Land use effects on terrestrial carbon sources and sinks

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Abstract Current and past land use practices are critical in determining the distribution and size of global terrestrial carbon (C) sources and sinks. Although fossil fuel emissions dominate the anthropogenic perturbation of the global C cycle, land use still drives the largest portion of anthropogenic emissions in a number of tropical regions of Asia. The size of the emission flux owing to land use change is still the biggest uncertainty in the global C budget. The Intergovernmental Panel on Climate Change (IPCC) reported a flux term of 1.7 PgC • a^{-1} for 1990—1995 but more recent estimates suggest the magnitude of this source may be only of 0.96 PgC • a^{-1} for the 1990s. In addition, current and past land use practices are now thought to contribute to a large degree to the northern hemisphere terrestrial sink, and are the dominant driver for some regional sinks. However, mechanisms other than land use change need to be invoked in order to explain the inferred C sink in the tropics. Potential candidates are the carbon dioxide (CO_2) fertilization and climate change; fertilization due to nitrogen (N) deposition is believed to be small or nil. Although the potential for managing C sinks is limited, improved land use management and new land uses such as reforestation and biomass fuel cropping, can further enhance current terrestrial C sinks. Best management practices in agriculture alone could sequester 0.4—0.8 PgC per year in soils if implemented globally. New methodologies to ensure verification and permanency of C sequestration need to be developed.

Keywords: land use, terrestrial carbon, carbon emissions, sink mechanisms.

Atmospheric CO_2 concentration has departed from the narrow window of 180 to 280 ppm to the current 370 ppm for the first time in 420000 years[1]. There is absolute certainty that this departure is being driven by human activities that result in CO_2 emissions from fossil fuel combustion, land use change and cement production[2].

Concerns about the effects of the radiative forcing of CO_2 and other human driven greenhouse gas emissions on the climate system has brought the United Nations, under the Framework Convention on Climate Change and associated Kyoto Protocol, to initiate what has become the most complex international negotiation ever on a single environmental issue: human induced changes on climate patterns and variability.

A second concern is the potential effect of altered climate and atmospheric composition on terrestrial and aquatic ecosystems, and particularly on ecosystem services such as net primary production and water quality and quantity which human societies rely upon for their welfare and development.

Land use/cover type is an important control of C storage, and shifts from one type to another are responsible for large C fluxes in and out of the terrestrial biosphere. Historically, land use emissions have been responsible for a large portion of the cumulative human induced CO_2 emissions. Globally, land use C emissions are no longer dominating the human perturbation of the C cycle, but they are still dominant in many parts of the world particularly in the humid tropics. In addition, current land use change and the legacy of past practices (clearing followed by abandonment and regrowth) are now believed to contribute to a large extent to the current Northern Hemisphere terrestrial C sink of about 1.4 PgC • a^{-1}[3]. This new understanding brings a number of opportunities for steering the future dynamics of the global C cycle and associated impacts.

This paper will synthesize the state-of-the-art understanding of (i) the contribution of land use change to anthropogenic emissions of CO_2, with specific references to the Asia Pacific region, (ii) the effects of current and past land use change as drivers of C sinks, and the potential for further enhancement of terrestrial C sinks, and (iii) new international research efforts to study the C cycle in a new interdisciplinary and multiple-constraint framework.

1 Land use change effects on carbon sources

1.1 Historical land use/cover change

Historically, between 32.5 and 34.7×10^6 km^2 have been converted from natural vegetation, approximately 10% of the total land surface[4]. Since 1700 there has been a net loss of 11.4×10^6 km^2 of forests and woodlands to cropland, and 6.7×10^6 km^2 of savannas, grasslands, and steppes to cropland[5].

Given the complex political and economic history of the Asia Pacific region, land cover conversion and associated C emissions have varied spatially and temporally. More than 10000 years ago cropland started encroaching upon native vegetation along the Yellow River in China, while it has not been until the last century that emissions from the Asian tropical region have become significant at a global scale.

Recent deforestation estimates detected by satellite for the humid tropical regions show that $(5.8\pm1.4)\times10^6$ ha have been deforested annually between 1990 and 1997, and additional $(2.3\pm0.7)\times10^6$ ha of forest were annually degraded[6]. In this analysis, Southeast Asia had the highest deforestation rate followed by Latin America and Africa. However, given the large extension of tropical forest in Latin America, the annual loss of forest areas in Latin America and Southeast Asia were similar. Surprisingly, this new global estimate of deforestation in the humid tropics was 23% smaller than the one estimated by the Food and Agriculture Organization. This is an important result as it influences the calculations of the magnitude of C emissions and the inferred tropical sink.

