of land use (Betts, 2008; Runyan et al., 2012).

3 Results

3.1 Land use impacts on present day radiative forcing

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We estimate a RF in the year 2010 from LULCC of 0.9 ± 0.5 W m^{-2}, 40% (+/- 16%) of the present day total anthropogenic RF (Fig. 3, Table 2). By separating the total anthropogenic RF (sum of LULCC and other anthropogenic activities) into contributions by forcing agent we can compare our calculations to the central estimates of Myhre et al. (2013) (Fig. 3) and the reported RFs of van Vuuren et al. (2011) (Table 3). Our calculations of the total, present day, anthropogenic RF correspond closely to the van Vuuren et al. (2011) values.

The major contributors to the present-day LULCC RF are associated increases in atmospheric CO_2 and CH_4. Deforestation, driven largely by the demand for additional agricultural land, leads to an estimated net decrease in global forest area of roughly 5.5 million km^{-2} from 1850 to 2010 (Lawrence et al., 2012; Fig. A1), and a transfer of carbon from the terrestrial biosphere into the atmosphere. Past studies report a LULCC contribution to current CO_2 concentrations (either year 2000 or 2005) of 26 ppm (Matthews et al., 2004), 22 to 43 ppm (Brovkin et al., 2004), ~45 ppm (Strassmann et al., 2008), and 17 ppm (Arora and Boer, 2010). After adjusting for the CO_2 fertilization feedback, we estimate a LULCC contribution of 28 ppm CO_2 in the year 2010. Our approach results in a year 2010 CO_2 concentration of 399 ppm (285 ppm preindustrial, 86 ppm fossil fuels, 28ppm LULCC), which overshoots the observed change in CO_2 over the same period by about 10% but is well within the range of values from the CMIP5 fully coupled climate model experiment, 368 ppm to 403 ppm in 2005 (Friedlingstein et al., 2013). The overestimate is in this case attributable to uncertainty in the total LULCC CO_2 emissions and uncertainty regarding the airborne fraction of historical emissions.

Present day LULCC and non-LULCC anthropogenic activities each emit close to 150 Tg CH_4 annually (van Vuuren et al., 2007), yet the RF from LULCC CH_4 is roughly double the RF from non-LULCC CH_4 (Fig. 3). The RF of non-LULCC CH_4 is diminished relative to LULCC CH_4 by the concurrent emission of non-LULCC NO_x, which leads to greater tropospheric ozone (O_3) production, an increase in the oxidation capacity of the troposphere, and as a result, a 20% reduction in CH_4 lifetime with respect to removal by reaction with OH (Appendix B3).

From CAM4 simulations of atmospheric chemistry we find that tropospheric O_3 increases from 192 Tg in 1850 to 304 Tg in 2010, when all anthropogenic activities are included. The O_3 increase of 112 Tg falls within the range of previous estimates (Lamarque et al., 2005). Here we separate the increase in O_3

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concentrations into a non-LULCC contribution, 87%, and a LULCC contribution, 13%. The large non-LULCC contribution is attributable to additional O_3 formation from NO_x emissions from fossil fuel burning sources. The contribution of LULCC to changes in O_3 combines several competing effects (Ganzeveld et al., 2010) including attributed changes in biogenic emissions of volatile organic compounds (virtually no contribution by historical LULCC on a global average) and reductions in emissions from wildfires (Table 1). The increase in tropospheric O_3 from LULCC is partially compensated for by a slight increase in the dry deposition of O_3 with LULCC (6%) between 1850 and 2010 as a result of the LULCC-enhanced O_3 concentration and despite the decrease in O_3 removal efficiency in deforested areas, similar to the findings of Ganzeveld et al. (2010). The small contribution of LULCC to global "short-lived" O_3 concentrations is augmented by additional O_3 (2.5 DU in 2010) produced in response to long-term increases in CH_4 (primary mode response; Appendix B2). The additional O_3 from this response accounts for 60% of the LULCC O_3 RF of 0.12 Wm^{-2} in 2010. The primary mode response O_3 is less important for non-LULCC activities because of the smaller CH_4 contribution from these activities.

We assume that long-lived greenhouse gases, CO_2, CH_4, and N_2O, with lifetimes on the order of years to centuries, are sufficiently well-mixed in the atmosphere that the forcing from these gases in spatially homogeneous (Table 4). The lifetime of tropospheric O_3 is considerably shorter, on the order of weeks, meaning concentrations can vary spatially, becoming higher near areas of O_3 production and remaining below the global average in remote regions away from areas of O_3 production. The RF varies in space with the concentration, although, these heterogeneities are moderate for O_3. The RF at 80% of grid points is within ± 0.07 Wm^{-2} of the global mean RF (Table 4).

While the positive RF from non-LULCC greenhouse gas emissions is offset to some extent by concurrent emissions of aerosols, LULCC contributes both increases and decreases in aerosol emissions resulting in nearly neutral aerosol RFs for the present day (Fig. 3). These opposing contributions to aerosol emissions are evident in the spatial variability in AOD attributable to historical LULCC, ranging between -0.18 to 0.29 (Table 4). Global average aerosol optical depth (AOD) is greater in 2010 and in 2100 for the RCP4.5, RCP6.0 and TEC scenarios when LULCC emissions are included, and lower for RCP2.6 and RCP8.5 scenarios, but in all cases the attributed share of LULCC is less than 0.01. The RF from aerosol deposition onto snow and ice surfaces is negligible on a global average (0.01 Wm^{-2} for

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historical LULCC) but exceeds ± 1 Wm^{-2} in some locations (Table 4). We also consider the impacts of aerosols and trace gas species on atmospheric CO_2 due to bio-fertilization by deposition of P, Fe and N emitted from fires, and N from agriculture (NH_3, NO_x, N_2O). For present day emissions of these species from LULCC activities (and land cover change impacts on fires), the drawdown of CO_2, enhanced particularly by agricultural emissions of N, leads to a negative RF of -0.10 Wm^{-2} that nearly compensates for the positive RF from the greenhouse effect of agricultural N_2O emissions (0.14 Wm^{-2}), a noteworthy aspect of agricultural emissions that was also suggested by Zaehle et al. (2011).

Estimates for the global RF from albedo changes range from -0.10 (Skeie et al., 2011) to -0.28 W m^{-2} (Lawrence et al., 2012), with a substantial percentage, potentially 25%, caused by preindustrial LULCC (Pongratz et al., 2009). Further estimates (Betts, 2001; Betts et al., 2007; Davin et al., 2007) fall near the IPCC AR5 central estimate of -0.15 Wm^{-2} (Myhre et al., 2013). The RF from albedo changes is near zero in most locations but has a high magnitude, up to 5 Wm^{-2}, in some localities on an annual average (Table 4), similar to the findings of Betts et al. (2007). Our estimate for the global RF from historical land surface albedo change, -0.05 Wm^{-2}, is at the higher end of the range of previously published estimates, yet still within the 90% confidence interval around the central estimate of Myhre et al. (2013). Reductions in fire area burned that result from historical LULCC act to decrease the magnitude of the surface albedo change forcing, although by less than 0.01 Wm^{-2} for the present day. The use of a less altered, more natural background state than our year 1850 landscape would likely increase the magnitude of this forcing (Sitch et al., 2005; Pongratz et al., 2009).

