Accepted (post-print) version of the published article

Land use protection for climate change mitigation

Alexander POPP[1*], Florian HUMPENÖDER[1], Isabelle WEINDL[1], Benjamin Leon BODIRSKY[1,2], Markus BONSCH[1],Hermann LOTZE-CAMPEN[1], Christoph MÜLLER[1], Anne BIEWALD[1], Susanne ROLINSKI[1], Miodrag STEVANOVIC[1], Jan Philipp DIETRICH[1]

Affiliation of authors
[1] Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
[2] Commonwealth Scientific and Industrial Research Organization, St. Lucia, QLD 4067, Australia

*Corresponding author
Email: popp@pik-potsdam.de
Phone: ++49 331 288 2463

http://www.nature.com/nclimate/journal/vaop/ncurrent/full/nclimate2444.html

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[1,2,3]. 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 higher 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 was a terrestrial sink for carbon in recent decades (Pan et al. 2011). 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].

Besides the general scientific agreement on environmental benefits of forest conservation and although the United Nations Framework Convention on Climate Change (UNFCCC) 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[8]. Especially the design of financing mechanisms[4], but also environmental and sociopolitical concerns associated with REDD (Reduced Emissions from Deforestation and Degradation) and its variations are 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 of all, areas under natural vegetation other than forests, such as shrublands and savannahs, 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 have therefore 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 that focuses only on REDD implementation, recent global modeling assessments have focused on the implementation of a global terrestrial carbon policy covering all regions and land types[17,18]. In order to avoid 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)[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: (1) No terrestrial carbon policy in the reference scenario (*Ref*), (2) a global terrestrial land use policy that considers carbon emissions from deforestation only in the *REDD* scenario and (3) 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 five different global circulation models' (GCMs) implementation of the RCP2.6 scenario. We generally report mean values across all GCMs while single GCM outputs and standard deviations can be found in the Supporting Information (SI) table SI-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 SI). It is important to note that the land-use model does not only embrace (a) the calculation of emissions from deforestation and other land use change, but also (b) the uptake of carbon from regrowth of secondary natural vegetation on abandoned agricultural land and (c) 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 validation section in the SI). 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 the Methods description). Our model results show that agricultural production increases are mainly realized by intensification on existing agricultural land (Figure SI-1) as well as by agricultural land expansion. In 2010, global cropland area is 1454 mio ha, pasture land area 3079 mio ha, global forest area 4144 mio ha and global other land area 4229 mio ha (see also fig SI-2). At the global level, cropland increases by 237 mio ha until the year 2050 and 239 mio ha until 2100, compared to 2010 (Figure 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) (Figure SI-3). As a consequence, agricultural land is abandoned in the developed regions but also in LAM and

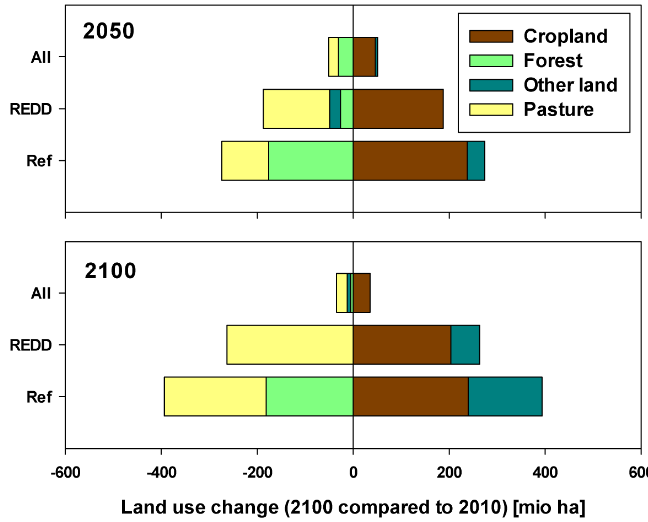

Figure 1|Change in global land pools (million ha). *The upper figure shows changes from 2010 to 2050 and the lower figure changes from 2010 to 2100 for the reference case (Ref) without land use mitigation, a terrestrial land use policy that considers carbon emissions from deforestation only (REDD) and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