There are land uses that are not necessarily detected by satellite techniques and that result in forest impoverishment. These are activities that may not change the land cover type. For instance, there are regions in Amazonia where only one tenth of the area classified as forest by the Brazilian authorities supports undisturbed forest[7]. The reason for this inconsistency is due to the unaccounted selective logging and surface fires which was only revealed after a thorough ground validation. C emissions due to these disturbances could double estimates of C emissions in the region if only deforestation were accounted.

1.2 Carbon emissions

The cumulative anthropogenic C emissions over the last two centuries are 180—200 PgC from land use change[4], largely from deforestation, and 280 PgC from fossil fuel emissions[8]. Between 1850 and 1890, 60% of the emissions from land use change came from tropical areas and 40% from temperate areas[9,10]. However, during the decade of the 1990s almost all land use change emissions came from tropical regions.

Overall, changes in land use and cover since 1850 are responsible for 33% of the increased in CO_2 concentrations observed in the atmosphere[11], 68% of which were due to permanent cropland establishment[9].

For the 1990s C budget, CO_2 emissions from land use change account for 10%—30% of the total anthropogenic C[12]. Fossil fuel emissions are 6.3 ± 0.4 PgC • a^{-1} and the wide range of estimates for land use emissions are largely associated with uncertainty on deforestation rates.

For the period of 1990 to 1995, estimates of CO_2 emissions from land use change are 1.6 PgC • a^{-1}, consisting of 1.7 in the tropics and a 0.1 sink in temperate and boreal areas[10]. Other analyses using four terrestrial process models estimate global land use change emissions between 0.6 and 1.0 PgC • a^{-1}[13]. Most recently, satellite-based analyses estimate a maximum global net emission from land use change in the humid tropics of 0.96 PgC • a^{-1}[6]. Notice that this figure does not include loss of C from certain types of forest degradation.

Current fossil fuel and land conversion emissions in tropical Asia total 1.8 PgC • a^{-1} made up equally by emissions from fossil fuel and land conversion. In contrast, total emissions from China of 1.0 PgC • a^{-1} are almost exclusively dominated by fossil fuel combustion[14].

Carbon losses due to land use change become especially critical when they deplete the soil stocks, which are slowly replenished. A meta-analysis of 74 studies revealed that conversion from grassland to cropland resulted in the largest loss of soil C (59%) followed by conversation of native forest to crops (42%)[15]. The same dataset suggest that some land use changes have impacts that may have not been intuitive a priori. For instance, pine plantations replacing native forest or pasture reduced soil C stocks by 12%—15%, a result far much less expected than other land conversions.

1.3 Future projections

Future projections of land use/cover change will affect predictions of atmospheric CO_2 concentration. Scenario studies indicate that due to the increasing population, increased consumption, and apparent shifts in diets, either land must become more productive or agricultural area has to expand. In most regions agricultural intensification will not be sufficient to cope with the shift in demands from a growing world population, particularly in the less developed countries where technology or capital may not be available for intensification. Major changes in land cover are forecasted as a result of conversion to agriculture in subtropical and tropical Africa and in Asia[16,17]. Using the UN intermediate population estimates adopted by the IPCC[18], about one-third of the Earth's land cover will change in the next hundred years, with the largest changes expected within the next three decades[19]. Only in the temperate developed world is it expected that total agricultural area will contract. Global forest area will decrease because grasslands and croplands expand. An additional feature of several scenario studies is that new land uses emerge (e.g., biomass for energy).

Using the new IPCC emission scenarios[20] IMAGE calculated atmospheric concentrations for 2100 ranging from 714 to 1009 ppm[21]. These concentrations are higher than the ones reported in the SRES because this particular experiment allowed for a full suite of interactions between climate, vegetation, and anthropogenic emissions.