3.2 Future land use impacts on radiative forcing

In the year 2100 the RF attributable to anthropogenic LULCC, as projected by the RCPs, ranges between 0.9 to 1.9 Wm^{-2} (Fig. 4), although as a percentage of the projected total anthropogenic RF (as computed for RCP4.5), land use is less important in year 2100 than in 2010 (Table 2). Despite diverging trajectories for forest area and crop area for RCP2.6, RCP4.5 and RCP6.0 in the 21st century (Fig. A1), the year 2100 LULCC RFs are similar between these scenarios (Fig. 4). The RCP8.5 RF is characterized by relatively high contributions from CO_2 and CH_4 resulting in a total LULCC RF that is double the average of the other three RCP scenarios. The difference between RCP8.5 and the other scenarios suggests that decisions regarding global land policy similar to those used to develop the RCPs

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could reduce or increase global anthropogenic RF by 1 Wm^{-2} by 2100.

The LULCC projections for all four RCP scenarios include future decreases in global deforestation rates compared to recent historical rates (Fig. 5). A recent satellite assessment of global forest area gain and loss reported a global forest loss rate of 12.5 Mha yr^{-1} between 2000 and 2012 (Hansen et al., 2013), suggesting the census-reported rates for 2000 to 2010 (FAO, 2010) may be estimating less deforestation than is really occuring. If recent rates of observed forest area change persist, the global forest area projected in all four RCP scenarios by Hurtt et al. (2011) will become overestimates in the near future, especially in RCP4.5 and RCP6.0. More extreme land use scenarios are plausible, and would have a larger effect on climate. The theoretical extreme case, in which all arable land is converted to agricultural land and all remaining land that is pasturable is converted to grasses by the year 2100, does not take some important agricultural factors, such as changes in crop yields and per capita caloric intake, into account, but was created to represent a limit to cropland expansion on Earth. Since we designate arable land using a measure of climate suitability (Appendix A), following Ramankutty et al. (2002), crop area could conceivably expand beyond this limit with the use of irrigation. In fact, areas of South Asia currently support more agriculture than estimates of climate suitability suggest they should (Ramankutty et al., 2002).

In the theoretical extreme case, crop area roughly doubles by the year 2050, and continues to increase at the same rate to 2100. The rate of deforestation required to accommodate the expanded agriculture is three times greater than upper estimates from the RCPs for year 2000-2030 forest loss (Fig. 5), resulting in the near complete removal of tropical forests by the year 2100 (Fig. A2), and a global release of ~500 PgC from vegetation to the atmosphere. Loss of soil carbon often accompanies forest conversion to crops or grasses (Lal, 2004) but this process is not well simulated in this generation of terrestrial models. House et al. (2002) estimate terrestrial carbon loss from a complete deforestation to be between 450 to 820 PgC, with much of the uncertainty in the range due to different estimates of carbon loss from soils. The version and configuration of CLM used in this study does not include the process of carbon loss from soils from cultivation. Still, loss of carbon from vegetation alone in the theoretical extreme case corresponds to roughly two-thirds of the value of the proven reserves of fossil fuels (760 PgC) (Meinshausen et al., 2009). The substantial loss of terrestrial carbon to the atmosphere in the theoretical extreme case leads to a RF of 1.3 Wm^{-2} for CO_2 (Fig. 4). The magnitudes of all other forcing agents are

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enhanced in this scenario, leading to a sum RF of 3.9 ± 0.9 Wm^{-2} at the year 2100.

4.3 Enhancement of land use CO_2 radiative forcing

On average over all converted land types and land management histories, CO_2 RF from LULCC is enhanced by the accompanying (although not necessarily concurrent) emissions of non-CO_2 greenhouse gases and aerosols, such that the total RF is 2 to 3 times that of the CO_2 alone. For example, we estimate the net carbon flux from LULCC between 1850-2010 to be 140 PgC, leading to a RF from CO_2 of ~0.4 W m^{-2} in 2010, or about half of the total LULCC RF. In contrast, for other anthropogenic activities the RF from CO_2 and the total RF are roughly equal (Fig. 3, Fig. 4). Therefore, while LULCC accounted for about 20% of anthropogenic CO_2-equivalent emissions in 2010 (Tubiello et al., 2013), its contribution to the anthropogenic RF is 40% (+/- 16%). We can express this enhancement factor as the ratio of the sum RF to the CO_2 RF for LULCC, divided by the same ratio for other anthropogenic activities (FF+), or $E = (RF_{sum}/RF_{CO2})_{LULCC}/(RF_{sum}/RF_{CO2})_{FF+}$. For all future LULCC scenarios the enhancement factor is between 2.0 to 2.9 (Table 5). We compute the maximum enhancement of the CO_2 RF for the RCP4.5 scenario (E = 2.9). In the development of the RCP4.5 scenario, international carbon trading incentivizes preservation of forests and reforestation, which reduces CO_2 emissions and the resulting CO_2 RF from LULCC, increasing the enhancement factor.

The uncertainties in this factor (computed using the monte carlo method are described in Appendix C3) are large but suggest that the enhancement is unlikely to be less than 1.3 for the year 2010 or any of the given future scenarios. Values above 4.0 for the enhancement factor are within the uncertainty range for the RCP4.5, RCP8.5 and TEC scenarios. The large enhancement factors for the RCP8.5 and TEC scenarios result mainly from the substantial CH_4 RF relative to the CO_2 RF. For RCP4.5, this is a reflection of the low CO_2 RF attributed to LULCC and relatively high total RF with contributions from all other non-CO_2 greenhouse gases. The aerosol forcings play a minor role in the sum RF attributed to LULCC but impact the enhancement factor by reducing the non-LULCC forcing considerably. The aerosol ERFs are the source of much of the uncertainty surrounding the enhancement factor. Since the RF calculations presented here are within uncertainty estimates across many models and estimates (Fig. 3), it is likely that other models or approaches would obtain similar results if the same processes and activities were considered. We do not expect that the LULCC activities and biogeophysical forcings that

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we exclude from this study would have a substantial impact on the enhancement as these forcings have been shown to be small when considered on a global scale (Lawrence and Chase, 2010). Including model representation of LULCC impacts on soil carbon could increase the CO_2 and total RF attributed to LULCC (Levis et al., 2014) and lead to a small reduction in the enhancement factors compared to the values we report.