MAF where less pasture land is needed due to more intensified livestock production systems that require less roughage for ruminant feed. Therefore, abandoned land increases by 154 mio ha globally until 2100. According to this scenario, global land use change emissions accumulate to 173 Gt CO_2 over the 21st century (Fig 2a). Due to regrowth of secondary natural vegetation, 84 Gt CO_2 are sequestered on abandoned agricultural land until 2100 (Figure 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 but cropland expansion is reduced only marginally (cropland expansion of 203 mio ha until 2100) compared to the *Ref* scenario (239 mio ha) without any land use policy. Such a policy restricts the areas available for cropland expansion whereas agricultural expansion has to switch to less suitable land. This also incentivizes intensification of existing croplands, leading to improved agricultural management and higher investments into yield-increasing technology (Fig SI-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 reference 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 like precipitation and temperature changes and CO_2 fertilization based on RCP2.6 affect 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 mid of the 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 would be included in a terrestrial land use policy (*All*), taking up 191 Gt CO_2 until 2100 (Fig 2d). Compared to that, if only forest conservation measures are considered (*REDD*), the carbon uptake would be by 55 Gt CO_2 lower compared to *All*, mainly due to leakage effects into non-forest ecosystems and associated carbon emissions. Lowest net carbon uptake of 88 Gt CO_2 can be observed

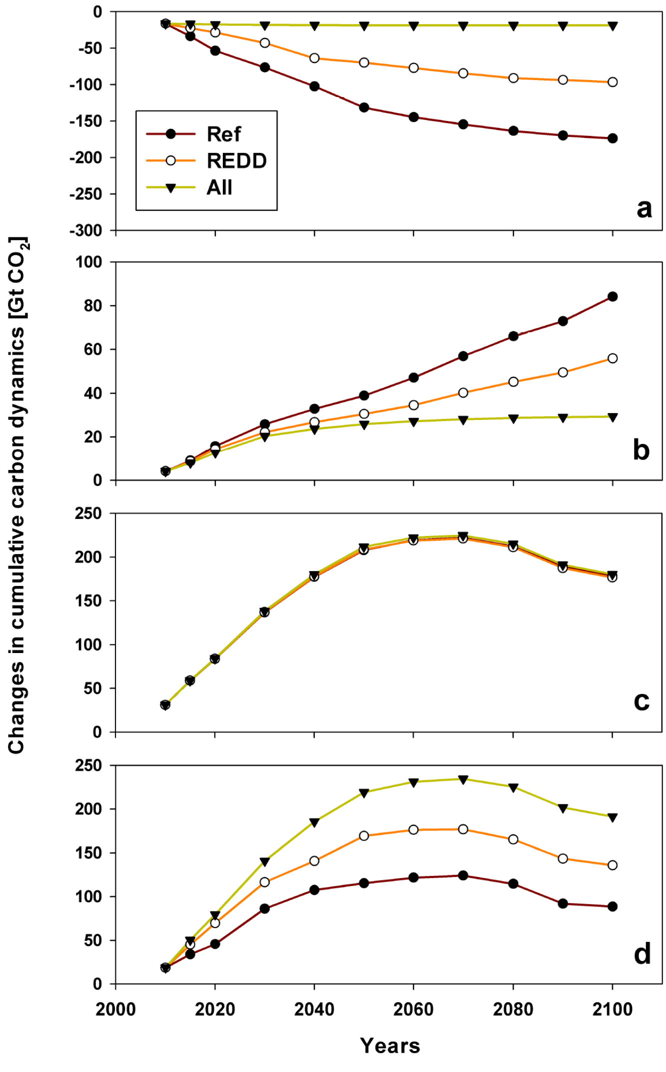

Figure 2| Cumulative global carbon dynamics over the 21st century (Gt CO_2). *Mean changes in carbon dynamics are calculated for all scenarios and across 5 GCMs for (a) carbon losses due to land use change, (b) carbon uptake due to regrowth of secondary natural vegetation on abandoned agricultural land, (c) carbon dynamics driven by climate change and CO_2 fertilization under RCP2.6, (d) net carbon dynamics. Positive values represent terrestrial carbon sequestration, while negative values indicate loss of terrestrial carbon to the atmosphere.*

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 1000 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 importance of controlling land use dynamics for climate change mitigation, which were analyzed here, such policies should also account for other environmental assets like 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 for 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 (Figure SI-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] but also 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 SI). Large production increases are possible from e.g. 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 Fig SI-4 and sensitivity analysis in the SI). In contrast to such processes helping to reduce land use pressure, enhanced competition in the land system could emerge due to financial reward for the regrowth of natural vegetation (afforestation), mainly at the expense of pasture areas[33].

