5-28-2015

High carbon and biodiversity costs from converting Africa's wet savannahs to cropland

Timothy D. Searchinger
Princeton University

Lyndon Estes
Clark University, lestes@clarku.edu

Philip K. Thornton
CGIAR Research Program on Climate Change

Tim Beringer
Institute for Advanced Sustainability Studies

An Notenbaert
International Centre of Insect Physiology and Ecology Nairobi

See next page for additional authors

nature climate change

ARTICLES

PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NCLIMATE2584

High carbon and biodiversity costs from converting Africa's wet savannahs to cropland

Timothy D. Searchinger[1]*, Lyndon Estes[1]*, Philip K. Thornton[2], Tim Beringer[3], An Notenbaert[4], Daniel Rubenstein[1], Ralph Heimlich[5], Rachel Licker[1] and Mario Herrero[6]

Do the wet savannas and shrublands of Africa provide a large reserve of potential croplands to produce food staples or bioenergy with low carbon and biodiversity costs? We find that only small percentages of these lands have meaningful potential to be low-carbon sources of maize (∼2%) or soybeans (9.5–11.5%), meaning that their conversion would release at least one-third less carbon per ton of crop than released on average for the production of those crops on existing croplands. Factoring in land-use change, less than 1% is likely to produce cellulosic ethanol that would meet European standards for greenhouse gas reductions. Biodiversity effects of converting these lands are also likely to be significant as bird and mammal richness is comparable to that of the world's tropical forest regions. Our findings contrast with influential studies that assume these lands provide a large, low-environmental-cost cropland reserve.

How much land could help meet global demands for new cropland for staple crops or bioenergy at low carbon and biodiversity costs?

Influential studies have assumed that wetter tropical and subtropical savannas, shrublands and sparse woodlands, particularly in Africa, provide a large cropland reserve that can be farmed at low environmental cost. We call these lands collectively 'wet savannas' because what defines them in these studies is only their sufficient rainfall for crops and their lack of dense forest cover. For example, studies by the Food and Agriculture Organization of the United Nations (FAO) of potentially suitable cropland[1], and other studies building on them[2,3], exclude denser forests because of their carbon and biodiversity concerns but treat wet savannas as implicitly suitable for conversion[1–3]. Several modelling studies used by the Intergovernmental Panel on Climate Change assumed that wet savannas could provide new cropland for food and bioenergy without a carbon cost (Supplementary Information). Leading bioenergy studies have identified those wet savannas, particularly in Africa, as much of the global area for environmentally sustainable production[4–9]. In one study, the World Bank and FAO dubbed a 718 million hectare (Mha) swath of these lands in sub-Saharan Africa (SSA) the Guinea Savanna (GS; Fig. 1), and explicitly called for converting up to 400 Mha for staple crops and bioenergy[9]. Many of these studies acknowledge potential biodiversity costs, but implicitly treat them as acceptable or view biodiversity as adequately preserved by a network of protected areas. None of these studies calculates the carbon costs of converting wet savannas.

Although the rationale in these studies is that wet savannas are less valuable than forests, lower environmental cost does not necessarily mean low cost in any absolute sense or by reference to average croplands. The difference is important because government policies can influence not merely where land conversion occurs but also how much, and judgements about wet savannas can influence policy decisions that help shape how much. For example, through biofuel policies, governments are now directly expanding demand for cropland by tens and potentially hundreds of millions of hectares[10], and judgements about Africa's wet savannas seem to be a factor. The demand for cropland also responds to any policies that influence crop and pasture yields including levels of agricultural research funding[10], and direct support for intensification[11]. Governments can influence the need for cropland through their influence on food waste through crop storage infrastructure and policies, and food labelling standards[12], and they might influence food demands through strategies to reduce consumption of meat[13]. Governments also influence the supply of new cropland, and therefore farmer choices whether to expand land or intensify production, through land-use regulation[14], through construction of roads and other infrastructure[15], and through transfers of government-owned land[16,17]. Whether wet savannas provide a large low carbon and biodiversity cropland reserve for Q.2 biofuel or food crops can appropriately influence the cost/benefit calculations for all of these policies globally.

Although the previous studies we cite do not offer criteria for low carbon or biodiversity costs, existing croplands provide one useful benchmark. There is wide agreement that the conversions of natural areas to existing croplands have come with high carbon[18] as well as high biodiversity costs[19,20]. Logically, therefore, wet savannas cannot be viewed as potential low-cost sources of new crops unless the carbon and biodiversity costs of their conversion would be significantly lower.

