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Land-use protection for climate change mitigation

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Land-use change, mainly the conversion of tropical forests to agricultural land, is a massive source of carbon emissions and contributes substantially to global warming[1–3]. Therefore, mechanisms that aim to reduce carbon emissions from deforestation are widely discussed. A central challenge is the avoidance of international carbon leakage if forest conservation is not implemented globally[4]. Here, we show that forest conservation schemes, even if implemented globally, could lead to another type of carbon leakage by driving cropland expansion in non-forested areas that are not subject to forest conservation schemes (non-forest leakage). These areas have a smaller, but still considerable potential to store carbon[5,6]. We show that a global forest policy could reduce carbon emissions by 77 Gt CO_2, but would still allow for decreases in carbon stocks of non-forest land by 96 Gt CO_2 until 2100 due to non-forest leakage effects. Furthermore, abandonment of agricultural land and associated carbon uptake through vegetation regrowth is hampered. Effective mitigation measures thus require financing structures and conservation investments that cover the full range of carbon-rich ecosystems. However, our analysis indicates that greater agricultural productivity increases would be needed to compensate for such restrictions on agricultural expansion.

Driven mainly by the fertilizing effects of increased levels of CO_2 in the atmosphere, the land system has been a terrestrial sink for carbon in recent decades[2]. However, the role of land for sequestering carbon is counteracted, as the carbon emissions from land-use and land-cover change accounted for approximately 12% of all anthropogenic carbon emissions from 1990 to 2010[3]. The future development of forest area is uncertain, but deforestation is projected to persist as a significant emission source in the absence of new forest conservation policies, especially under increasing demand for agricultural commodities. Compared to climate change mitigation options in the energy and transport sector, recent research has indicated low opportunity costs and significant near-term mitigation potential through reducing deforestation, promoting avoided deforestation in tropical countries as a cost-effective mitigation option[7].

Despite the general scientific agreement on environmental benefits of forest conservation, and although the United Nations Framework Convention on Climate Change (UNFCCC) has affirmed the potential role of forests in stabilizing the global climate, no global action has yet emerged to conserve natural forests. Several issues have so far prevented the development of conservation mechanisms supported under the UNFCCC (ref. 8). In particular, the design of financing mechanisms[4], but also environmental and socio-political concerns associated with REDD (Reduced Emissions from Deforestation and Degradation) and its variations are being intensively discussed[9,10]. One key issue for the implementation of REDD is how to address leakage of emissions[11]. Without full participation of all countries in a forest conservation scheme, emission reductions in one location could result in increased emissions elsewhere, as agricultural expansion, the main driver for deforestation, could just be displaced rather than avoided[12].

However, carbon leakage is not only relevant in the context of regionalized forest protection efforts. Another risk associated with a global REDD scheme that so far has not been quantified in the literature is the shift of land-use pressures to non-forest ecosystems (non-forest leakage) simply because they are the only remaining resource for agricultural expansion[13]. Such ecosystems may also be rich in carbon. First, areas under natural vegetation other than forests, such as shrublands and savannas, can also store considerable amounts of aboveground carbon, especially in Africa, but also in Latin America and Asia[6]. Second, carbon-rich soils also play a major part in the terrestrial carbon balance and have to be taken into consideration[5,14]. Grasslands and pastures, unlike cropland, maintain a permanent vegetation cover and, therefore, have a high root turnover, leading to substantial soil organic carbon storage[15]. For this reason, carbon stocks decline strongly after land is converted from grasslands and pastures to cropland[5]. Finally, agricultural activity can reduce carbon sequestration by preventing regrowth of natural vegetation on abandoned agricultural land[16].

In contrast to the current political discussion, which focuses only on REDD implementation, recent global modelling assessments have focused on the implementation of a global terrestrial carbon policy covering all regions and land types[17,18]. To avoid the negative consequences of a global forest conservation policy, a profound understanding of potential implementation failures, such as leakage into land types other than forests, is needed.

