TERRESTRAIL ECOSYSTEM MANAGEMENT FOR CLIMATE CHANGE MITIGATION[1]

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Introduction

Six out of the nine global planetary boundaries defining the safe operating space of the Earth system [1] are directly connected to the management of terrestrial ecosystems. These six land-use-related planetary boundaries are the regulation of greenhouse gases, rate of biodiversity loss; interference with both nitrogen and phosphorus cycles; global freshwater use and change in land use. Concerning the latter, tropical deforestation and degradation is considered the second largest source of anthropogenic greenhouse gas emissions [2], while the northern extra tropical belt is considered to be a net carbon sink. Responsible management of terrestrial carbon stocks and fluxes, thus, appears as a precondition for global environmental security. Mitigation scenarios such as those from IIASA's Integrated Assessment Modeling Framework project that the agricultural sector might become the single largest emission sector [3] by 2050. Contrarily, large amounts of bioenergy, eradication of deforestation and substantial efforts increasing forest area and increasing forest biomass density are required to reduce the pressures towards the climate planetary boundaries. All of these terrestrial mitigation measures induce competition for land. There are considerable trade-offs between different mitigation measures which are rarely assessed in combination. The currently most active controversy over indirect land use emissions from biofuels [4] serves as a good illustration. Apart from these interactions between terrestrial climate mitigation sectors there are also strong linkages to food security as well as energy security, which recently have become a concern in major food exporting countries. Food and energy supplies are geopolitical assets. The confluence of these three multifaceted security issues, environment-food-energy security, makes the question of terrestrial ecosystem management to one of the most challenging governance problems in the 21st century.

The main rational behind this article is to assess design options for climate effective, cost efficient and equitable terrestrial ecosystem management solutions. We review the current understanding (past two years) of single mitigation measures as well as their interaction in terms of trade-offs and synergies. The political feasibility and economic efficiency of terrestrial mitigation strongly depend on both the internal interaction between different mitigation measures and their interaction with other ecosystem or strategic values of land. This double interaction term makes good governance of terrestrial ecosystem management key for effective implementation.

There are two principal pathways of mitigating climate change by terrestrial ecosystem management: (A) improve the greenhouse gas (GHG) balance within the biosphere and (B) manage for biomass production to substitute emissions from fossil fuels and sequester bio-carbon containing materials/substances outside the biosphere. Figure 1 illustrates that both strategies have different aims. While (A) aims at maximizing carbon stocks in the biosphere option (B) would maximize efficiency of energy and material production compared to a fossil fuel reference case. Moreover, both strategies are not independent. Biomass utilization interferes with biosphere GHG management and vice versa. Both are also influenced by factors outside the sector.

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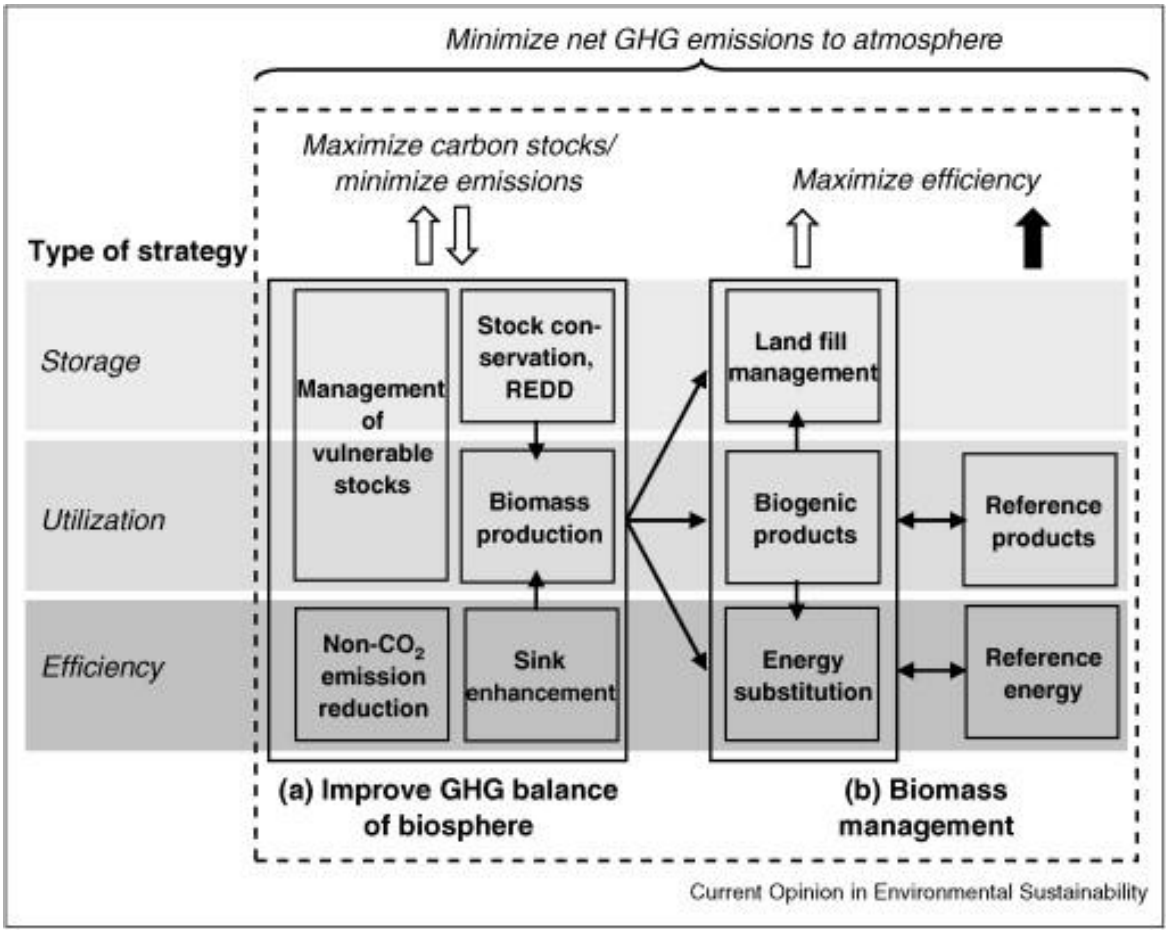