The ratio of carbon lost from the formation of existing croplands relative to their crop output establishes a global average 'carbon conversion efficiency' of cropland for food crops. Here we compare this efficiency to the potential carbon conversion efficiencies of converting Africa's wet savannas, nearly half of remaining wet savannas globally. In the case of biofuels, we determine the likelihood of generating large greenhouse gas reductions compared with gasoline when factoring in the costs of land conversion because

Q.1 [1]Princeton University, Princeton, New Jersey, USA. [2]CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), ILRI, Nairobi, Kenya. [3]Potsdam Institute for Climate Impact Research, Potsdam, Germany. [4]International Center for Tropical Agriculture, Nairobi, Kenya. [5]Agricultural Conservation Economics, Laurel, Maryland, USA. [6]Commonwealth Scientific and Industrial Research Organisation, St Lucia, Australia.
*e-mail: tsearchi@princeton.edu; lestes@princeton.edu

that provides an objective standard for low-carbon lands. We also compare the biodiversity of Africa's wet savannas with other global biomes. Although the available global data sets and vegetation models needed for these analyses have many uncertainties, their use is both appropriate and necessary for evaluating the assumptions of other global analyses.

Findings

Land use in the GS. To analyse the precise assumptions of at least one prominent analysis, our identification of the wet savannas of Africa tracks the map used by the World Bank to identify the GS. That generally identifies lands with a potential crop-growing season based on adequate soil moisture between 150 and 239 days per year (roughly areas with >600 mm rainfall per year that are not dense forests). In reality, this term extends the name Guinea Savanna, which properly refers to a particular ecosystem in West Africa, to a wide range of savannas, shrublands and woodlands. We calculate that 51% of the 718 Mha area has canopy cover of 10–30%, 33% has canopy cover of 30–50%, and 3% has canopy cover over 50%. Wetlands cover 47 Mha (6%), and protected areas cover 106 Mha (Fig. 1), but croplands already cover 82 Mha (11%). On the basis of an existing database[21], 260 Mha of the GS was used for pasture in 2000, but the densities vary greatly with 3.5% of pasture in excess of 50 tropical livestock units (TLU) km^{-2}; 33.5% of pasture with 10–50 TLU km^{-2} and 63% of pasture with 0–10 TLU km^{-2}. Some of the studies we cite exclude some more managed grazing lands from their estimates of potentially suitable lands.

Potential to be a low-carbon source of staple crops. We analyse the potential of additional cropland in the GS to be a low-carbon source of staple crops first by estimating the carbon conversion efficiencies of maize or soybeans on existing global cropland. (The World Bank found that maize and soybean are the optimal staple crops for 88% of the suitable potential new cropland in SSA (ref. 2; Supplementary Information)). Studies of agricultural conversion costs typically focus on carbon releases per hectare[22], but if crop yields are low, using land with little carbon can result in more hectares of conversion and more overall release of carbon. Here, we focus instead on the carbon releases from land conversion per ton of crop because that precisely measures land's ability to contribute to food needs while minimizing total carbon releases. Following ref. 23, we calculate these efficiencies as the carbon lost by the conversion of native ecosystems to cropland divided by the current annual yields of those croplands, so the lower the number the more efficient. Unlike in ref. 23, however, we analyse these ratios for individual crops rather than aggregate crops. The different yields of different crops will lead to different carbon loss/yield ratios. The ratios must be compared for the same crops to properly reflect the differences in land characteristics alone.

Using methods described below, we find that lands used for maize globally have experienced a mean average carbon loss of 20.8 tons per ton of annual crop yield (tC tY^{-1}), and a median of 14 tC tY^{-1}). For soybeans, the mean ratio (carbon conversion efficiency) is 44.5 tC tY^{-1} and the median ratio is 41 tC tY^{-1}.

We compare these global conversion efficiencies with estimates of carbon release per potential ton of rain-fed maize and soybeans on wet savannas in the GS while excluding existing cropland and protected areas. To provide sensitivities for our analysis, we base our spatial estimates of carbon first on soil and vegetation carbon maps, and alternatively on the same vegetation and soil model used for the global analysis (LPJmL; Supplementary Information).

For yields, our first method estimates potential yields optimistically assuming high inputs and absence of major crop diseases for the whole GS using a crop model (DSSAT; Supplementary Information; Supplementary Figs 1–4 map and show distributions for this approach). We alternatively estimate potential yields using a yield