Here, we estimate land-use and associated carbon dynamics for different global terrestrial carbon policies at global and regional scale using the land-use optimization model MAgPIE (Model of Agricultural Production and its Impacts on the Environment—see Methods)[19]. Biophysical inputs for MAgPIE, such as agricultural yields, carbon densities and water availability, are derived from a dynamic global vegetation, hydrology and crop growth model, the Lund–Potsdam–Jena model for managed Land (LPJmL; refs 20,21). LPJmL provides the climate- and CO_2-driven changes in carbon densities, agricultural productivity and water availability of a 2 °C scenario (RCP2.6) to drive MAgPIE simulations. For this study, we assume ambitious mitigation policies with different contributions of the land-use sector in three scenarios: no terrestrial carbon policy in the reference scenario (Ref); a global terrestrial land-use policy that considers carbon emissions from deforestation

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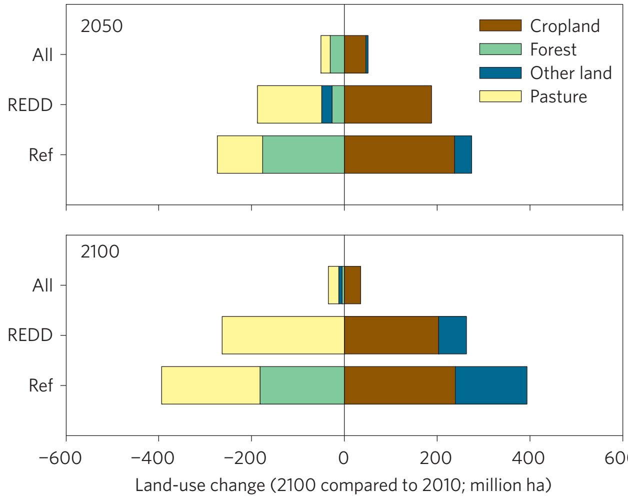

Figure 1 | Change in global land pools. The upper figure shows changes from 2010 to 2050 and the lower figure changes from 2010 to 2100 for the reference case (Ref) without land-use mitigation, a terrestrial land-use policy that considers carbon emissions from deforestation only (REDD) and a terrestrial carbon policy that accounts for emissions from all land types (All).

only in the REDD scenario; a global terrestrial carbon policy introduced by a universal carbon tax on greenhouse gas emissions from all terrestrial systems in the All scenario. To account for uncertainty in climate projections, we compute changes in carbon densities, agricultural productivity and water availability for the implementation of the RCP2.6 scenario in five different global circulation models (GCMs). We generally report mean values across all GCMs, while single GCM outputs and standard deviations can be found in Supplementary Table 1. In addition to the default scenarios with different GCM inputs, we perform sensitivity analyses with crucial exogenous parameters (demand for agricultural products, costs for agricultural yield increases and tax on terrestrial carbon emissions) to test the stability of our results in terms of cumulative carbon emissions (see sensitivity analysis in the Supplementary Information). It is important to note that the land-use model not only embraces the calculation of emissions from deforestation and other land-use change, but also the uptake of carbon from regrowth of secondary natural vegetation on abandoned agricultural land and carbon dynamics driven by climate change and CO_2 fertilization. In contrast to the mitigation of carbon emissions from land-use change, carbon uptake is not rewarded financially in our scenarios, as we focus in this study on protection policies. The MAgPIE model has been validated intensively for land-use, agricultural yield and land carbon dynamics and reproduces historical trends well (see also the validation section in the Supplementary Information). In addition, the ability of LPJmL to simulate global terrestrial carbon dynamics has been demonstrated in several previous studies[21,22].

Our reference scenario (Ref) without any terrestrial carbon policy is parameterized according to the 'SSP2' storyline of the shared socio-economic pathways[23] (see more detail in Methods). Our model results show that agricultural production increases are mainly realized by intensification on existing agricultural land (Supplementary Fig. 1) as well as by agricultural land expansion. In 2010, global cropland area was 1,454 million ha, pasture land area 3,079 million ha, global forest area 4,144 million ha and global other land area 4,229 million ha (see also Supplementary Fig. 2). At the global level, cropland increases by 237 million ha until the year 2050 and by 239 million ha until 2100, compared to 2010 (Fig. 1). Cropland area expands in developing and emerging regions, including countries of the Middle East and Africa (MAF), countries of Latin America and the Caribbean (LAM) and Asian countries, with the exception of the Middle East, Japan and Former Soviet Union states (ASIA), whereas it decreases in OECD90 countries (OECD; Supplementary Fig. 3). As a consequence, agricultural land is abandoned in the developed regions, as well as in LAM and MAF, where less pasture land is needed owing to more intensified livestock production systems that require less roughage for ruminant feed. Therefore, abandoned land increases by 154 million ha globally until 2100. According to this scenario, global land-use change emissions accumulate to 173 Gt CO_2 over the twenty-first century (Fig. 2a). Because of regrowth of secondary natural vegetation, 84 Gt CO_2 is sequestered on abandoned agricultural land up to 2100 (Fig. 2b).