Figure 1. Overview of principal pathways and strategies of ecosystem management for climate change mitigation.

Improve the GHG Balance

Improving GHG balance by managing terrestrial ecosystems involves the generation of a GHG gain compared to a baseline. Avoided emissions from deforestation, agriculture or impacted vulnerable carbon stocks are about decreasing emissions while enhancing sinks involves making an existing sink even stronger compared to a baseline trajectory.

Avoided Emissions From Deforestation and Degradation

Emissions from deforestation are considered to be a main source of some 20% of the world's anthropogenic green house gas emissions. The global net carbon flux resulting from land use changes during the 1990s, is rather uncertain and has been estimated to be between 0.5 and 2.7 Gt C yr^{-1} [5]. A number of questions remain to be answered in negotiating a workable international architecture addressing deforestation and degradation in a post-Kyoto agreement. These issues include: (1) providing sufficient financial resources; (2) procedures for setting reference levels against which efforts can be benchmarked; (3) methodologies for monitoring, reporting, and verification; and (4) processes to promote the participation of indigenous peoples and local communities [6]. The financial needs for reduced emissions from deforestation and degradation (REDD) readiness and implementation were estimated to range between USD 15 and USD 35 billion per year for a 50 percent global reduction in forest emissions, while funds currently available are around USD 2 billion [7]. These costs also crucially depend on how national baseline emissions from deforestation are determined. Griscom *et al.* [8••] find that depending on the baseline approach currently suggested, the total credited emissions avoided ranged over two orders of magnitude for the same quantity of actual emission reductions. Transaction costs are relatively low for Monitoring, Reporting, Verification (MRV) [9]. However, they might turn out to be prohibitive if participatory processes are poorly designed.

Reduce Non-CO_2 Emissions in the Agricultural Sector

Significant mitigation potential could be provided by water and rice management, set-aside, land use change and agroforestry, livestock management and manure management [10]. Large potentials for GHG reduction are associated with livestock management (accounting for 80% of total anthropogenic land use and 18% of GHG emissions). Dietary changes, rumen fermentation modifiers, as well as improvements in forage quality may allow for further reductions in methane emissions in particular from cattle. In addition to these efficiency measures, reduced consumption of livestock products has significant potential not only for methane and nitrous oxide mitigation but also for reducing land use change emissions [11]. It has been identified that the global population of small-holder farmers should be the first target for policies to intensify production in mixed system [12•]. However, at least in the short run, a chronic lack of functioning institutions appears as the major hindering block to adequate investment and subsequent induced technological change in this sector.

Sink Enhancement

There seems to be a huge theoretical potential for carbon storage through increasing forest area, establishment of forest management systems which are guided by close-to-nature principles effectively increasing forest carbon density, and refilling depleted soil carbon reservoirs. Agricultural practices like improved cropland and grazing land management and restoration of degraded lands and cultivated organic soils have potential for mitigation [10]. In general the presence of management leads to a depletion of soil organic carbon [13]. Activities leading to high rates of carbon accumulation in the soil are no-till farming, crop residue retention as mulch, growing cover crops in the rotation cycle and adopting complex farming systems including agroforestry, and afforestation of degraded soils [13]. Restoring degraded soils and ecosystems is a strategy with multiple benefits for water quality, biomass productivity and for reducing net CO_2 emissions. Formation of charcoal and biochar amendment to the soil is another option. Biochar use increases soil carbon and enhances soil fertility [[14] and [15]].