5. Conclusions

Effective strategies for mitigation of human impacts on global climate require an understanding of the major sources of those impacts (Unger et al., 2010). Anthropogenic land use and changes to land cover have long been recognized as important contributors to global climate forcing (Feddema et al., 2005), and yet most studies on this topic focus on either land use (e.g. Unger et al., 2010) or land cover change (e.g. Davin et al., 2007; Pongratz et al., 2009), but not both. In this study we compute the fraction of anthropogenic RF that is attributable to LULCC activities including a more comprehensive range of forcing agents.

Current estimates of the net LULCC carbon flux between 1850 and 2000 are between 108 PgC and 188 PgC (Houghton, 2010), while here we estimate 131 PgC. Estimates from this study using the future scenarios analyzed in the IPCC (the representative concentration scenarios or RCPs) suggest between 20 and 210 carbon will be released, consistent with Strassmann et al. (2008), and at the higher end of the model range reported by Brovkin et al. (2013). Our model underpredicts the uptake of land carbon relative to other models (e.g Arora et al., 2013), and unlike other estimates includes the explicit interplay between changes in land use and fires (e.g. Marlon et al., 2008; Kloster et al., 2010). The RCP scenarios were designed to cover a diverse set of pathways and create a broad range in possible outcomes for the next century (Moss et al., 2010). Given that the RCP scenarios all project decreases in global forest area loss rates in the 21st century relative to current rates, these scenarios are likely to be lower bounds on deforestation rates in the future (Fig. 5). To explore higher rates of global forest loss and crop and pasture expansions, we introduce a theoretical extreme case, in which all the arable land is converted to agriculture and pasture usage by 2100. Since the rates of deforestation in this scenario are higher than current rates, this scenario is an upper bound on what could occur. We calculate that with the intense pressures on land inherent to this scenario, between 590 and 700 PgC would be released from LULCC in

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this century.

We find that the total RF contributed by LULCC is two to three times the RF from CO_2 alone when additional positive forcings from non-CO_2 greenhouse gases and relatively small forcings from aerosols and surface albedo are considered. The RF of other anthropogenic activities (largely fossil fuels) in 2010 and in 2100 (RCP4.5), relative to 1850, includes a large magnitude negative aerosol forcing that offsets enough of the warming contribution from greenhouse gases that the total RF matches closely with the RF from CO_2. The result of this enhancement of the LULCC RF with respect to its CO_2 emissions, and lack of enhancement of the other anthropogenic activities RF, is a 40% LULCC contribution to present day anthropogenic RF, a substantially larger percentage that is deduced from greenhouse gas emissions alone (Tubiello et al., 2013). The percentage of anthropogenic RF attributable to LULCC activities is likely to decrease in the future, even as the magnitude of the RF could increase by up to 1.0 Wm^{-2} from 2010 to 2100. The lifetime and distribution of short-lived species makes simplification difficult in terms of equating CO_2 RF to other constituents (Shine et al., 2007), but simple approaches of controlling cumulative carbon (Allen et al., 2009) should account for the two to three times enhancement of the LULCC RF over long time periods per unit CO_2 emitted relative to other sources of CO_2.

Including forcings from aerosols in our assessment, while only slightly affecting the mean estimate of the total LULCC RF, greatly increases the uncertainty in the estimate. Much of the uncertainty arises from the simulation of aerosol/cloud interactions and the indirect effect for which very little model consensus exists on a global scale (Forster et al., 2007). In addition to these uncertainties, the perturbations of natural aerosol emissions by LULCC activities (mineral dust, SOA, wildfire smoke) are only beginning to be better understood on a global scale (Ginoux et al., 2012; Ganzeveld et al., 2010). Further research into the sources and lifetimes of natural aerosols, and anthropogenic impacts on their emissions, could efficiently reduce our uncertainty in the contribution of LULCC to global RF.

While it is likely that advances in, and proliferation of, agricultural technologies will be sufficient to meet global food demand without such an extreme increase in crop and pasture area, investment in foreign lands for agriculture, as a cost-effective alternative to intensification of existing agriculture, may be hastening the conversion of unprotected natural lands (Rulli et al., 2013). Given the huge potential

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for climate impacts from LULCC in this century, estimated here to be 3.9 ± 0.9 Wm^{-2} at the maximum, similar to some estimates of future climate impacts from fossil fuels (e.g. Van Vuuren et al., 2011), our study substantiates that not only energy usage but land use and land cover change needs to remain a focus of climate change mitigation.

Appendix A

Crop suitability calculations for theoretical extreme case

To estimate the maximum extent of crop and pasture for the theoretical extreme future scenario requires criteria that measure the potential of a land area to support agriculture. We follow the methodology of Ramankutty et al. (2002) to define the suitability of the climate and soil properties at model grid point locations for crops or pasture. In that study the authors define suitability based on the growing degree days, moisture index, soil organic carbon content, and soil pH that are characteristic of present day agricultural areas. Areas with a long enough growing season and sufficient water resources to support present day crops, absent irrigation (which is not included in their analysis), are considered suitable based on climate. For both soil organic carbon content and soil pH the authors find an ideal range of values that support agriculture and categorize areas that meet the criteria as suitable based on the soil. We repeat their analysis with temperature and precipitation data from the Climatic Research Unit TS3.10 dataset (Harris et al., 2014), soil data from the International Soil Reference and Information Centre – World Soil Information database (Batjes, 2005) and a simplified moisture index (Willmott and Feddema, 1992).

In this approach, sigmoidal functions are fit to probability density functions of gridbox fractional crop area and four environmental factors; growing degree days (GDD), moisture index, soil pH and soil organic carbon density. These functions describe where crops grow in today's world and how well they grow there. The functions are then applied to current global climate and soil datasets to identify areas that could support crops but have yet to, and also some areas where crops outdo their potential based on the local climate and soil, usually due to irrigation.

We use the Ramankutty et al. (2002) definitions for soil pH, soil carbon, defined as the mass of carbon per meter squared in the top 30 cm of the non-gravel soil, and for GDD, defined as the number of ˚C by

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which daily mean temperature exceeds 5 ˚C.

For the moisture index we use the Climate Moisture Index (CMI) (Willmott and Feddema, 1992) which is defined using precipitation, P, and potential evaporation, PE, data as:

$$\begin{aligned} CMI &= 1 - PE/P \quad when \quad P \geq PE \\ CMI &= P/PE - 1 \quad when \quad P < PE \\ CMI &= 0 \quad when \quad P = PE = 0 \end{aligned} \qquad \text{(A1)}$$

We use 1979-2009 averages for climate variables and year 2000 crop area data (Ramankutty et al., 2008). For fitting the individual sigmoidal curves, we restrict the data to only those points that are otherwise optimal for crops, as in Ramankutty et al. (2002). For example, when fitting the CMI data, we restrict the crop area data to regions where the GDD, soil carbon, and soil pH support crops. This isolates grid points that could be CMI limited.