Accuracy of the land use emission term in the global C balance is important as it is a key factor in calculating the size and distribution of terrestrial C sinks. The Northern Hemisphere temperate sink is relatively well constrained, but atmospheric inverse calculations find no net C sink over the tropics or a small C source[3,22]. If the former is true and tropical C emissions from deforestation are between 1.0 and 1.6 $PgC \cdot a^{-1}$ as reported above, then a large biological sink of similar magnitude is inferred in order to counteract the emissions from deforestation. If the deforestation term changes so does the sink size. Size and distribution of the terrestrial sinks are the first step towards understanding the underlying driving mechanisms and the likely future dynamics of the terrestrial C sink in response to global warming.

2 Land use change effects on C sinks

2.1 Sink mechanisms

Despite increasing certainty about the spatial patterns and variability of the terrestrial C sink, there is still limited understanding about the magnitude and contribution of different processes. There are multiple candidate mechanisms that could explain the observed sinks although it is likely that multiple mechanisms will need to be invoked in order to fully explain them. Clear candidate mechanisms are the fertilization effect of increasing atmospheric CO_2 and N deposition, climate change, regrowth of previously abandoned croplands, woody encroachment, regrowth of previously disturbed forest (e.g., after fire, harvest), fire suppression, decreased deforestation, improved agricultural techniques, and sediment burial. Seven of the ten mechanisms mentioned above are related to current or past land practices. Although the degree to which these human actions drive the current C sinks still needs further study, the large number of mechanisms show the multiplicity of entry points for human intervention into the C cycle in order to steer the future of terrestrial C sinks.

The most comprehensive study on sink attribution at a regional scale is that on the US sink of

0.37—0.71 PgC • a^{-1} for the period 1980—1989[23]. Surprisingly, only half of the sink was associated with the country's forests, with another 20% combined sink due to wood products and C buried in reservoirs, alluvium, and colluvium. Only a quarter of the total sink (forest trees) is subject to the potential enhancement by the effects of CO_2 and N fertilization which before were thought to be the primary mechanisms driving terrestrial sinks. In fact, a partial analysis of the US sink focusing on 5 eastern states showed that 98% of the sink was due to land use history, largely due to forest regrowth after crop abandonment, reduced harvesting, and fire suppression[24]. Only the remaining 2% of the sink was due to CO_2 and N fertilization, and climate change.

Crop abandonment and subsequent regrowth is also observed in Eurasia, although to a lesser extent than in the US, followed by some countries in South America and Africa[5]. Globally since 1850, 1.5 million km^2 of cropland in previously forested areas has been abandoned, and 0.6 million km^2 in areas previously occupied by savannas, grasslands, and steppes. In most cases the process of regrowth after abandonment offers the possibility for increased C sequestration.

Contrary to the temperate and boreal world, land use change in the tropics is largely contributing to C emissions and not processes that lead to C uptake. Therefore, if the inferred tropical sink is confirmed, CO_2 fertilization and climate change are likely to drive the sink[25]. Anthropogenic inputs of N into tropical forests, which are not N-deficient, are unlikely to increase productivity[26].

Lateral C fluxes are also crucial in the balance of regional C budgets and have been suggested as important contributors to the observed biospheric sink. For instance, surface erosion due to intensification and extensification of land use is contributing to the 20 Pg • a^{-1} of bulk sediment transported in the world's rivers[27]. Of this sediment, 1.5 Pg • a^{-1} is organic C from which up to 1.0 PgC • a^{-1} could be stored in large water catchment impoundments[28]. This carbon was earlier believed to be largely oxidized during transport and in coastal zones.

2.2 Managing the terrestrial C cycle

There exist a number of land use practices that could play an important role in managing the distribution and magnitude of terrestrial C sinks with the goal of increasing net C uptake.

In recognition of this potential, the Kyoto Protocol under the UN Framework Convention on Climate Change is allowing developed countries signatories of the Protocol to use both increased C sequestration and reduced fossil fuel emissions in order to meet their target emission reductions.

The first commitment period (2008—2012) will be of relatively small assistance to the slow down of atmospheric CO_2 build up, with an estimated savings of 5 ppm by 2010[29] or about 0.6 PgC • a^{-1}[30] if the Kyoto Protocol is fully enforced. However, it is expected that during this first period participant countries will build the technical capacity and systems with the appropriate verification (detection in increased C pools) and permanency (increased C pools will remain on land) to fully explore the use of land sinks to assist in stabilizing CO_2 concentrations.