Options in forestry for sink enhancement include creating new forests, changing management of existing forests by changing rotation length, thinning intensity, enhancing biomass growth, through choice of tree species and treatment of harvest residues or through protection from disturbances. Through these measures, forest management can introduce new and enhance existing sinks, affecting the biomass (above and belowground), litter, dead wood, and soil organic matter. Biomass C is the pool most directly affected by land management while effects on soil carbon are indirect (e.g. through changed litter input [16]) and often delayed (e.g. afforestation of grasslands [17]). Especially with respect to allocation of C in plant and soil more research on processes is needed, for example, through more sophisticated system science approaches to plant and microbial biology [18].

Estimates of the global area that is suitable and available for increasing forest area amounts between 300 and 1000 Mha. The potentials vary inter alia with assumptions on land quality, demand for agricultural land, policy interventions such as subsidies and commodity prices [[19], [20] and [21]]. To make carbon sequestration in ecosystems more effective globally, environmental constraints and their expected changes in the future should be taken into account. There have been suggestions of a framework for identifying forests of high potential for carbon storage using criteria like relatively cool temperatures and moderately high precipitation producing rates of fast growth but slow decomposition [22]. The risk of natural disturbance should be added to such a framework.

Existing forests in the northern hemisphere are currently a sink for CO_2 from the atmosphere, partly due to regrowth [[23] and [24]], and elevated CO_2 and nitrogen deposition [25]. There appears to be evidence for old growth forests being global carbon sinks [26]. According the Kyoto Protocol such effects would have to be treated as 'indirect human induced', meaning that forest regrowth after past intensive harvest cannot be accounted for as climate mitigation. Sink enhancement against a business as usual management would require for example the extension of rotation lengths and change in thinning regimes and residue treatment in forest management. Scientific methods exist to factor out directly such human-induced effects against natural and indirect effects with the help of models [[27] and [28]]. Such a partial accounting would allow for a better market integration by increasing the incentives for improved GHG management and by reducing the variability of fluxes that are accounted towards the overall national emission target. However, such a proposal ignores large fluxes of GHG associated with large-scale disturbances that the atmosphere actually 'sees'.

Managing Vulnerable Carbon Stocks Under Climate Change

Existing carbon stocks can be affected by climate change. There are still large knowledge gaps in the understanding, prediction and management of vulnerable carbon stocks. Forest carbon modelers included uncertainties in their models [29••] and found that the risk of natural disturbances in Canada's forests (dominated by insect infestation and fire [30]) makes future contribution to the global carbon cycle highly uncertain. Moreover, the projection of large-scale biospheric instabilities (see Friedlingstein and Prentice, this issue) as a combination of direct human impact (degradation) and climate changes [[31] and [32]] will require an adaptive and anticipative disturbance management to limit carbon efflux from affected ecosystems. To efficiently manage vulnerable carbon stocks an accounting of improved GHG management is a precondition to provide incentives for positive management change. Furthermore, the issues related to the financing and ex ante capacity building for resilience increasing, direct intervention and recovery measures in natural ecosystems are far from being solved today mainly due to ignorance about possible future consequences and the inherent unpredictability of major emission events from terrestrial carbon stocks.

Biomass Production

Large amounts of biomass are already appropriated by humans and thus biomass use already constitutes a large human impact on the earth system. Additional use of biomass for energy generation will not only lead to increased interference with the terrestrial biosphere, but also contribute to significant climate mitigation. Controversies on these issues have dominated recent discussion on the use and potential biomass for energy purposes.

Manage Biomass Products and Biogenic Waste Streams

Wood products and biomaterials form a carbon pool that can be managed. The use of biomass (e.g. wood in construction) can lead to the substitution of more GHG-intensive materials and energy production. Given a large number of important parameters such as country-specific product flows of wood products and their alternative products that have to be considered, an assessment is most reasonable on a national basis [33]. However, transnational trade of harvested wood products causes a displacement of carbon stock changes and emissions in forests and the pool of products. Various approaches on accounting for HWPs were proposed [[34] and [35]], often resulting in very different numbers for mostly importing or exporting countries. An effective recycling of wood products frees land for long-term sustained C sequestration by conservation, or alternative non-marketable uses, without additional emissions from shifting production or intensification [36].