Following Ramankutty et al. (2002), we fit a single sigmoidal curve to the GDD data, and the CMI data, a double sigmoidal curve to the soil carbon data and explicitly define a pH limit function. The expressions for these functions from Ramankutty et al. (2002) are given below with new coefficients computed for our study:

$$f_1(GDD) = \frac{1}{\left[1 + e^{a(b-GDD)}\right]} \qquad \text{(A2)}$$

$$f_2(\alpha) = \frac{1}{\left[1 + e^{c(d-\alpha)}\right]} \qquad \text{(A3)}$$

Where a=0.0037, b=1502, c=10.16, and d=0.3544.

$$g_1(C_{soil}) = \frac{a}{\left[1 + e^{b(c-C_{soil})}\right]} \frac{a}{\left[1 + e^{d(h-C_{soil})}\right]} \qquad \text{(A4)}$$

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Where a=22.09, b=3.759, c=1.839, d=0.0564, and h=106.5.

$$g_2(pH_{soil}) = \begin{cases} -1.64 + 0.41 pH_{soil} & if \quad pH_{soil} \le 6.5 \\ 1 & if \quad 6.5 < pH_{soil} < 8 \\ 1 - 2(pH_{soil} - 8) & if \quad pH_{soil} \ge 8 \end{cases} \qquad (A5)$$

These functions are multiplied together to create suitability indices: the product of the f functions gives the climate suitability index and the product of the g functions gives the soil suitability index. Natural land that is "suitable" for crops based on these criteria is converted to cropland (on a linear year-to-year basis) between years 2006-2100. We assume area that is suitable for crops based on climate, but not soil characteristics, can support grass and is used for pasturing animals. This assumption leads to the replacing of most tropical forests by crops or grasslands. The global potential crop area computed here for present day climate is 4,180 Mha and the potential pasture area is 3,110 Mha, compared to reported year 2010 utilized areas of 1,570 Mha for crops and 2,030 Mha for pasture (Hurtt et al., 2011). Published estimates of potential crop area range from 1552 Mha to 5131 Mha (Eitelberg et al., 2014). Our estimate for potential crop area would be classified as "high" within this range (Eitelberg et al., 2014), most similar to the results of Bruinsma (2003).

Since the potential crop area depends on climate, it is likely to change in the future. One estimate, using a business-as-usual greenhouse gas emissions scenario, yields a 16% increase of the 1961-1990 potential crop area by 2070-2099, mainly in high latitudes (Ramankutty et al., 2002). We did not include climate-dependent trends in potential crop area in this study but note here that doing so may increase the year 2100 RF of the theoretical extreme case LULCC.

The PFT timeseries for the theoretical extreme case is put together as follows. First, the potential crop area and potential pasture area are used to give the year 2100 crop area and minimum grassland area, respectively. Crop area is increased linearly starting in year 2006 at the expense of grassland first, then shrubs, then forest area. Pasture is increased at the expense of shrubs, then forest area. Different PFTs within those general categories are lost or gained in proportion to their year 2006 fractions. In this scenario, global crop area increases 200% with substantial expansion into tropical Africa and South

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America, and southeast Asia (Fig. A1, Fig. A2). The expansion of crops and pasture into the tropics occurs at the expense of forests, which have virtually disappeared from the tropics by the year 2100 (Fig. A2). Global forest area decreases by 65% in the theoretical extreme case. Emissions of CH_4 and N_2O from agriculture in the theoretical extreme case are based on emissions of these gases per area of crop/pasture in the RCP8.5 scenario and scaled by the differences in crop and pasture area between RCP8.5 and the theoretical extreme case. We do not consider possible future changes in natural emissions of CH_4 and N_2O.

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Appendix B

This appendix includes the details of the methods that we used to compute the RFs of all forcing agents from the LULCC emissions described in Sections 2.2 and 2.3. For atmospheric constituents the methods for computing the change in atmospheric concentrations are explained first, followed by the calculations for the RF.

B1 CO_2

CO_2 is chemically inert in the atmosphere but, over time, the airborne fraction of emitted CO_2 decreases as ocean and land uptake of carbon occurs. Therefore, the most recent CO_2 emissions will have the highest airborne fraction. We apply a CO_2 pulse response function (Enting et al., 1994) to compute the airborne fraction of the yearly pulse emissions at the year 2010 or 2100, following previously used methods (e.g. Randerson et al., 2006; Ward et al., 2012). This weighting is especially important for non-LULCC emissions, which have been largest over the most recent decades.

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After changes in the CO_2 concentration due to LULCC or other anthropogenic emissions are calculated, simple expressions from the IPCC TAR (Ramaswamy et al., 2001) can be used to estimate the adjusted radiative forcing (ΔF). For CO_2:

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$$\Delta F = 5.35 * \ln\left(\frac{C}{C_o}\right) \quad \text{(B1)}$$

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Here C_o is the atmospheric CO_2 concentration in the unperturbed state (with no LULCC emissions, or no

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emissions from other anthropogenic activities) and *C* is the perturbed atmospheric CO_2 concentration containing both all anthropogenic contributions. In this way the CO_2 saturation effect of the different perturbed CO_2 concentrations on the RF is taken into account.

B2 Tropospheric O_3

Atmospheric chemistry is simulated with CAM version 4 with MOZART chemistry (Emmons et al., 2010). In all cases CAM4 is setup with horizontal grid spacing of 1.9 degrees latitude by 2.5 degrees longitude with 26 vertical levels and a timestep of 30 minutes. Each simulation is branched from a two-year spinup using year 2000 climate conditions (air temperature, sea surface temperature, solar forcing, etc.). Model setup is identical for all simulations except for trace gas emissions, and CH_4 concentrations, which are specific to the case (LULCC vs. no-LULCC, year 2010 vs. year 2100). In these simulations the tropospheric chemistry evolves differently depending on the initial emissions but does not interact with the model radiation. Therefore the CAM4 model climate is identical for all simulations and the RF of the changes in chemistry can be isolated. A one-year post-spinup CAM4 integration is used for analysis of the RF.

To assess the global mean RF of O_3 from the changes in emission of short-lived precursors and deposition, we compute radiative fluxes at the tropopause with the CAM4 output three-dimensional O_3 fields included, and also with tropospheric O_3 removed. This is accomplished by running the CAM4 radiation package offline with the Parallel Offline Radiative Transfer (PORT) tool (Conley et al., 2013). The difference in net radiative flux at the tropopause caused by removing O_3 gives the total RF of tropospheric O_3 in each case. The difference in O_3 RF between cases with LULCC and the corresponding case without LULCC is equivalent to the contribution from LULCC to the RF. The contribution of other anthropogenic activities is estimated by computing the difference between the year 2010 or 2100 simulations without LULCC, and the 1850 simulation without LULCC.

