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Implementation and opportunity costs of reducing deforestation and forest degradation in Tanzania

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The Cancún Agreements provide strong backing for a REDD+ (Reducing Emissions from Deforestation and Forest Degradation) mechanism whereby developed countries pay developing ones for forest conservation[1]. REDD+ has potential to simultaneously deliver cost-effective climate change mitigation and human development[2–5]. However, most REDD+ analysis has used coarse-scale data, overlooked important opportunity costs to tropical forest users[4,5] and failed to consider how to best invest funds to limit leakage, that is, merely displacing deforestation[6]. Here we examine these issues for Tanzania, a REDD+ country, by comparing district-scale carbon losses from deforestation with the opportunity costs of carbon conservation. Opportunity costs are estimated as rents from both agriculture and charcoal production (the most important proximate causes of regional forest conversion[7–9]). As an alternative we also calculate the implementation costs of alleviating the demand for forest conservation—thereby addressing the problem of leakage—by raising agricultural yields on existing cropland and increasing charcoal fuel-use efficiency. The implementation costs exceed the opportunity costs of carbon conservation (medians of US\$6.50 versus US\$3.90 per Mg CO_2), so effective REDD+ policies may cost more than simpler estimates suggest. However, even if agricultural yields are doubled, implementation is possible at the competitive price of ∼US\$12 per Mg CO_2.

Understanding the economics of carbon conservation is especially important in sub-Saharan Africa, the world's most income-poor region, where it has the potential to affect ∼200 million food-insecure people and where forest conversion is still strongly linked to subsistence agricultural expansion and fuel extraction[7–9]. Over the next 40 years forests are likely to be lost faster here than in any other part of the tropics[10], leading not just to direct CO_2 emissions, but also the erosion of a globally significant net carbon sink[11]. REDD+ payments hold considerable potential for tackling these problems.

Attempts to estimate how much REDD+ might cost have focused on the opportunity costs of carbon conservation[4,5], but have been limited by the coarse scale of available data and the lack of information on some important benefits of forest conversion. A second problem is that simply paying people not to clear forests will mean rising demand for food and fuel goes unmet locally, leading to leakage—where deforestation is simply displaced elsewhere. Implementing policies that instead address these demands in other ways might well cost more than opportunity-cost calculations suggest, yet may be essential if REDD+ as a performance-dependent payment mechanism is not to be short-lived.

To establish more robust measures of the opportunity costs of REDD+ and assess how they compare with these implementation costs we therefore compiled and analysed data on carbon pools, carbon losses, and the dynamics and economics of forest conversion in Tanzania—a country where otherwise unmet demands for food and fuel lead to large-scale deforestation and degradation[12]. Focusing on 53 eastern districts (518,000 km^2, ∼14.5 million people; Supplementary Fig. S1) for which we had carbon, agriculture and charcoal data, we calculated the level of carbon payments needed to offset the opportunity costs of stopping further forest loss, and to meet the implementation costs of an illustrative programme for meeting food and fuel demand without clearing or degrading more forest.

Starting with the opportunity-cost approach to estimating the carbon price necessary for REDD+ to be economically viable, for each district we quantified the likely financial rent from forest conversion relative to the gains from forest carbon conservation. For the rent of agriculture we used data from the Tanzania Ministry of Agriculture's 2003 agricultural census, which surveyed over 3,000 villages and 50,000 households[13], as well as market surveys and published cost data (see Methods). Across the districts there was a wide range of net rents to agriculture, driven primarily by crop choice and yield (interquartile range of Net Present Values: US\$663–US\$1,456 ha^{-1}; median: US\$942 ha^{-1}; Fig. 1a; Supplementary Table S1)

What about other opportunity costs of stopping deforestation and forest degradation?

The woodlands that dominate our study region are not used extensively for timber. Instead, the most important non-agricultural use, in monetary terms, is charcoal production[12,14]. This charcoal is used almost entirely in towns and cities, with >80% of urban Tanzanians relying on it for cooking[14]. We therefore also calculated the potential returns from charcoal production during forest conversion (see Methods), but did not include other minor opportunity costs of forest conservation. Comparing our district-specific estimates of opportunity costs suggests that, although ignored by previous analyses, lost charcoal rent is a major cost (interquartile range of Net Present Values: US\$358–US\$502 ha^{-1}; median: US\$416 ha^{-1}; Fig. 1b; Supplementary Table S1); on average it represents 33% ±13% (1 s.d.) of the total opportunity cost of conservation that we calculate (Fig. 2).