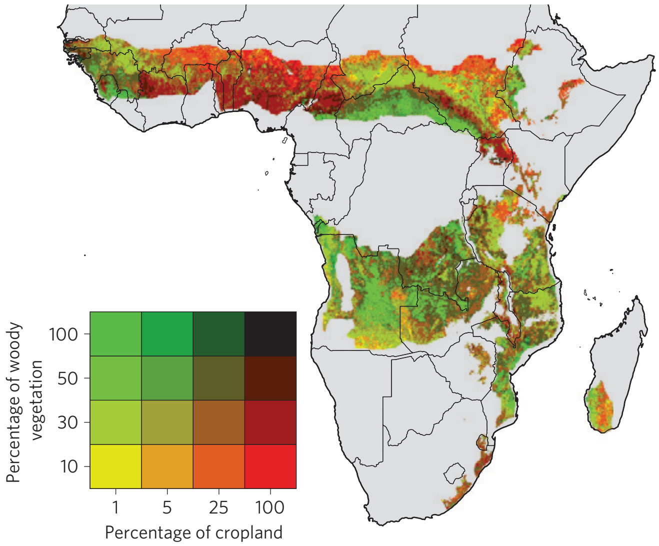

Figure 1 | Cropland and tree cover in Africa's wet savannas and shrublands.

gap analysis that estimates the 90th percentile of reported yields within zones of comparable climate. The two methods generate quite similar patterns of yield estimates overall, although the DSSAT yields are modestly lower (Supplementary Table 1), and there are spatial differences (Supplementary Fig. 6). The two estimates for potential yields and the two estimates of carbon losses generate four different estimates overall of carbon conversion efficiencies.

According to these four estimates, 18.3–19.2% of the GS has potential to convert maize while releasing less carbon per ton of crop than the global mean. The potential areas for soybeans are 30.8–32.9%. Conversion of only 6.3–7.8% (maize) and 12.1–16.2% (soybeans) would release at least one-third less carbon than the global mean (Supplementary Figs 7a and 8), which we consider a modest standard for 'low' carbon costs per ton.

As a minimum level of yield and acceptable yield variability are needed to justify high inputs, we calculated areas in the GS that also meet three modest practicability tests for high inputs, leading to four total criteria for potentially low-carbon cropland: carbon loss/yield ratios for maize or soybeans under our optimistic assumptions of potential yields would be at least one-third lower than the world mean; potential yields would reach at least 4 t ha^{-1} yr^{-1} for maize or 1.5 t ha^{-1} yr^{-1} for soybeans, roughly half the yields of high-exporting countries; the yield coefficient of variation (CV) would be less than 30%; the cropland season failure rate would be less than 10%. Using our crop-modelled yields, 2–2.2% meet criteria for maize and 9.5–11.5% for soybeans. (Figure 2 shows lands that pass these tests using the DSSAT/database carbon method. The Supplementary Information includes statistics for different combinations of criteria (Supplementary Tables 2 and 3).) Analyses that use attainable yields from the yield gap study[24], which are methodologically restricted to the first two 'suitability' criteria, produced estimates of 1.2–3.6% (maize) and 10.5–12% soybeans (Supplementary Tables 4 and 5). These similar estimates suggest limited practical capacity to generate crops with low carbon costs.

If cropland expansion occurred at existing yields[25] (Supplementary Information), the results would be less promising. Only 1.7% of the GS for maize and 2.9% for soybeans would release less carbon per ton of crop than the global mean, and only 0.6% (maize) and 0.8% (soybeans) would release one-third less carbon (Supplementary Information).

Even if some wet savannas provide a potential low-cost cropland reserve for staple crops, SSA cannot become a net exporter of

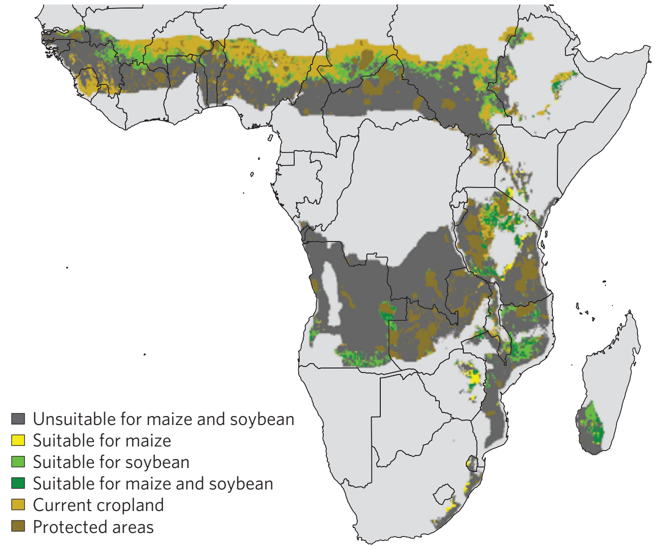

Figure 2 | Low-carbon potential cropland sites. Suitable: yields $\geq$4 t ha^{-1} (maize) or 1.5 t ha^{-1} (soybeans), yield CV $\leq$30%, crop season failure rates $\leq$10%, and carbon loss/yield ratios 33% lower than global averages for each crop.