When biogenic products reach the end of their lifetime there are two options for end use: landfilling or incineration. Both options result in emissions of all or parts of the biogenic carbon; both options can include energy recovery, but differ in their time profile of release. Significant amounts of biogenic carbon may still be stored within the landfill body after 100 years, while landfill gas can be used for electricity generation and reduce landfill emissions [37]. Depending on (a) the biogenic waste composition, (b) the effective binding of biogenic carbon in landfills and (c) the efficient utilization of the energy recovered, the net GHG balances of landfilling and waste incineration can be very similar [38]. Rational biomass management has to take into account the very specific regional conditions when it is targeting efficient GHG emission reduction. Improving the overall GHG balance of biomass use involves an efficient use of the processing chain from the use of by-products to recycling, waste to energy conversion and landfilling in an integrated biomass management [39].

Bypassing the product and recycling chain by wood burial is another sequestration option [40]. The reduced chain would obstruct the wide range of GHG management options involving HWPs and energy substitution. Nevertheless, burial of carbon captured through photosynthesis has potential in a portfolio of other measures to create negative carbon emissions when fossil substitution is no longer necessary in times when energy is produced from zero emission sources only.

Manage Biomass Production to Substitute Fossil Fuel Emissions

The social and environmental net benefits of bioenergy systems depend on their contribution to land use change, direct impacts for producing the feedstock, the conversion technology and scale as well as end use efficiency. Feedstocks that involve the conversion of agricultural area will affect food security [41] and cause indirect land use change [4] across national borders, while those that replace forests, wetland or natural grasslands will worsen the GHG balance [42] and will damage biodiversity. The effect of the GHG balance can be mitigated if biomass sources come from feedstocks which would otherwise have been decomposed and the productivity of a particular field or landscape can be increased.

Large-scale biomass production systems carry the potential to undermine land and labor rights, and inflict on indigenous peoples' territories ignoring their customary rights to the land [43]. On the other hand economies of scale are the dominating factors determining the economic competitiveness of bioenergy systems [44]. However, distributed and smaller scale biomass production can exploit economies of scope when run in polyproduction mode producing power, heat, fuels and chemicals. Also staged conversion systems involving the production of biogas and syngas in small units and subsequent transport in pipelines to refineries allow for cost saving, more rent sharing along the value chain and improved environmental performance compared to centralized production systems and long-distance transport of solid biomass. [45].

The dimension of scale is also related to land requirements of biomass production and the associated land use impacts [46]. Pacca and Moreira [47·] estimate that 70 Mha of sugar cane for energy use, which corresponds to 4.7% of all cultivated land would be enough to mitigate 1 Gt C yr^{-1}. There is still large controversy about methods [48] and the adequacy of the basic land cover and land use data to provide robust estimates of these indirect effects [49].

Nonetheless, the total emissions from bioenergy today are underestimated owing to a carbon accounting error ignoring such indirect effects [[50] and [51]]. EU and US domestic laws do not limit most land-based emissions in the Kyoto Protocol, which means that emissions from the production and use of biomass are treated as carbon neutral. Proper accounting schemes are necessary that provide a fair level playing field between competing renewable energy technologies.

Conclusions

Most of the climate mitigation literature so far has assessed the potential contribution of purposeful management of terrestrial ecosystem management in terms of delivery of carbon neutral biomass for energy production where the overall terrestrial sink was assumed to stay constant over time. Only few studies so far have assessed more comprehensively the interaction of many terrestrial mitigation measures and their competitive interaction. The latter studies do not produce consistent conclusions on how to manage best terrestrial ecosystems [52]. In particular, with respect to the role of bioenergy, which carries the potential to deliver the highest long-run climate benefits, robust insights cannot yet be derived from the literature. This might, in part, be due to the fact that the models underlying these studies differ significantly with respect to basic assumptions. In the future studies will have to be complete along the following dimensions:

- *Space*: Including indirect land use effects by budgeting all land categories to achieve global consistency of local action.
- *Time*: Integrate benefits of measures over time and allow for the probability of innovative new technologies to occur.
- *Sector*: Sector interaction needs to be considered in terms of direct provisioning services such as timber, bioenergy, food and more indirect such as biodiversity, water, cultural heritage. In addition, accounting for market feedback effects such as price increases of agricultural commodities because of bioenergy policy shocks and REDD need to be considered.
- *Technology*: The full chain of GHG emissions from cradle to grave and production systems needs to be assessed with respect to polyproduction. Interaction with the rest of the technosphere and social sphere need to be considered within integrated assessments.

In the search for climate effective, cost efficient and equitable solutions to avoid dangerous interference with the globe's earth system boundaries and its associated socio-economic bounds the global society cannot afford to miss out on the benefits integrated terrestrial ecosystem management could potentially offer. Thus, the current decision paralysis in part caused by ignorance/inconclusiveness on the full impacts of integrated global ecosystem management can no longer be tolerated.

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