Increased influence of nitrogen limitation on CO_2 emissions from historical and future land use and land-use change

Atul K Jain[1], Prasanth Meiyappan[1] and Joanna I House[2]

[1]Department of Atmospheric Sciences, University of Illinois, Urbana, IL 61801, USA
[2]Department of Geography, Cabot Institute, University of Bristol, Bristol, BS8 1SS, UK

Abstract
We estimate the impacts of nitrogen limitation on the CO_2 emissions from land use and land-use change (LULUC), including wood harvest, for the period 1900-2100. We use a land-surface model that includes a fully coupled carbon and nitrogen cycle, and accounts for forest regrowth processes following agricultural abandonment and wood harvest. Future projections are based on the four Representation Concentration Pathways used in the IPCC Fifth Assessment Report. Results show that excluding nitrogen limitation will underestimate global LULUC emissions by 34-52 PgC (20-30%) during the 20th century and by 128-187 PgC (90-150%) during the 21st century. The underestimation increases with time because: (1) Projected annual wood harvest rates from forests summed over the 21st century are 380-1080% higher compared to those of the 20th century, resulting in more regrowing secondary forests, (2) Nitrogen limitation reduces the CO_2 fertilization effect on net primary production of regrowing secondary forests following wood harvest and agricultural abandonment, and (3) Nitrogen limitation effect is aggravated by the gradual loss of soil nitrogen from LULUC disturbance. Our study implies that: (1) Nitrogen limitation of CO_2 uptake is substantial and sensitive to nitrogen inputs, (2) If LULUC emissions are larger than previously estimated in studies without nitrogen limitation, then meeting the same climate mitigation target would require an equivalent additional reduction of fossil fuel emissions, and (3) The effectiveness of land-based mitigation strategies will critically depend on the interactions between nutrient limitations and secondary forests resulting from LULUC.

Key Words
nitrogen cycle; carbon cycle, carbon emissions; uncertainties; climate projections, ISAM

Introduction
In a recent article, we studied the role of land use and land use change (LULUC) emissions on the carbon budget for the period 1765-2010 (Jain et al., 2013). The study used a terrestrial ecosystem component of a land surface model, the Integrated Science Assessment Model (ISAM) that includes a fully coupled carbon-nitrogen cycle and detailed representation of secondary forest dynamics to account for forest regrowth processes following agricultural abandonment and wood harvest. We showed that failing to account for nitrogen dynamics, a key process limiting forest regrowth, underestimated LULUC emissions by ~70% in the non-tropics, ~10% in the tropics, and ~40% globally during 1990s compared to simulations that included the nitrogen dynamics. The study conveyed two key messages: (1) nitrogen limitation will significantly reduce the effect of carbon sinks on regrowing secondary forests, and (2) historically, more secondary forests have resulted from wood harvest than from agricultural abandonment, underscoring the importance of forest management in estimating LULUC emissions.

The 21st century scenarios based on the Coupled Model Intercomparison Project phase 5 (CMIP5) project a 380-1080% rise in total global forest wood harvest area compared to the 20th century, due to rapid increase in demand for bioenergy and wood products (Hurtt et al., 2011). Therefore, the effect of nitrogen limitation on the rates of carbon sink on regrowing secondary forests could be much greater in the future compared to history, having significant implications for the effectiveness of land-based mitigation policies. Accounting for both nitrogen limitation and forest management are beyond the current capabilities of many global climate models involved in CMIP5 (Ciais et al., 2013), thus giving them the tendency to be too optimistic in simulating future carbon sinks. Accordingly, the overall aim of this study is to understand how future LULUC emissions are influenced by the interactions among LULUC, nitrogen limitation, and anthropogenic environmental changes (CO_2 fertilization, climate change, and nitrogen deposition that reduce the nitrogen limitation effect). We place specific emphasis on land management. The overall aim can be split into three parts: (1) we study the magnitude of LULUC emissions (with nitrogen limitation effect) attributable to "land use" (management) as compared to "land-use change", and how their magnitude is influenced by anthropogenic environmental changes; (2) we study the impact of nitrogen limitation on the 21st century LULUC fluxes; and (3) we carry out a comprehensive assessment of the uncertainties in estimates of future LULUC emissions due to the different mitigation scenarios of the IPCC Fifth Assessment Report, and uncertainties in climate projections underlying each scenario.