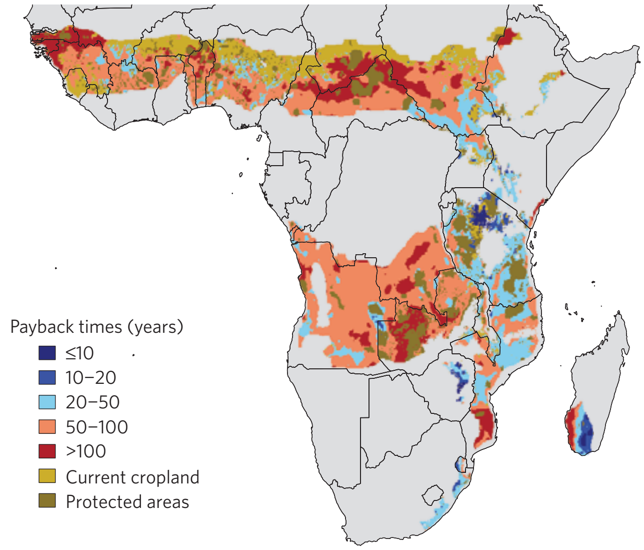

Figure 3 | Carbon payback times for use of dedicated perennial grasses for ethanol.

low-carbon staple crops—except by depriving its own people of food—unless it first uses such lands to meet its own needs. (Devoting low-carbon lands to expand exports would otherwise just require offsetting imports or more expansion into high-carbon lands to meet domestic needs.) For SSA to become self-sufficient in food production at the improved nutritional levels predicted by FAO in 2050, overall production of crop calories would need to grow to 4.2 times 2007 levels. To avoid cropland expansion, average cereal yields would have to grow from 1.23 t ha^{-1} in 2007 to 5 t ha^{-1} yr^{-1} in 2050, more than double the global yield growth rates for cereals from 1961 to 2006. Even to produce all needed crops at the substantially improved yields in SSA estimated by FAO in 2050, and with continued heavy reliance on staple imports, SSA would need to expand cropland by ~140 Mha. That is more than double our four-criterion estimate of potential low-carbon cropland for maize or soybeans (using high inputs) of ~60 Mha. Converting 140 Mha would release ~33 Gt of carbon dioxide even if focused on lands with the lowest carbon loss/yield ratios for maize (Supplementary Table 8). SSA has important potential to boost staple crop yields and has started to boost yields in recent years, but unless yield growth far exceeds FAO predictions, SSA is unlikely to have excess low-carbon lands to contribute to global staple crop needs.

Potential for low-carbon bioenergy. According to many studies[4–9], the GS serves as a large potential source of land for low-carbon biofuels, but these studies do not calculate the carbon costs from the conversion of non-forests. Here we use optimistic assessment of bioenergy crop yields to calculate the 'carbon payback' time, which is the number of years before fossil fuel greenhouse gas savings compensate for the initial release of carbon from land conversion.

Our central analysis adjusts our biomass crop model (LPJmL; Supplementary Information) to match the net primary productivity of native vegetation, which rain-fed agriculture rarely exceeds[26]. The model projects average biomass yields at 8.8 tDM ha^{-1} yr^{-1}, which are greater than the highest US yields estimated in regulatory analyses used by the US Environmental Protection Agency for the US (ref. 27). Using a life cycle model (GREET; Supplementary Information) that calculates that each megajoule of ethanol generates only 12% of the greenhouse gases of gasoline without counting land-use change (LUC), each ton of carbon in bioenergy crops saves 0.44 tons of greenhouse gases (C eqv.) before factoring in LUC. Including LUC, 52% of the GS that is not protected or already cropland has carbon payback times in excess of 50 years, and 98% in excess of 20 years (Fig. 3). Only 0.6% of the area would result in payback times less than 10 years, which is closest to the European Union standard in effect in 2017 that biofuels must produce 50% less greenhouse gas than gasoline over 20 years.

We alternatively adjusted our biomass crop model to match the biomass yields in test plots of perennial grasses including *Miscanthus x giganteus* (Supplementary Information). In that scenario, average biomass yields rise to 15.9 tDM^{-1} ha^{-1} yr^{-1}, and the area with 10-year payback times rises to 2.8%. Using a variety of different databases and assumptions does not significantly change these results (Supplementary Table 9).

Biodiversity. Agricultural conversion nearly always has large impacts on local biodiversity[19,20]. Species diversity counts inform these impacts although the relationship is not as quantitatively precise as carbon calculations. We evaluated the potential impacts to biodiversity of converting the GS to croplands by comparing biodiversity in the GS with that of other regions, using bird, mammal and amphibian species counts calculated from range maps (Supplementary Information). As bird species greatly outnumber mammals and reptiles, we rescaled the number of species in each taxon in each pixel to a 0–1 range based on its relationship to the global range in diversity for that taxon (excluding Antarctica). The index of all vertebrates sums the number of the three vertebrate subsets to a maximum score of 3. Figure 4 maps the distribution and compares the GS with other biomes.