The short-lived O_3 RF estimated here is an instantaneous forcing since we do not allow for stratospheric temperature adjustment. Hansen et al. (2005) estimate a ratio of adjusted RF to instantaneous RF of approximately 0.8 in global simulations for the period between 1880 to 2000. We multiply the instantaneous RFs for O_3 by 0.8 to account for the stratospheric adjustment and report adjusted RFs.

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Tropospheric O_3 acts as a source for OH. Therefore, changes to O_3 concentrations lead to a response in CH_4 and, as a consequence, a response in peroxy radical concentrations (Naik et al., 2005). The changes in peroxy radical concentrations, an end result of the changes in emissions of O_3 precursors caused by LULCC or other anthropogenic activities, feeds back onto O_3, a response which is approximated with the following expression (Naik et al., 2005):

$$\left(\Delta O_3\right)_{primary} = \frac{\Delta\left[CH_4\right]}{\left[CH_4\right]} * 6.4DU \quad \text{(B2)}$$

We use a value of 0.032 +/- 0.006 W m^{-2} DU^{-1} (Forster et al., 2007) to compute the additional RF of O_3 caused by this process, known as the primary mode response.

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B3 CH_4

To compute direct (through emissions) and indirect (through altered chemical lifetime) changes in CH_4 concentrations (due to LULCC and other anthropogenic activites) we treat them as separate perturbations to observed (year 2010) and projected (year 2100) concentrations. We compare the concentration with all anthropogenic CH_4 sources/influences to the concentration with either LULCC or other anthropogenic sources/influences removed to compute the change in concentration for each case. The lifetime of CH_4 in the atmosphere (~9 years) means our simulations are too short to directly simulate the changes in CH_4 concentration. Instead we use approximations based on the known emissions of CH_4 and changes in the quick-adjusting main chemical sink for CH_4 – the hydroxyl radical (OH).

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If we remove direct emissions of CH_4 from a particular source such as LULCC, a new steady state concentration can be approximated using the following expression from Ward et al. (2012):

$$\Delta\left[CH_4\right] = F * {\Delta E}/{E_O} * \left[CH_4\right]_O \quad \text{(B3)}$$

such that a percentage change in CH_4 emissions, E, leads to a percentage change in concentration, $[CH_4]$, times the ratio of the perturbation lifetime to the initial lifetime, F. We do not calculate F from

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our simulations but use $F = 1.4$ as recommended by the IPCC (Prather et al., 2001).

Changes in global OH concentration can be used to approximate the change in CH_4 lifetime caused by a change in emissions (Naik et al., 2005). Here we use the OH concentrations predicted in the CAM4 simulations for each case. The impact of non-LULCC emissions on CH_4 lifetime is taken as the difference between the year 2010 or 2100, and year 1850 CH_4 lifetime in the simulations with no LULCC emissions. Estimated this way, the CH_4 lifetime decreases by more than two years between 1850 and 2010 and by one and a half years between 1850 and 2100.

We compute the change in concentration due to the change in CH_4 lifetime, τ, with respect to reaction with OH using this expression (Naik et al., 2005):

$$\Delta[CH_4] = F * [CH_4]_O * \frac{\Delta\tau}{\tau_O} \quad \text{(B4)}$$

Here we also use F = 1.4 to account for the positive feedback between CH_4 and OH (Naik et al., 2005).

The adjusted RF for the changes in CH_4 concentration can be computed with the following expressions (Ramaswamy et al., 2001):

$$\Delta F = 0.036\left(\sqrt{M} - \sqrt{M_O}\right) - \left[f(M, N_O) - f(M_O, N_O)\right] \quad \text{(B5)}$$

$$f(M,N) = 0.47 * \ln\left[1 + 2.01\times10^{-5}(M*N)^{0.75} + 5.31\times10^{-15} M (M*N)^{1.52}\right] \quad \text{(B6)}$$

using the average tropospheric concentrations of CH_4 (ppb) and N_2O (ppb) in the perturbed state with LULCC or other anthropogenic emissions removed (M and N, respectively), and in the unperturbed, reference state (M_o and N_o, respectively).

B4 N_2O concentration

Nitrous oxide is a long-lived greenhouse gas with a lifetime in the troposphere of over 100 years.

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Therefore, we use a simple atmospheric box model that can be run quickly for many model years to diagnose changes in N_2O concentration that result from LULCC and other anthropogenic emissions. The box model uses an expression of N_2O mass balance to predict changing concentrations, C, with time given yearly emissions, E, and a dynamic N_2O lifetime, τ (Kroeze et al., 1999):

$$\frac{dC}{dt} = \frac{E}{S} - \frac{C}{\tau} \quad \text{(B7)}$$

Here, S is a conversion factor (4.8 Tg N $ppbv^{-1}$) and t is time (years). The N_2O lifetime is dependent on its own concentration, which we account for here following Meinshausen et al. (2011b) and using a year 2000 reference state:

$$\tau = \tau_O \left(\frac{C}{C_O} \right)^{-0.05} \quad \text{(B8)}$$

We run the box model from simulation year 1850 through 2100 with natural and anthropogenic emissions, but with emissions from the source of interest, either LULCC or other anthropogenic activities, removed. We assume that the decrease in natural N_2O emissions (Syakila and Kroeze, 2011) is attributable to LULCC. This decreases the net LULCC emissions of N_2O.

The adjusted RF for the changes in N_2O concentration can be computed with Eq. B6 and the following expression from Ramaswamy et al. (2001):

$$\Delta F = 0.12\left(\sqrt{N} - \sqrt{N_O}\right) - \left[f\left(M_O, N\right) - f\left(M_O, N_O\right)\right] \quad \text{(B9)}$$

using the average tropospheric concentrations of CH_4 (ppb) and N_2O (ppb) in the perturbed state with LULCC or other anthropogenic emissions removed (M and N, respectively), and in the unperturbed, reference state (M_o and N_o, respectively).

B5 Aerosol effects

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CAM5 is used to simulate aerosol dynamics and the resulting radiative flux changes, as opposed to CAM4, to allow use of MAM3, which is not available for CAM4. Unfortunately chemistry was not yet available in CAM5 at the time of this study, so that different versions of the model had to be run for chemistry and aerosols. Since we use CAM4 and CAM5 to model concentration changes for separate forcing agents (trace gases in CAM4 and aerosols in CAM5), differences in physics between the two models do not affect our results. CAM5 is setup with horizontal grid spacing of 1.9 degrees latitude by 2.5 degrees longitude with 26 vertical levels and a timestep of 30 minutes. Each simulation is branched from a two-year spinup using year 2000 climate conditions (air temperature, sea surface temperature, solar forcing, etc.). Model setup is identical for all simulations except for aerosol emissions, which are specific to the case (LULCC vs. no-LULCC, year 2010 vs. year 2100). In CAM5, aerosols are both radiatively and microphysically active. This enables simulation of aerosol indirect effects but leads to different model climates for different initial aerosol emissions. To isolate the impacts of aerosols on the RF we integrate CAM5 for four years post-spinup and use the annual average for analysis. This smooths out the interannual variability in the model climate state to minimize its impact on the RF (Wang et al., 2011).