The IPCC special report on "Land use, land use-change, and forestry" identifies a large number of land uses that can lead to increased C sequestration[31]. Sequestration is achieved either by increasing C uptake (e.g., reforestation) or by reducing C loss (e.g., no tillage agriculture). For instances, agricultural best management practices have been estimated to offer the potential to restore some of the worldwide loss of soil C. If best management practices could be implemented at the global scale, 0.4—0.8 PgC could be sequestered in agricultural soils each year, corresponding to an increase of 40—80 PgC over 100 years[32].

In the humid tropics, maximum potential in C sequestration will be achieved by focusing on increasing above-ground biomass as opposed to soil C given the smaller pool and fast turnover time of the latter. A number of techniques alternative to slash-and-burn have been also proposed to minimize C emissions from forest conversion[33].

In addition to changes in agricultural management, practices that could lead to C sequestration in terrestrial ecosystems include the creation of biomass cropland, grassland, rangeland and forest, the protection and creation of wetlands and urban forest/grass land, the manipulation of deserts and degraded lands and the protection of sediments, aquatic systems, tundra and taiga[34]. Over a 50 year time period, the total terrestrial C sequestration potential including all of these activities is estimated to be 5.7—8.7 PgC • a^{-1}, roughly 10 times the C sequestration potential of agricultural land alone.

To assess the potential impacts of all land use and forestry activities on C sinks is difficult, let alone the complex institutional requirements that would be needed for those activities to be implemented. However, an estimate of the maximum potential impact that reforestation could have on atmospheric CO_2 concentrations can be calculated by subtracting the historical C emissions owed to deforestation (180—200 PgC)[4] from the current atmospheric C storage. That is, the scenario that all cropland returns to native vegetation. The effect then would be a reduction of 70 ppm in the atmospheric CO_2 concentration[12], a totally unrealistic scenario. However, one could imagine a high intensive agriculture scenario for 2100 that only takes half of the current cropland, and thus removing 45 ppm from current estimates of 540 ppm to 970 ppm for the end of this century[20].

3 International efforts on integrative carbon research

The challenge to the scientific community is to monitor, understand and predict the evolution of the carbon cycle in the context of the whole Earth system, including its human components. This demands new scientific approaches and syntheses that cross both disciplinary and geographic boundaries, with particular emphasis on the carbon cycle as an integral part of the human-environment system.

There are two major coordinated efforts to further promote integrative research on the carbon cycle. The first effort is the new research agenda being developed by the Global Change and Terrestrial Ecosystems (GCTE) core project of the International Geosphere-Biosphere Programme

(IGBP) and Land Use/Cover Change (LUCC) core project of IGBP and the International Human Dimensions Programme (IHDP). The research agenda is not yet fully developed but information will be posted at:

http://www.gcte.org

http://www.geo.ucl.ac.be/LUCC/lucc.html

The second effort is the newly established Global Carbon Project (GCP) by three sponsor programs: IGBP, IHDP and the World Climate Research Programme (WCRP). The GCP's goal is to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them. The three science themes of the GCP are:

1. Patterns and Variability: the current geographical and temporal distributions of the major stores and fluxes in the global carbon cycle;

2. Processes, Controls and Interactions: the underlying mechanisms and feedbacks that control the dynamics of the global carbon cycle, including interactions with human activities;

3. Future Dynamics of the Carbon Cycle: the range of plausible trajectories for the dynamics of the global carbon cycle into the future.

The science goals will be achieved with the following implementation strategies:

● To develop a research framework for integration of the biogeochemical, biophysical and human components of the global carbon cycle, including the development of data-model fusion schemes, and design of cost effective observational and research networks.

● To synthesize current understanding of the global C cycle and provide rapid feedback to the research and policy communities, and general public.

● To develop tools and conceptual frameworks to couple the biophysical and human dimensions of the carbon cycle.

● To provide a global coordinating platform for regional/national carbon programs to improve observation network design, data standards, information and tools transfer, and timing of campaigns and process-based experiments.

● To strengthen the broad carbon research programs of nations and regions, and those of more disciplinary projects in IGBP, IHDP, WCRP, and operational observing programs (IGCO, GTOS) through better coordination, articulation of goals, and development of conceptual frameworks.

● To develop a small number of new research initiatives that are feasible within a 3—5 year time framework on difficult and highly interdisciplinary problems of the carbon cycle.

● To foster new carbon research in regions (e.g., tropical Asia) that will provide better constrains of continental and global carbon budgets through promoting partnerships between institutions and exchange visits.

Further information can be found at: http: //www.globalcarbonproject.org.

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