The GS has lower vertebrate species richness on average than wet tropical forests, but the difference is modest, and the GS has almost identical average richness for birds and mammals (Fig. 4). Median and mean biodiversity vertebrate biodiversity are roughly double the world average, and 75% of the GS has more diversity than 75% of the rest of the world excluding Antarctica (Supplementary Fig. 11). Species richness within the GS is comparable to that of African protected areas outside the GS and is significantly higher than all non-desert areas in Africa outside the GS (Supplementary Fig. 12). The biota within the GS, particularly the flora and mammalian vertebrates, is also largely distinct from that of other continents[28].

The bioenergy studies cited assume that a proper network of protected areas would make bioenergy sustainable in much of the

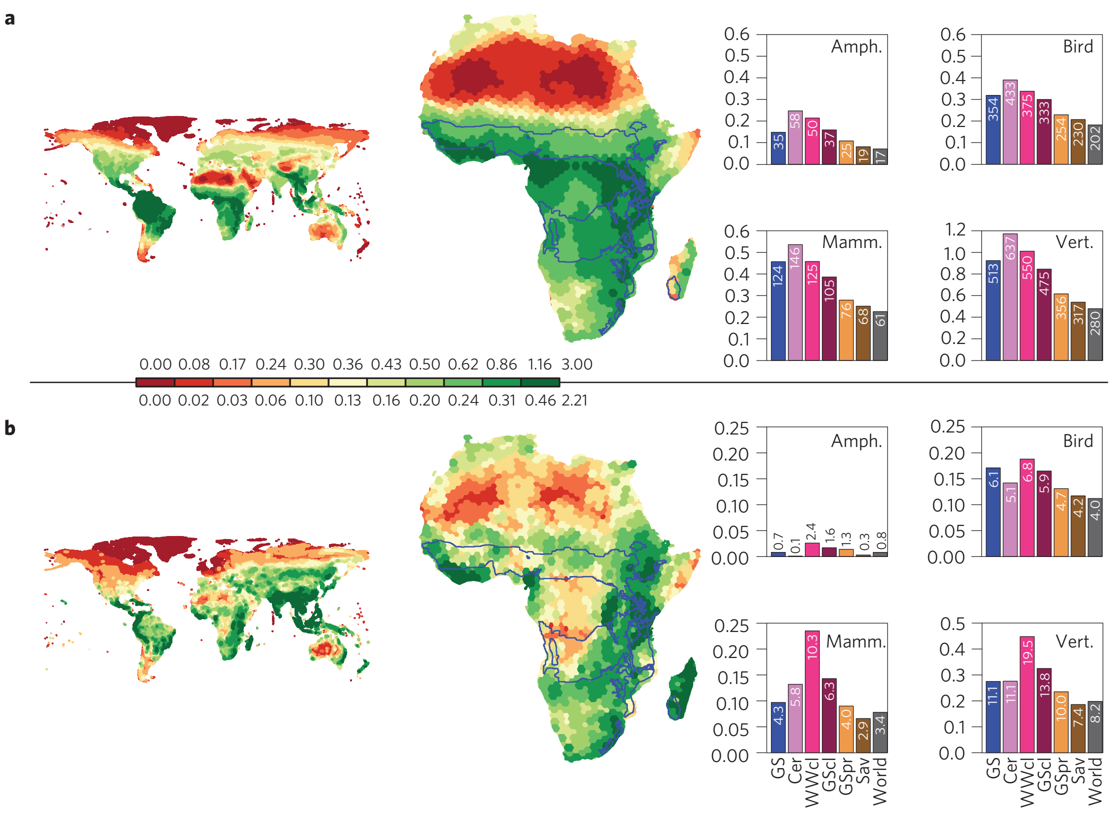

Figure 4 | Comparison of GS vertebrate diversity with rest of world. a,b, Global total vertebrate (mammals, birds and amphibians) richness (**a**) and threatened vertebrate richness (**b**), excluding Antarctica. Bar charts show the mean standardized diversity values by height; numbers within or above show actual mean species count for the GS and different habitat climatic zones and eco-regions: the Cerrado (CER); warm wet climates, which correspond to dense tropical rainforests (WWcl); climates like the GS but outside the GS (GScl); world regions with comparable rainfall outside the GS (GSrf); savannas, woodlands, and shrublands outside the GS (Sav): and the whole world outside the GS except Antarctica (World). The locations of these regions relative to the GS are illustrated in Supplementary Fig. 10.

GS (refs 4,5,9). The GS protection rate of 14.7% is already slightly higher than the world average of 13%. Although beneficial, even strong networks of protected areas rarely conserve biodiversity fully if agriculture surrounds them because of edge effects, failure to provide habitat for all species, and intrusions from hunting, invasive species and pollution[29–32]. Many species that use protected areas also rely on habitat outside those areas for at least part of their life cycle[33] or as a source of clean water[34].