Aerosols impact radiative transfer directly by scattering and absorbing shortwave and some longwave radiation, and also indirectly by their effects on clouds. We compute the direct effect of changes in aerosols from LULCC by running the CAM5 radiation online in a diagnostic mode separately from the prognostic radiation in the model. The radiation package is run at every timestep through the model atmosphere with all aerosols and again with aerosols removed from interactions with radiation. The difference in top-of-atmosphere net radiative flux when aerosols are removed is the all-sky direct radiative effect. We compute this effect for shortwave and longwave interactions.

Indirect effects are defined here as the change in total cloud forcing between the simulations with and without LULCC (referenced to 1850), where total cloud forcing is the sum of the longwave and shortwave cloud forcing. This quantity is assessed after the direct effects of aerosols have been removed with the online diagnostics. Therefore, the sum of the direct effects and indirect effects of aerosols is equal to the total radiative change caused by aerosols in the CAM5 simulations.

In CAM5, the indirect effects of aerosols on clouds includes the first indirect effect by which aerosols,

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acting as cloud condensation nuclei, lead to changes in cloud droplet size and, as a consequence, cloud albedo. CAM5 also simulates aerosol/cloud interactions that are considered secondary indirect effects. These include aerosol impacts on stratiform cloud lifetime and height, and the semi-direct effect. The semi-direct effect refers to the change in cloud fraction that results from the warming of an air layer by aerosol absorption of shortwave radiation (Lohmann and Feichter, 2005). Aerosol impacts on convective clouds are not included in our simulations.

These aspects of the CAM5 microphysics may lead to bias in our calculations when compared to the model consensus ERFs from the IPCC AR5 (Myhre et al., 2013). For this reason, and because models generally disagree on the magnitude of the aerosol effects (Forster et al., 2007), we use our results only to determine the proportion of the forcings from LULCC and non-LULCC, as explained in section 2.4.

In addition to these effects in the atmosphere, light-absorbing aerosols, particularly BC and dust, can decrease the albedo of the Earth's surface when they are deposited onto snow and ice surfaces. The Snow, Ice, and Aerosol Radiative (SNICAR) model (Flanner and Zender, 2006) is run online with CAM5 to simulate this process and estimate the RF. For all cases the RF of aerosol deposition onto snow and ice surfaces is between 0 and 0.03 W m^{-2}. Note that we only capture aerosol deposition on snow and ice covering land and not over sea. This will reduce our estimates of the RF compared to estimates including sea-ice, although the RF from aerosol deposition onto sea-ice is thought to be less important than deposition onto land-covering snow and ice (Flanner et al., 2007).

B6 Land surface albedo

Albedo changes, apart from those caused by fires, are simulated by CLM (Sect. 2.4). For albedo changes from wildfire activity, post-fire albedo response curves (Ward et al., 2012) are applied to the difference in burned area with LULCC and without LULCC at each grid point. Fires lead to negative (cooling) RF from albedo changes on a global average (Ward et al., 2012). Since historical and projected LULCC reduced burned area in CLM, the result was a small but positive RF in all cases, acting in the opposite direction of the overall negative LULCC albedo change RF.

B7 Biogeochemical and carbon-climate feedbacks

The importance of aerosol biogeochemical feedbacks onto CO_2 concentrations is beginning to be

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recognized and known impacts have recently been quantified (Mahowald, 2011). We consider changes to terrestrial uptake of carbon by the addition of N transported by aerosols, and also by modifications of climate.

N deposition from anthropogenic sources fertilizes vegetation growth and increases the drawdown of CO_2, causing a present day RF of -0.12 to -0.35 W m^{-2}. We multiply this forcing by the ratio of N emissions (NH_3, NO_x) from LULCC or other anthropogenic activities for each case to year 2010 total anthropogenic N emissions.

Changes in global surface temperature caused by the previously described RFs of LULCC and non-LULCC activities lead to a response in carbon uptake by the terrestrial biosphere and the ocean (Mahowald, 2011; Arneth et al., 2010). Moreover, aerosols affect vegetation by redistributing precipitation and changing the ratio of diffuse to direct radiation incident on the surface. While not very well understood, these biogeochemical feedbacks can be estimated by coupled carbon-climate models that suggest a roughly linear response of between 0 and 40 ppm CO_2 for a RF of 1.4 W m^{-2} (Mahowald et al., 2011). We sum the total RF of LULCC for all cases from greenhouse gases, aerosol effects and albedo changes, to estimate the impact of the potential changes in climate on atmospheric CO_2. In all cases, since the total RF from LULCC is positive, the RF of the feedback onto CO_2 concentrations is also positive.

The total RFs of these biogeochemical feedbacks are included with the CO_2 RF in the tables and figures since they impact climate through changing CO_2 concentrations.

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Appendix C

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Computing uncertainties

The uncertainties in RF estimations are substantial (Myhre et al., 2013) and include uncertainties in the model representation of physical and chemical processes, model internal variability and imperfect knowledge of processes. Here we describe the calculation of uncertainties for the RFs reported in this paper and we assume the uncertainty has three sources: model and RF computations, partitioning of emissions between LULCC and non-LULCC, and uncertainty in the emissions from future fires (values

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given in Table C1).

C1 Anthropogenic RF calculation uncertainties

For the uncertainty in the total anthropogenic RF calculations, we take the 90% confidence intervals generated by the IPCC (Myrhe et al., 2013) for each forcing agent and assume these represent a Gaussian probability density function around the central estimate (Table C1, "Model" column). This assumption may not be appropriate for all forcing agents if the goal were to compute uncertainties that could be interpreted probabilistically. Therefore we stress that the calculated uncertainties are rough estimates and should not be interpreted as probabilistic. We propagate this uncertainty to LULCC and non-LULCC by multiplying by the corresponding fraction of the RF from LULCC or non-LULCC, or in the case of the aerosol forcings, by the fraction of AOD from LULCC or non-LULCC. Since we use the IPCC aerosol forcings in our total LULCC RF estimates, we do not include uncertainty introduced by the secondary aerosol effects.

C2 Partitioning uncertainty

The partitioning uncertainty is determined from previous estimates of the error in sector-specific trace gas and aerosol emissions. We define this uncertainty as the maximum range in the ratio of LULCC to non-LULCC emissions that could result from the two sources varying from plus to minus one standard deviation of their own source-specific uncertainty (Table C1, "Partitioning" column).