Methods

We use a data-modeling approach to study the three objectives discussed above. This section briefly describes: the land surface model used to simulate LULUC fluxes, model forcing data, and model simulations performed.

Model details

We use a terrestrial ecosystem component of a land surface model, Integrated Science Assessment Model (ISAM) to assess the impacts of LULUC on terrestrial carbon fluxes. The terrestrial component of ISAM simulates carbon and nitrogen fluxes between the vegetation and the atmosphere (net land-to-atmosphere flux), above and below ground litter, and soil organic matter at 0.5ºx0.5º spatial resolution (Jain et al., 2009). ISAM includes detailed representation of nitrogen dynamics and secondary forest dynamics (Yang et al., 2010). The carbon cycle feedbacks modeled includes the influence of: (1) increasing atmospheric [CO_2] on Net Primary Productivity (NPP), (2) temperature and precipitation changes on photosynthesis, autotrophic and heterotrophic respiration, and (3) nitrogen deposition on carbon uptake by plants. The modeled nitrogen cycle accounts for major processes such as denitrification, mineralization, immobilization, nitrification, leaching, symbiotic, and non-symbiotic biological nitrogen fixation. Results from ISAM have been a part of the global carbon budget (Le Quéré et al., 2015), and several IPCC Assessment Reports, including the most recent Fifth Assessment Report (Ciais et al., 2013).

Model forcing data

The basis of our study is driving data and climate model output from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for future RCP scenarios of land-use change and fossil fuel emissions. The products for each RCP include gridded estimates of LULUC, and atmospheric emissions and concentrations of GHGs for the future that connect smoothly with historical estimates/observations. Coordinated experiments, carried out by more than 20 modeling group from around the world used these data products for conducting a range of climate modeling experiments that includes projecting future climate change patterns. The RCPs have been extensively discussed in literature (Moss et al., 2010). Data for atmospheric [CO_2] is as per CMIP5 experiments (Meinshausen et al., 2011). Gridded estimates of airborne nitrogen deposition are from Lamarque et al. (2011). Climate data for the historical period is from CRU TS3.21 (Harris et al., 2014). To account for the climate uncertainties for the RCPs (2006-2100), we use climate projections from a suite of 43 climate models from the CMIP5 multi-model ensemble database. We prescribed LULUC data from the land-use harmonization (LUH) database used for CMIP5 (Hurtt et al., 2011). The data covers the period 1500-2100 annually and at 0.5°x0.5° lat/lon resolution.

Discussion

Historical emissions

Globally, the total LULUC emissions averaged across the three LULUC reconstructions were 163 PgC (range: 156-174 PgC) cumulated over the 20th century (all numbers discussed include nitrogen limitation effect, unless explicitly noted). The total LULUC emissions are about 58-65% of fossil fuel emissions, and 37-40% of total carbon emissions over the 20th century. Most of the historical total LULUC emissions were direct emissions. The indirect emissions averaged across the three reconstructions were close to zero (-22 to 21 PgC), because of partly offsetting environmental effects. For example, enhanced carbon sinks in regrowing forests under increasing [CO_2], also leads to higher emissions when harvested.

Regionally, the non-tropics accounted for about two-thirds (52-71%) of cumulative 20th century total LULUC emissions. The total LULUC emissions from non-tropics are greater mainly because: (1) nitrogen limitation in the non-tropics reduced the carbon uptake rates on regrowing secondary forests, and (2) historically, two-thirds of global secondary forest area resulting from wood harvest is from the non-tropics. The area deforested for agricultural expansion was similar for both the tropics and the non-tropics for the 20th century, when averaged across the three reconstructions. Therefore, 20th century total emissions from land-use change only are comparable between the tropics and non-tropics.

Future emissions

Both globally and regionally, the total LULUC emissions estimated across the four RCPs are smaller or comparable to 20th century mean estimates. Globally, the direct LULUC emissions due to human activity estimated across the RCPs are a smaller source to the atmosphere by 40-80% compared to 20th century estimates. In contrast, the indirect LULUC emissions due to human environmental change are a much larger source to the atmosphere compared to 20th century, making the total LULUC emissions much larger than when considering direct emissions alone.