In the GS, for example, the southeastern portion of the vast Sud wetland in the Sudan and western Ethiopia supports a 300–400 km migration of some 800,000 white-eared kob, and 1.3 million total animals. Even though the area is rich with protected areas, much of the migration route is not protected and is threatened by large-scale conversions of the 2.5 Mha Gambella region owing to long-term leases to foreign investors[35] (Supplementary Fig. 13). Similarly, the highly diverse Okavango Delta in Botswana outside the GS depends on clean water flows from an unprotected, relatively natural watershed within the GS (Supplementary Fig. 13). Because neither the unprotected portions of the Gambella nor the Okavango watershed areas have exceptionally high biodiversity themselves, they are unlikely candidates for protected areas, but their conversion would threaten biodiversity in their broader landscapes.

Although high biodiversity scores are meaningful over broader areas, scores for each grid cell are less informative because data on the presence of animals do not factor in these landscape and watershed functions. Impacts of agricultural conversion also vary as a function of species range size, mobility, habitat preferences and other factors. We therefore did not calculate a quantitative biodiversity cost/benefit index by cell. However, the generally high biodiversity in the GS relative to the temperate zone, and the relatively low yields, imply that only modest portions of the GS should qualify as potential cropland with low vertebrate biodiversity costs relative to output.

Discussion

Our findings imply that many other global studies have overestimated the quantity of potential cropland with low carbon and biodiversity costs. If preserving carbon and biodiversity are important goals, the potential for cropping African savannas therefore does not justify large bioenergy targets but does justify enhanced efforts to meet food needs on existing land.

The coarse resolution, potential inaccuracies and inconsistencies in global data sets and models imply that studies of this type should be used for their general findings rather than their precise numbers. The finding that Africa's wet savannas are generally not low cost seems robust because multiple data sets and yield estimation methods produced similar results. Our analysis also deliberately includes many optimistic assumptions about crop and bioenergy yields. Irrigation could improve potential African yields beyond our estimates, but faces many biophysical and economic challenges[36], and would introduce other environmental costs. At a minimum, global studies should not assume that tropical areas other than forests are low cost.

Although our findings suggest policies to limit the amount of cropland expansion, policies that influence where cropland expansion occurs are also important. Even if governments make great efforts to hold down cropland demand, some growth is probably necessary, particularly in SSA. Global demand is also likely to continue to rise for African cash crops, which use ~12% of cropland in the SSA, are mostly not produced in temperate zones, and are large sources of export revenues. We believe only finer-scale analyses than our analysis should be used to map less harmful expansion areas, but our analysis does suggest useful principles. Efforts to target new cropland should not be based on broad, unanalysed land-use categories or emissions per hectare, but should focus instead on areas with relatively lower carbon and biodiversity costs per likely ton of yield. Plausible economic potential to achieve high yields, foregone milk and meat output from pasture, and social implications to pastoralists and others should also be important considerations.

Methods

To estimate ratios of global carbon loss from land conversion to crop output, we used a global cropland map, FAO yield data, and estimates of native carbon stocks using the LPJmL global vegetation model (Supplementary Information). We assumed that cropland conversion led to the loss of all vegetative carbon in native vegetation and 25% of soil carbon within the top metre.

To estimate potential yields within the GS, we used the DSSAT (ref. 37) crop model and assumed high inputs of nitrogen, use of the highest yielding seed varieties, and alleviation of other prominent potential production problem such as pests, or lack of phosphorus. We also performed this analysis using a separate estimate of maximum attainable ('climatic potential') yields, which were based on the 90th percentile of observed yields[25] in the year 2000 within each of 100 distinct climatic zones identified for the globe[24]. For existing yields, we used the mean of observed actual yields within the GS for each climate zone in the data for that study and assumed any expansion within the same climate zone would have that mean yield. For carbon stocks in the GS, we used a spatial vegetation Q.5 carbon database from Ruesch & Gibbs (Supplementary Information) and the HWSD database (Supplementary Information) for soil carbon, and we alternatively used estimates of vegetative and soil carbon using the LPJmL model. Using the LPJmL model for global carbon estimates and using database estimates of carbon stocks in the GS creates a risk of potential inconsistencies, but we also used LPJmL to estimate carbon stocks in the GS, and it generated similar carbon loss/yield estimates to those based on the Ruesch & Gibbs (Supplementary Information) and the HWSD databases.

We derived estimates of 2007 and 2050 food consumption demands, net imports, land use and yield growth needs in SSA from data in FAOSTAT and projections by FAO (ref. 1), adjusting for higher UN population estimates in 2050 released in 2013.