The source uncertainties for trace gases CO_2, CH_4, NH_3, NO_x, and N_2O are taken from the IPCC AR4 (Forster et al., 2007). The source uncertainties in emissions of N species (that is, the range in the ratio of LULCC N emissions to non-LULCC N emissions varying within the uncertainties from each source reported by Forster et al. (2007)) are combined to produce the partitioning uncertainty of the aerosol biogeochemical feedback onto CO_2 concentrations. The feedback of RF from non-LULCC and LULCC separately onto the carbon cycle (Section 2.4) is also included here as part of the CO_2 partitioning uncertainty. The partitioning uncertainty for CH_4 is combined with uncertainty in global sinks of CH_4 (from Forster et al., 2007) that affect our understanding of the CH_4 atmospheric lifetime. For emissions of CO (used in O_3 partitioning uncertainty) we estimate a two times uncertainty in all emissions (Unger et al., 2010). Similarly, we begin with a two times uncertainty in aerosol emissions, as this has been estimated for carbonaceous aerosols (Unger et al., 2010), but noting that the emissions of dust and SOA

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are more uncertain than emissions of carbonaceous aerosols, we double this uncertainty for aerosol emissions (4 times uncertainty). The partitioning uncertainties for halocarbon emissions and land surface albedo changes are zero since we only consider one source, LULCC or non-LULCC, for these forcing agents.

C3 Summing the uncertainties

Using the Monte Carlo method with N=100,000 iterations, and assuming that the different forcing agents vary independently of one another, we produce Gaussian probability density functions for the combined RF (all agents, and LULCC and other anthropogenic sources) and for the LULCC RF (all agents, only LULCC sources). Adding these uncertainties together (root of the sum of squares) gives the uncertainty in the fraction of anthropogenic RF attributable to LULCC (Table 2). The assumption of independence among forcing agents is not perfect. For example, NO_x concentrations are used to predict changes in O_3, CH_4, and total N, and the same aerosol emissions are used to estimate several different forcings. However, given that there are large uncertainties specific to the calculation of each forcing agent, and apart from those associated with emissions, we retain the assumption of independence for approximating the sum of the uncertainties.

We apply the same uncertainties to the future RFs for LULCC and add additional uncertainty due to variability in global fire activity between 2010-2100 that is due to the different atmospheric forcing used in these simulations. We define this uncertainty as the total range in RF caused by using the different atmospheric forcing datasets to drive global fires in CLM (Table C1, "Fire" columns). The different forcing datasets were chosen to represent a large spread in projected temperature and precipitation by the year 2100 (Kloster et al., 2012). The uncertainties of the different forcing agents with regard to fire emissions are not independent of each other and, therefore, are added directly to the sum uncertainties after the Monte Carlo simulations have determined the sum of the other, more independent, uncertainties.

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Tables

Table 1.

Emissions of important aerosol and trace gases attributed to LULCC activities for year 2010 and year 2100 for the listed future scenarios (theoretical extreme case is abbreviated to TEC). Values are given in Tg (species) yr^{-1} except where noted otherwise. Values in parentheses are the percent change in global emissions attributed to LULCC for the year and scenario listed. Biogenic SOA precursors are considered the sum emissions of biogenic CO, isoprene, monoterpenes, and methanol.

	N_2O [$TgN(N_2O)yr^{-1}$]	Dust	Biogenic SOA Precursors [$TgCyr^{-1}$]	Fire (BC+OC)
2010	4.3	+619 (18)	+7 (1)	-2.2 (13)
RCP2.6	5.4	+1003 (28)	-141 (16)	-6.0 (25)
RCP4.5	2.9	+806 (23)	-54 (6)	+1.8 (8)
RCP6.0	3.8	+1008 (28)	-105 (12)	-4.0 (17)
RCP8.5	5.3	+866 (24)	-149 (16)	-8.1 (34)
TEC	11.7	+4330 (222)	-656 (74)	-15.4 (65)

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Table 2. LULCC RF values and uncertainties for year 2010 and all future scenarios (year 2100) relative to the year 1850. Sum RFs are the total of all forcing agents and have been rounded to the nearest 0.1 W m^{-2}. The theoretical extreme case is abbreviated to "TEC".

	LULCC RF					
Forcing	2010	R26	R45	R60	R85	TEC
CO2	0.43 [±0.28]	0.42 [±0.54]	0.29 [±0.52]	0.47 [±0.55]	0.67 [±0.58]	1.26 [±0.67]
N2O	0.14 [±0.05]	0.25 [±0.09]	0.18 [±0.08]	0.21 [±0.08]	0.25 [±0.09]	0.41 [±0.13]
CH4	0.30 [±0.07]	0.18 [±0.05]	0.31 [±0.07]	0.34 [±0.07]	0.67 [±0.12]	1.56 [±0.25]
Ozone	0.12 [±0.17]	0.06 [±0.13]	0.10 [±0.15]	0.10 [±0.15]	0.17 [±0.18]	0.29 [±0.23]
Aero DE	-0.02 [±0.19]	0.03 [±0.03]	0.02 [±0.03]	0.02 [±0.03]	0.01 [±0.05]	0.08 [±0.09]
Aero IE	-0.02 [±0.20]	0.04 [±0.14]	0.01 [±0.13]	0.02 [±0.13]	0.19 [±0.21]	0.37 [±0.29]
Albedo	-0.05 [±0.06]	-0.06 [±0.06]	-0.06 [±0.06]	-0.06 [±0.06]	-0.03 [±0.06]	-0.14 [±0.06]
Ice albedo	0.01 [±0.01]	0.01 [±0.00]	0.02 [±0.01]	0.01 [±0.00]	0.01 [±0.01]	0.03 [±0.01]
Sum	0.9 [±0.5]	0.9 [±0.6]	0.9 [±0.6]	1.1 [±0.6]	1.9 [±0.7]	3.9 [±0.9]
% Anthro	40 [±16]	21 [±12]	21 [±11]	24 [±12]	36 [±10]	53 [±8]

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Table 3. Radiative forcings (W m^{-2}) for the year 2010 and the year 2100 compared to Myrhe et al. (2013), and van Vuuren et al. (2011), respectively. For year 2100 we show the RF from RCP4.5 scenario emissions (referenced to year 1850) estimated from the modeling results in this study and from van Vuuren et al. (2011).