Methods Summary

MAgPIE is a mathematical programming model projecting spatially explicit land-use dynamics in 10-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 10 world regions (Figure SI-9 and table SI-3), at minimum costs under socio-economic and biophysical constraints. Major cost types in MAgPIE are factor requirement costs (capital, labor, fertilizer and other inputs), land conversion costs, transportation costs to the closest market, investment cost for yield-increasing technological change and costs for carbon emission rights[29,34]. While socio-economic constraints like trade liberalization and forest protection are defined at the 10-region scale, biophysical constraints such as crop and pasture yields, carbon density and water availability, derived from the DGVM LPJmL[20,21], as well as land availability, are introduced at the grid cell level (0.5 degree 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 (e.g. 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 of carbon stocks (vegetation, litter and soil) between simulated time steps (more information in the SI). Carbon uptake in MAgPIE occurs if regrowth of natural vegetation takes place on abandoned agricultural land (more information in the SI). Mitigation of carbon emissions is stimulated by an exogenous tax on terrestrial carbon emissions. The carbon tax is multiplied with carbon emissions in order 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[35] and the SSP 2 population and GDP projections (~65 EJ/yr in 2100, figure SI-4). The SSPs do not incorporate climate mitigation policies by definition. Carbon tax (~1500 \$/tCO_2 in 2100, figure SI-5) in our study is aimed at ambitious climate change mitigation (~RCP 2.6 in 2100). The carbon tax has a level of 30 \$/tCO_2 in 2020, starts in 2015 and increases non-linearly 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, we use in this study climate data of the five GCMs: HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M and NorESM1-M.

Acknowledgments

The research leading to these results has received funding from the European Union's Seventh Framework Program under grant agreement n° 265104 (VOLANTE) and n° 603542 (LUC4C). Funding from Deutsche Forschungsgemeinschaft (DFG) in the SPP ED 178/3-1 (CEMICS) is gratefully acknowledged.

Author contributions

A.P. designed the overall study; F.H. and M.B. handled 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 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. Correspondence and requests for materials should be addressed to A.P.

Competing financial interests

The authors declare no competing financial interests.

References

1. Van der Werf, G. R. *et al.* CO2 emissions from forest loss. *Nat. Geosci.* **2,** 737–738 (2009).
2. Pan, Y. *et al.* A Large and Persistent Carbon Sink in the World's Forests. *Science* **333,** 988–993 (2011).
3. Houghton, R. A. *et al.* Carbon emissions from land use and land-cover change. *Biogeosciences* **9,** 5125–5142 (2012).
4. Ebeling, J. & Yasué, M. Generating carbon finance through avoided deforestation and its potential to create climatic, conservation and human development benefits. *Philos. Trans. R. Soc. B Biol. Sci.* **363,** 1917–1924 (2008).
5. Don, A., Schumacher, J. & Freibauer, A. Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. *Glob. Change Biol.* **17,** 1658–1670 (2011).
6. Baccini, A. *et al.* Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. *Nat. Clim. Change* **2,** 182–185 (2012).
7. Kindermann, G. *et al.* Global cost estimates of reducing carbon emissions through avoided deforestation. *Proc. Natl. Acad. Sci.* **105,** 10302 –10307 (2008).
8. Nepstad, D. C., Boyd, W., Stickler, C. M., Bezerra, T. & Azevedo, A. A. Responding to climate change and the global land crisis: REDD+, market transformation and low-emissions rural development. *Philos. Trans. R. Soc. B Biol. Sci.* **368,** 20120167 (2013).
9. Ghazoul, J., Butler, R. A., Mateo-Vega, J. & Koh, L. P. REDD: a reckoning of environment and development implications. *Trends Ecol. Evol.* **25,** 396–402 (2010).
10. Gardner, T. A. *et al.* A framework for integrating biodiversity concerns into national REDD+ programmes. *Biol. Conserv.* **154,** 61–71 (2012).
11. Lambin, E. F. & Meyfroidt, P. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl. Acad. Sci.* **108,** 3465–3472 (2011).
12. Gan, J. & McCarl, B. A. Measuring transnational leakage of forest conservation. *Ecol. Econ.* **64,** 423–432 (2007).
13. Miles, L. & Kapos, V. Reducing Greenhouse Gas Emissions from Deforestation and Forest Degradation: Global Land-Use Implications. *Science* **320,** 1454–1455 (2008).
14. Smith, P. Land use change and soil organic carbon dynamics. *Nutr. Cycl. Agroecosystems* **81,** 169–178 (2008).
15. Guo, L. B. & Gifford, R. M. Soil carbon stocks and land use change: a meta analysis. *Glob. Change Biol.* **8,** 345–360 (2002).
16. Popp, A. *et al.* Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options. *Clim. Change* 1–15 doi:10.1007/s10584-013-0926-x