Subsequently, we estimate the impacts of two different terrestrial land-use policies on land-use and carbon dynamics. Consistent with previous findings[17], a global terrestrial carbon policy (All scenario), introduced by a universal carbon tax on greenhouse gas emissions from all terrestrial systems, halts land-use change and associated carbon emissions, but decreases carbon uptake from regrowth on abandoned land (29 Gt CO_2 until 2100). However, if a terrestrial land-use policy considers carbon emissions from deforestation only (REDD scenario), forest loss is stopped whereas cropland expansion is reduced only marginally (cropland expansion of 203 million ha until 2100) compared to the Ref scenario (239 million ha) without any land-use policy. Such a policy restricts the areas available for cropland expansion, forcing agricultural expansion to switch to less suitable land. This also incentivizes intensification of existing croplands, leading to improved agricultural management and higher investments in yield-increasing technology (Supplementary Fig. 1). Under the REDD scenario, additional pasture land of 51 million ha is lost until 2100 compared to the Ref scenario, mainly in Africa and Latin America. At the same time, abandoned agricultural land area is reduced by 94 million ha compared to the Ref scenario. The reason is that less agricultural land is abandoned in Africa and Latin America if production cannot be extended into forested areas, and more land with non-forest natural vegetation is lost in Asia and Africa. Under the REDD scenario, carbon emissions from land-use change accumulate to 96 Gt CO_2, which is approximately 55% of the land-use-change-related emissions in the Ref scenario without any land-based mitigation. In addition, less agricultural land is taken out of production, thereby decreasing the uptake potential of secondary natural vegetation regrowth on abandoned land to 55 Gt CO_2.

Climate impacts such as precipitation and temperature changes and CO_2 fertilization based on RCP2.6 affect the carbon dynamics of the terrestrial system in all scenarios. Globally, carbon uptake due to climate change and CO_2 fertilization of 178 Gt CO_2, 176 Gt CO_2 and 180 Gt CO_2 can be attributed to the Ref, REDD and All scenarios, respectively, until 2100 (Fig. 2c). In all scenarios, highest carbon uptake driven by climate change and CO_2 fertilization can be observed until the mid-century as RCP2.6 peaks at 490 ppm CO_2 and then declines[24]. As a consequence of land-use change and carbon uptake, we conclude that the land system could contribute most to climate change mitigation if all ecosystems were to be included in a terrestrial land-use policy (All), taking up 191 Gt CO_2 until 2100 (Fig. 2d). In comparison, if only forest conservation measures are considered (REDD), the carbon uptake would be 55 Gt CO_2 lower compared to All, mainly owing to leakage effects into non-forest ecosystems and associated carbon emissions. Lowest net carbon uptake of 88 Gt CO_2 can be observed in the reference scenario without any land-use policy (Ref).

Our study shows that until 2050, without any land-use policy (Ref), land-use change would contribute about 13% to the global budget of 1,000 Gt CO_2 that must not be exceeded if global warming is to be limited to 2 °C with 66% likelihood[25], and about 7% if forest conservation measures are considered (REDD).

The results of our study emphasize that land-use policies should cover all land types to avoid non-forest leakage effects. Beyond the