			Total	
2010	LULCC	Non-LULCC	Anthro	Myhre et al. 2013
Total	0.91	1.39	2.3	2.22
CO_2	0.43	1.4	1.83	1.82
CH_4	0.3	0.14	0.44	0.48
N_2O	0.14	0.03	0.17	0.17
Halocarbons	0	0.36	0.36	0.36
Aerosols/O_3/alb[a]	0.04	-0.54	-0.5	-0.61
2100-RCP4.5				Van Vuuren et al. 2011
Total	0.92	3.49	4.41	4.14
CO_2	0.29	3.17	3.46	3.47
CH_4	0.31	0.12	0.43	0.37
N_2O	0.18	0.12	0.3	0.31
Halocarbons	0	0.18	0.18	0.18
Aerosols/O_3/alb[a]	0.14	-0.1	0.04	-0.19

[a] This sum RF includes aerosols (direct effects, indirect effects on clouds, and deposition onto snow/ice surfaces), tropospheric O_3 and forcing from surface albedo changes.

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Table 4. Quantiles of the spatial distribution of the different forcings from historical LULCC (assessed in 2010) when represented as a probability density function. The grid spacing is 1.9 degrees latitude by 2.5 degrees longitude. Note that we show aerosol optical depth (AOD) in place of the aerosol forcings since the distribution of these forcings includes variability in cloud properties that are not directly attributable to changes in aerosols at this grid spacing.

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		Quantiles						
Forcing	Mean	Min.	$q_{0.1}$	$q_{0.25}$	Median	$q_{0.75}$	$q_{0.9}$	Max.
CO_2	0.43 [±0.27]	0.43	0.43	0.43	0.43	0.43	0.43	0.43
N_2O	0.14 [±0.04]	0.14	0.14	0.14	0.14	0.14	0.14	0.14
CH_4	0.30 [±0.07]	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Ozone	0.12 [±0.18]	-0.10	0.06	0.08	0.11	0.15	0.19	0.37
Albedo[a]	-0.05 [±0.12]	-5.6	-0.45	-0.09	0	0	0.08	2.5
Ice alb.[a]	0.01 [±0.02]	-1.52	-0.01	0	0	0.01	0.06	2.6
AOD								
AOD	0.005	-0.18	-0.02	0	0.03	0.07	0.11	0.29

[a] The spatial distribution of the RF from albedo changes is computed only for land points.

Table 5. Enhancement of CO_2 RF by other forcing agents for LULCC and non-LULCC activities. RFs are given in units of W m^{-2}.

	LULCC		Non-LULCC[a]		
Scenario	CO2 RF	TOTAL RF	CO2 RF	TOTAL RF	Enhancement[b]
2010	0.43	0.91	1.4	1.39	2.1 (+1.0,-0.5)
RCP2.6	0.42	0.93	3.17	3.49	2.0 (+1.4,-0.7)
RCP4.5	0.29	0.92	3.17	3.49	2.9 (+2.6,-1.6)
RCP6.0	0.47	1.11	3.17	3.49	2.1 (+1.5,-0.7)
RCP8.5	0.67	1.94	3.17	3.49	2.6 (+1.8,-0.8)
TEC[c]	1.26	3.86	3.17	3.49	2.8 (+1.3,-0.6)

[a] Other anthropogenic activities, dominated by fossil fuel burning, and including the aerosol effects RFs from the IPCC AR5 (Myhre et al., 2013)

[b] Enhancement is defined as the ratio of total RF to CO_2 RF for LULCC divided by the ratio of total RF to CO_2 RF for FF+.

[c] Theoretical Extreme Case

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Table C1. Values for the three types of uncertainty calculated in this study. Uncertainty due to fires is specific to each future LULCC scenario and for other future anthropogenic activities (FF+).

	Model	Partitioning	Fire					
	[W m^{-2}]	[%]	[W m^{-2}]					
Forcing			RCP2.6	RCP4.5	RCP6.0	RCP8.5	TEC[a]	FF+
CO_2	±0.12	±15	±0.04	±0.02	±0.04	±0.05	±0.15	0
N_2O	±0.01	±25	0	0	0	0	0	0
CH_4	±0.03	±15	±0.01	±0.01	±0.01	±0.01	±0.02	±0.02
Ozone	±0.12	±40	0	0	0	0	±0.01	±0.01
Aero DE	±0.30	±40	0	±0.02	±0.02	±0.02	±0.1	±0.1
Aero IE	+0.27, -0.46	±40	±0.05	±0.02	0	±0.14	±0.23	±0.28
Albedo	±0.06	0	±0.01	±0.01	0	0	±0.01	0
Ice alb.	+0.03, -0.01	±40	0	±0.01	0	0	0	0
HaloCs	±0.02	0	0	0	0	0	0	0

[a] Theoretical extreme case

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Figures

Fig. 1. A schematic illustration of the climate impacts of land use and land cover change. See Fig. 2 for a representation of the processes and emissions included in this study.

Fig. 2. A flow chart summarizing the methodology used in this study to compute the RF of the various forcing agents of LULCC. The colors of the boxes indicate processes that are independent of this study (orange), processes and computational steps that were completed as part of this study (green), and processes that were not included in this study, but are likely important for climate (blue). Acronyms are defined as follows: CLM-CN (Community Land Model with Carbon/Nitrogen cycles) (Oleson et al., 2008; Stockli et al., 2008), CAM (Community Atmosphere Model) (Gent et al., 2011), MOZART (Model for Ozone and Related Chemical Tracers) (Emmons et al., 2010), PORT (Parallel Offline Radiative Transfer) (Conley et al., 2013), TAR (Third Assessment Report) (Ramaswamy et al., 2001), and SNICAR (Snow Ice and Radiative Aerosol Model) (Flanner and Zender, 2006).
* Total nitrogen (N) includes contributions from NH_3, N_2O and NO_x emissions

Fig. 3. RFs for LULCC and other anthropogenic impacts estimated by this study for the year 2010 referenced to the year 1850. Total anthropogenic RF from the IPCC AR5 (Myhre et al., 2013) are shown for comparison (yellow). Error lines represent one sigma uncertainties in total anthropogenic RF for the IPCC bars and one sigma uncertainties in LULCC RFs as computed in this study (green bars, data given in Table 2). The "SUM" bars show the total RF when all forcing agents are combined. Note that aerosol ERFs are scaled to IPCC AR5 values, as explained in the main text.

Fig. 4. RF for all LULCC and non-LULCC anthropogenic impacts (RCP4.5 Non-LULCC) estimated by this study for the year 2100, referenced to the year 1850. Error bars show one sigma uncertainties as computed in this study (Table 2). The "SUM" bars show the total RF when all forcing agents are considered.

Fig. 5. Comparison of projected annual rates of forest area change. Color 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

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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.

Fig. A1. Change in global total (a) forest and (b) crop areal coverage with time for historical and Representative Concentration Pathway scenarios (Lawrence et al., 2012), and the theoretical extreme case (TEC; green).

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Fig. A2. Percent of gridbox area consisting of (a) year 2010 crops, (b) potential crops based on climate and soil suitability, (c) year 2010 forests, and (d) year 2100 forests in the theoretical extreme case.