We used the LPJmL (Supplementary Information) global vegetation model to spatially estimate yields of perennial grass bioenergy crops parameterized to match the net primary productivity of native vegetation and alternatively to match yields of *Miscanthus x giganteus* and switchgrass in test plots (Supplementary Information). We used the GREET model (Supplementary Information) to estimate greenhouse gas emissions relative to gasoline, ignoring land-use change, and LPJmL as well as alternative methods to estimate vegetation and soil carbon losses.

We estimated vertebrate biodiversity using data from the International Union for the Conservation of Nature (Supplementary Information), subject to a variety of spatial and statistical analyses. The Supplementary Information provides extensive additional material regarding methods.

Received 15 June 2014; accepted 14 January 2015; published online XX Month XXXX

References

1. Alexandratos, N. & Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012 Revision* (ESA Working paper Rome, FAO, 2012); http://environmentportal.in/files/file/World%20agriculture%20towards%202030.pdf
2. Deininger, K. & Byerlee, D. *Rising Global Interest in Farmland: Can it Yield Equitable and Sustainable Results?* (World Bank, 2011).
3. Lambin, E. F. & Meyfroidt, P. Global land use change, economic globalization, and the looming land scarcity. *Proc. Natl Acad. Sci. USA* **108,** 3465–3472 (2011).
4. Hoogwijk, M., Faaij, A., Eickhout, B., de Vries, B. & Turkenburg, W. Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass Bioenergy* **29,** 225–257 (2005).
5. Van Vuuren, D. P., van Vliet, J. & Stehfest, E. Future bio-energy potential under various natural constraints. *Energy Policy* **37,** 4220–4230 (2009).
6. Cai, X., Zhang, X. & Wang, D. Land availability for biofuel production. *Environ. Sci. Technol.* **45,** 334–339 (2011).
7. Chum, H. *et al.* in *IPCC Spec. Rep. Renew. Energy Sources Clim. Change Mitig.* (eds Edenhofer, O. *et al.*) (International Panel on Climate Change, 2011).
8. Bauen, M. *Bioenergy-A Sustainable and Reliable Energy Source. A Review of Status and Prospects* (International Energy Agency, 2009); http://www.ieabioenergy.com/wp-content/uploads/2013/10/MAIN-REPORT-Bioenergy-a-sustainable-and-reliable-energy-source.-A-review-of-status-and-prospects.pdf
9. Morris, M. & Byerlee, D. *Awakening Africa's Sleeping Giant* (World Bank and FAO, 2009).
10. Stevenson, J. R., Villoria, N., Byerlee, D., Kelley, T. & Maredia, M. Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. *Proc. Natl Acad. Sci. USA* **110,** 8363–8368 (2013).
11. Gebara, M. F. & Thuault, A. *GHG Mitigation in Brazil's Land Use Sector* (World Resources Institute, 2013).
12. Lipinsky, B., Hanson, C., Waite, R. & Searchinger, T. *Reducing Food Loss and Waste* (World Resources Institute, 2013).
13. Wirsenius, S., Hedenus, F. & Mohlin, K. Greenhouse gas taxes on animal food products: Rationale, tax scheme and climate mitigation effects. *Climatic Change* **108,** 159–184 (2011).
14. Soares-Filho, B. *et al.* Cracking Brazil's forest code. *Science* **344,** 363–364 (2014).
15. Wilkie, D., Shaw, E., Rotberg, F., Morelli, G. & Auzel, P. Roads, development, and conservation in the Congo Basin. *Conserv. Biol.* **14,** 1614–1622 (2000).
16. Rosenberger, A., Gingold, B., Prasodjo, R., Alisjahbana, A. & Putraditama, A. *How to Change Legal Land Use Classifications to Support More Sustainable Palm Oil Production in Indonesia* (World Resources Institute, 2013).
17. Rulli, M. C., Saviori, A. & D'Odorico, P. Global land and water grabbing. *Proc. Natl Acad. Sci. USA* **110,** 892–897 (2013).
18. Houghton, R. A. & Hackler, J. L. *Carbon Flux to the Atmosphere from Land-Use Changes* (TRENDS Compend. Data Glob. Change, 2002); http://www.ornl.gov/~webworks/cpr/misc/108689_.pdf
19. Tilman, D. Global environmental impacts of agricultural expansion: The need for sustainable and efficient practices. *Proc. Natl Acad. Sci. USA* **96,** 5995–6000 (1999).
20. Foley, J. A. *et al.* Solutions for a cultivated planet. *Nature* **478,** 337–342 (2011).
21. Ramankutty, N., Evan, A. T., Monfreda, C. & Foley, J. A. Farming the planet: 1. Q.6 Geographic distribution of global agricultural lands in the year 2000. *Glob. Biogeochem. Cycles* **22,** 19 (2008).
22. Palm, C. A., Vosti, S. A., Sanchez, P. A. & Ericksen, P. J. *Slash-And-Burn Agriculture: The Search for Alternatives* (Columbia Univ. Press, 2013).
23. West, P. C. *et al.* Trading carbon for food: Global comparison of carbon stocks Q.7 vs. crop yields on agricultural land. *Proc. Natl Acad. Sci. USA* http://dx.doi.org/10.1073/pnas.1011078107 (2010).
24. Licker, R. *et al.* Mind the gap: How do climate and agricultural management explain the 'yield gap' of croplands around the world? *Glob. Ecol. Biogeogr.* **19,** 769–782 (2010).
25. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Glob. Biogeochem. Cycles* **22,** GB1022 (2008).
26. Haberl, H. *et al.* Bioenergy: How much can we expect for 2050? *Environ. Res. Lett.* **8,** 031004 (2013).
27. Thomson, A. M., Izaurralde, R. C., West, T., Parrish, D. J. & Tyler, D. D. *Simulating Potential Switchgrass Production in the United States* (Pacific Northwest National Laboratory, 2009); http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19072.pdf
28. Mistry, J. *World Savannas: Ecology and Human Use* (Prentice Hall, 2000).
29. Laurance, W. F. *et al.* Ecosystem decay of Amazonian forest fragments: A 22-year investigation. *Conserv. Biol.* **16,** 605–618 (2002).
30. Laurance, W. F. *et al.* The fate of Amazonian forest fragments: A 32-year investigation. *Biol. Conserv.* **144,** 56–67 (2011).
31. Terborgh, J. *et al.* Ecological meltdown in predator-free forest fragments. *Science* **294,** 1923–1926 (2001).
32. Walsh, P. D. *et al.* Catastrophic ape decline in western equatorial Africa. *Nature* **422,** 611–614 (2003).
33. Gaston, K. J., Jackson, S. F., Cantú-Salazar, L. & Cruz-Piñón, G. The ecological performance of protected areas. *Annu. Rev. Ecol. Evol. Syst.* **39,** 93–113 (2008).
34. Rodrigues, A. S. L. *et al.* Effectiveness of the global protected area network in representing species diversity. *Nature* **428,** 640–643 (2004).
35. Heckett, T. & Aklilu, N. *Agrofuel Development in Ethiopia: Rhetoric, Reality, and Recommendations* (Forum for Environment, in partnership with Horn of Africa Regional Environmental Center and Heinrich Boell Stiftung, 2008); http://boell-ethiopia.org/downloads/Binder1.pdf Q.8
36. You, L. *et al.* What is the irrigation potential for Africa? A combined biophysical and socioeconomic approach. *Food Policy* **36,** 770–782 (2011).
37. Jones, J. W. *et al.* The DSSAT cropping system model. *Eur. J. Agron.* **18,** 235–265 (2003).