In general, across all the RCPs, the net deforestation rates are significantly lower compared to the 20th century resulting in smaller direct emissions. Further, large amount of cropland and pastureland expansion that occurred in the 20th century, are being abandoned in the future (RCP 4.5 and RCP6.0) due to land protection policies. Specifically, forest expansion in RCP4.5 is due to carbon taxation policies that encourage protection of forests. The higher emissions in the 20th century from land clearing are partly offset in the future under RCP4.5 and RCP6.0 because of carbon accumulation in forests regrowing on abandoned land. This resulted in negative direct emissions from land-use change (sinks) for RCP4.5 globally, and for both RCP4.5 and RCP6.0 in the tropics.

In contrast to land-use change, direct emissions from wood harvest are equal to or larger than the 20th century estimates across all the RCPs (excluding one outlier RCP6.0 elaborated in discussion section), especially in the non-tropics. This is because the RCPs project a 380-1080% global rise in wood harvest rates compared to 20th century due to rapid increase in demand for bioenergy and wood products. The higher wood harvest results in more regrowing forests that become increasingly nitrogen limited due to the mechanisms explained in previous section (excluding [CO_2] down-regulation that is an indirect effect). Thus emissions become much greater compared to slower and smaller sinks in regrowth plus temporary sinks in product pools. As a result, the wood harvest contribution to direct LULUC emissions increase in the future, especially in the already nitrogen limited non-tropics. The higher rates of wood harvest also result in higher direct (and total) LULUC emissions in the non-tropics than in the tropics during the 21st century.

Conclusions

Our analysis offers insight into complex interactions among CO_2 emissions from LULUC, environmental changes, and nitrogen limitation effect on the regrowth sinks. There are three key conclusions from our modeling study.

First, nitrogen limitation of CO_2 uptake is substantial and sensitive to nitrogen inputs. In our model, excluding nitrogen limitation underestimated global total LULUC emissions by 34-52 PgC (~21-29%) during the 20th century and by 128-187 PgC (90-150%) during the 21st century. Without large amounts of nitrogen input to the system, the regrowing forests are likely to be nitrogen limited. To meet the same mitigation target despite larger total LULUC emissions would require an equivalent greater reduction of fossil fuel emissions.

Second, including nitrogen limitation flips the total LULUC emissions from the non-tropics to become greater than the tropics. This result is contrary to our total LULUC emissions estimated without nitrogen limitation, and also earlier studies that considered only the interactive effects of CO_2 and climate. Total LULUC emissions from the non-tropics are greater mainly because the carbon uptake capacity of secondary forests resulting mainly from wood harvest is limited by nitrogen deficiency.

Third, when nitrogen limitation is included, future LULUC emissions are sensitive to its definition i.e. if indirect LULUC emissions are included or not. We find that indirect LULUC emissions for the 21st century are a much larger source to the atmosphere when nitrogen limitation is included. This is because of the gradual weakening of the photosynthetic response to elevated [CO_2] caused by nitrogen limitation. For the purpose of this study, we separately accounted for the effects of nitrogen limitation in both direct and indirect LULUC emissions. In principle, the nitrogen limitation effects are also an indirect effect of anthropogenic activity due to environmental change impacts on natural plant processes, hence can be fully counted within indirect emissions.

While interpreting our results, the limitations highlighted earlier should be kept in mind. Notably, using one land-surface model is potentially a limiting factor because it does not represent a broad range of model physics response, especially given that there are significant uncertainties in modeling both nitrogen and carbon cycles, LULUC activities considered, and even the method of implementing a given LULUC dataset across biosphere models. Conversely, using a single land-surface model is more appropriate for our analysis because we can consistently isolate the effects on LULUC emissions due to different LULUC activities, LULUC flux definitions, historical LULUC forcings, and future climate forcings. The above effects cannot be consistently isolated using multi-model comparisons because model-based differences (e.g. different land cover representations) make attribution difficult.

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