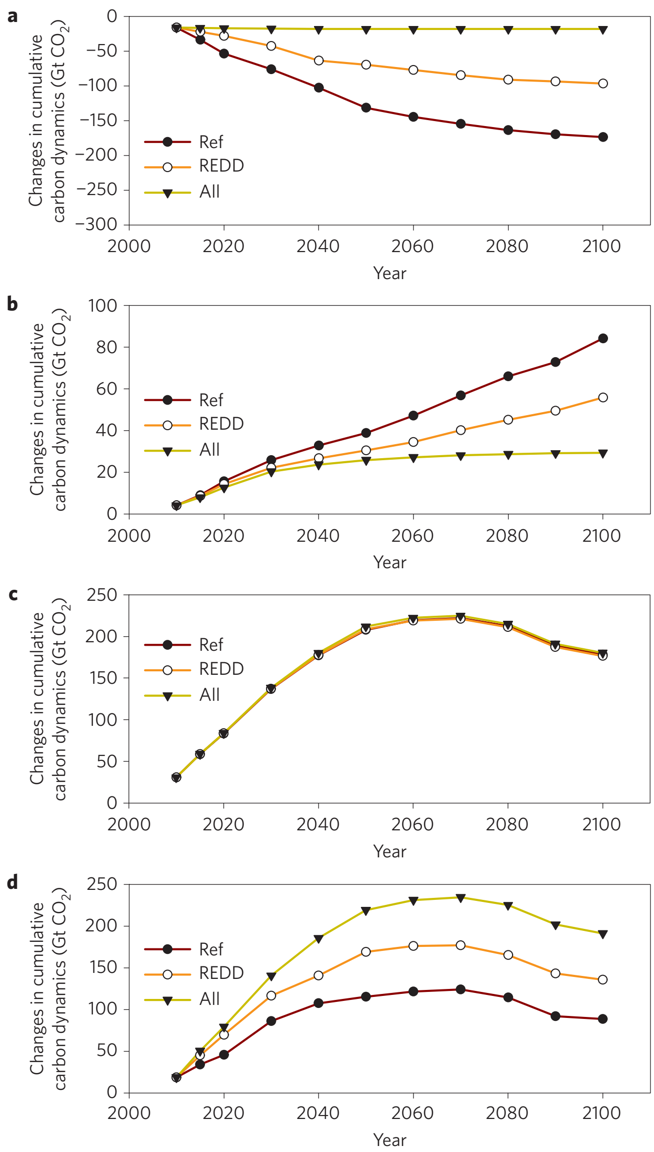

Figure 2 | Cumulative global carbon dynamics over the twenty-first century. a–d, Mean changes in carbon dynamics are calculated for all scenarios and across five GCMs for carbon losses due to land-use change (**a**), carbon uptake due to regrowth of secondary natural vegetation on abandoned agricultural land (**b**), carbon dynamics driven by climate change and CO_2 fertilization under RCP2.6 (**c**), and net carbon dynamics (**d**). Positive values represent terrestrial carbon sequestration, whereas negative values indicate loss of terrestrial carbon to the atmosphere.

importance of controlling land-use dynamics for climate change mitigation, which were analysed here, such policies should also account for other environmental assets, such as biodiversity. Land-use policies provide a huge opportunity to protect biodiversity as a co-benefit of maintaining forests[26]. But, as our analysis shows, forest protection policies such as REDD can lead to displacement of pressures, resulting from increasing demand for agricultural products, to less productive, non-forest ecosystems perceived to contain lower carbon levels. Those ecosystems, such as the tropical savannas of the Brazilian Cerrado, that nevertheless can support great levels of biodiversity or are home to endemic species of high conservational value can become increasingly threatened under such incomplete policies[13,27,28].

Implementing a global terrestrial carbon policy that includes all land types would have the largest benefits for both climate change mitigation and the protection of pristine landscapes. However, the implementation of such a scheme may be regarded as optimistic, given the slow progress in recent international negotiations. If a land-use policy that embraces all land types is considered politically impossible to implement, a simpler and more easily achievable approach to minimize the risks of any forest conservation scheme would be to identify and protect non-forest ecosystems of high value for carbon and biodiversity. So, if a forest conservation mechanism comes into operation, financing structures would have to be implemented which ensure that conservation investment is spread over the range of ecosystems not covered by REDD funding[13].

Our analysis indicates that higher agricultural productivity increases would be needed to compensate for reduced land availability for agricultural use (Supplementary Fig. 1). Generally, preserving ecosystems while enhancing agricultural production is a central challenge for sustainability[11]. Restrictions to agricultural expansion due to land conservation may affect land-use competition, with substantial effects on agricultural production costs and food prices[17,29,30]. And even if REDD is currently seen as a low-cost climate mitigation option, additional costs for the implementation and verification of REDD projects[7], as well impacts on downstream economic values of current land uses, including employment and wealth generated by processing and service industries[9], could occur. These possible impacts need to be balanced against positive effects on CO_2 reductions. More efficient land management and major technological innovations in agriculture have the potential to prevent a global shortage of productive land[29], decrease carbon emissions from land-use change and enhance uptake of carbon from regrowth of secondary natural vegetation on abandoned agricultural land (see sensitivity analysis in the Supplementary Information). Large production increases are possible from, for example, closing yield gaps, but they will require considerable changes in nutrient and water management as well as shifting productivity frontiers to meet sustainability challenges[31]. On the other hand, demand-side measures such as changes in diet towards less products of animal origin can have 'land sparing' effects[32] which reduce the pressure from agricultural expansion on forests and other land (see Supplementary Fig. 4 and sensitivity analysis in the Supplementary Information). In contrast to such processes helping to reduce land-use pressure, enhanced competition in the land system could emerge due to financial rewards for the regrowth of natural vegetation (afforestation), mainly at the expense of pasture areas[33].