Acknowledgements

The authors wish to thank N. Walker for encouragement and for helping to organize the workshop that gave rise to this paper, and for financial support, the authors wish to thank the David & Lucile Packard Foundation, the Norwegian Agency for Development Cooperation, the Gordon and Betty Moore Foundation, the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) from the CGIAR Fund and associated donors and the European Union Seventh Framework Programme (FP7/2007–2013) under grant agreement no 308371.

Author contributions

T.D.S. wrote the paper and contributed to all analyses. L.E. undertook the biodiversity and land-use analyses and contributed to all other analyses. P.K.T. performed the DSSAT crop modelling. T.B. led the bioenergy analysis and all work involving the LPJmL model. A.N. contributed to land-use analysis and mapping. D.R. contributed to the biodiversity analysis. R.H. carried out bioenergy analysis with the GREET model and food and land-use demand needs in SSA. R.L. performed yield gap analysis. M.H. contributed land-use analysis. All authors contributed to the general paper content, thinking and writing.

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 T.D.S. or L.E.

Competing financial interests

The authors declare no competing financial interests.

Queries for NPG paper nclimate2584

Page 1

Query 1:
Please provide more details, including the postcode, for all affiliations.

Query 2:
Should the text here be hyphenated to 'a large low-carbon and -biodiversity cropland reserve'?

Page 2

Query 3:
Please note that reference numbers are formatted according to style in the text, so that any reference numbers following a symbol or acronym are given as 'ref. XX' on the line, whereas all other reference numbers are given as superscripts.

Page 4

Query 4:
Captions of figures 2 and 4 amended. Please check.

Page 5

Query 5:
Can 'Ruesch & Gibbs' be treated as a reference? If so, please provide further details.

Query 6:
Please provide page range/article id for ref. 21

Query 7:
Please provide page range/article and volume number for ref. 23

Query 8:
Please check the URL given in reference 35 as it seems to generate an error.