17. Wise, M. *et al.* Implications of Limiting CO2 Concentrations for Land Use and Energy. *Science* **324,** 1183–1186 (2009).

18. Reilly, J. *et al.* Using Land To Mitigate Climate Change: Hitting the Target, Recognizing the Trade-offs. *Environ. Sci. Technol.* **46,** 5672–5679 (2012).

19. Lotze-Campen, H. *et al.* Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. *Agric. Econ.* **39,** 325–338 (2008).

20. Müller, C. & Robertson, R. D. Projecting future crop productivity for global economic modeling. *Agric. Econ.* **45,** 37–50 (2014).

21. Bondeau, A. *et al.* Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Glob. Change Biol.* **13,** 679–706 (2007).

22. Schaphoff, S. *et al.* Contribution of permafrost soils to the global carbon budget. *Environ. Res. Lett.* **8,** 014026 (2013).

23. O'Neill, B. C. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* **122,** 387–400 (2014).

24. Vuuren, D. P. van *et al.* The representative concentration pathways: an overview. *Clim. Change* **109,** 5–31 (2011).

25. Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458,** 1158–1162 (2009).

26. Harvey, C. A., Dickson, B. & Kormos, C. Opportunities for achieving biodiversity conservation through REDD. *Conserv. Lett.* **3,** 53–61 (2010).

27. Stickler, C. M. *et al.* The potential ecological costs and cobenefits of REDD: a critical review and case study from the Amazon region. *Glob. Change Biol.* **15,** 2803–2824 (2009).

28. Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B. & Kent, J. Biodiversity hotspots for conservation priorities. *Nature* **403,** 853–858 (2000).

29. Popp, A. *et al.* The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environ. Res. Lett.* **6,** 034017 (2011).

30. Popp, A. *et al.* Additional CO_2 emissions from land use change — Forest conservation as a precondition for sustainable production of second generation bioenergy. *Ecol. Econ.* **74,** 64–70 (2012).

31. Mueller, N. D. *et al.* Closing yield gaps through nutrient and water management. *Nature* (2012). doi:10.1038/nature11420

32. Smith, P. *et al.* How much land based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Glob. Change Biol.* n/a–n/a (2013). doi:10.1111/gcb.12160

33. Humpenöder, F. *et al.* Investigating afforestation and bioenergy CCS as climate change mitigation strategies. *Environ. Res. Lett.* **9**, 064029 (2014).

34. Dietrich, J. P., Schmitz, C., Lotze-Campen, H., Popp, A. & Müller, C. Forecasting technological change in agriculture—An endogenous implementation in a global land use model. *Technol. Forecast. Soc. Change* doi:10.1016/j.techfore.2013.02.003

35. Bodirsky, B. L. *et al.* N2O emissions from the global agricultural nitrogen cycle – current state and future scenarios. *Biogeosciences* **9,** 4169–4197 (2012).