Methods

MAgPIE is a mathematical programming model projecting spatially explicit land-use dynamics in ten-year time steps until 2100 using recursive dynamic optimization[19]. The objective function of MAgPIE is the fulfilment of exogenously calculated food and livestock demand, defined for ten world regions (Supplementary Fig. 9 and Table 3), at minimum costs under socio-economic and biophysical constraints. Major cost types in MAgPIE are factor requirement costs (capital, labour, fertilizer and other inputs), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change and costs for carbon emission rights[29,34]. Whereas socio-economic constraints such as trade liberalization and forest protection are defined at the ten-region scale, biophysical constraints such as crop and pasture yields, carbon density and water availability, derived from the dynamic global vegetation model LPJmL (refs 20,21), as well as land availability, are introduced at the grid-cell level (0.5° longitude/latitude). The cost-minimization problem is solved through endogenous variation of spatial production patterns (intra-regionally and inter-regionally through international trade), land expansion and yield-increasing technological change (TC).

MAgPIE features land-use competition based on cost-effectiveness between food and livestock production and land-use-based mitigation such as avoided deforestation. Available land types are cropland, pasture, forest and other land (for example, non-forest natural vegetation, abandoned land, desert). Grid-cell-specific carbon densities for the different carbon stocks (vegetation, soil, litter) of the various land types are based on LPJmL simulations and IPCC guidelines for National Greenhouse Gas Inventories (IPCC 2006). MAgPIE calculates carbon emissions as the difference in carbon stocks (vegetation, litter and soil) between simulated time steps (more information in the Supplementary Information). Carbon uptake in MAgPIE occurs if regrowth of natural vegetation takes place on abandoned agricultural land (more information in the Supplementary Information). Mitigation of carbon emissions is stimulated by an exogenous tax on terrestrial carbon emissions. The carbon tax is multiplied by carbon emissions to calculate carbon emission costs, which enter the cost-minimizing objective function of MAgPIE. Therefore, stopping land-use change is an economic decision when emissions from land-use change are priced. In contrast, carbon uptake due to regrowth of natural vegetation is not rewarded financially in MAgPIE.

Our socio-economic assumptions are based on the Shared Socio-economic Pathways (SSPs) for climate change research[23]. In this study we choose SSP 2, a 'Middle of the Road' scenario with intermediate socio-economic challenges for adaptation and mitigation. Food, livestock and material demand is calculated using the methodology described in ref.35 and the SSP 2 population and gross domestic product projections (~65 EJ yr^{-1} in 2100, Supplementary Fig. 4). The SSPs do not incorporate climate mitigation policies by definition. Carbon tax (~US\$1,500 per tonne of CO_2 in 2100, Supplementary Fig. 5) in our study is aimed at ambitious climate change mitigation (~RCP 2.6 in 2100). The carbon tax has a level of US\$30 per tonne of CO_2 in 2020, starts in 2015 and increases nonlinearly at a rate of 5% per year. For consistency, MAgPIE simulations include temperature, precipitation and CO_2 trends and corresponding impacts on agricultural yields, water availability and carbon stocks in vegetation under a RCP2.6, derived by LPJmL. To account for uncertainty in climate projections for RCP 2.6, in this study we use climate data of the five GCMs: HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M.

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Author contributions

A.P. designed the overall study; F.H. and M.B. carried out the MAgPIE model runs. A.P. wrote the manuscript with important contributions from F.H., B.L.B., C.M. and M.B.; A.P., F.H., M.B. and B.L.B. analysed the results; F.H., I.W., B.L.B., M.B., J.P.D., A.P., M.S., A.B. and H.L-C. contributed in developing and improving the MAgPIE model; C.M. and S.R. provided biophysical input data from LPJmL; all authors discussed and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.P.

Competing financial interests

The authors declare no competing financial interests.