To estimate the carbon that could be saved by REDD+, we next assumed that the carbon stored in the average next-to-be-converted

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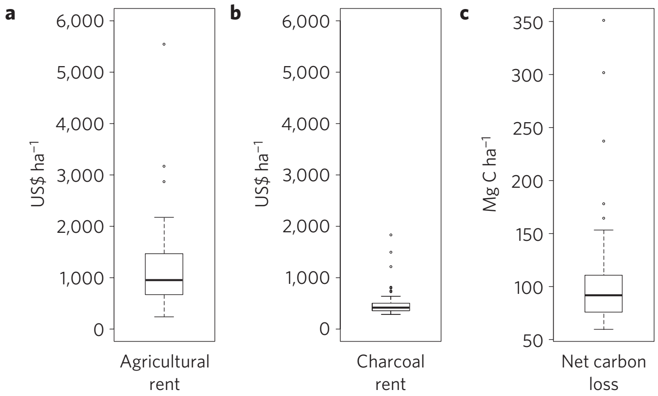

Figure 1 | District-level results for agricultural rent, charcoal rent and carbon lost under forest conversion. Net present value of **a**, agricultural rent and **b**, charcoal rent (US$ ha^{-1}). **c**, Net carbon lost when converting the 'average hectare' of forest to agriculture (Mg C ha^{-1}). Dark bars represent median values, boxes represent interquartile ranges, whiskers equal 1.5 times the interquartile range.

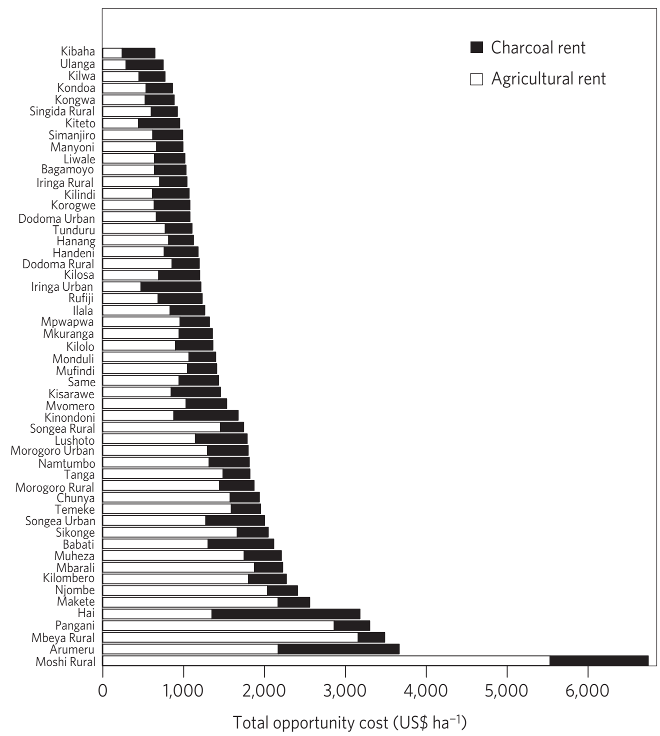

Figure 2 | Opportunity cost of forest conservation. Opportunity costs (US$ ha^{-1}) for each of the 53 eastern Tanzanian districts as the sum of net agricultural rent (white) and charcoal rent (black). Agricultural rents are a net present value. Districts are ranked in order of increasing total opportunity cost.

hectare of forest in each district was equal to the mean of total carbon storage (summed over the five carbon pools required for Intergovernmental Panel on Climate Change reporting requirements) of each forest class, weighted by the area of each class within the district (see Methods and Supplementary Table S2). We then calculated the net carbon change on conversion as this value minus the total carbon storage under the alternative agricultural land use for each district (Fig. 1c; Supplementary Table S1). Last, we divided the sum of the net agricultural rent and the charcoal rent from forest conversion by the corresponding estimate of net carbon loss to derive each district's carbon offset price.

Using this approach the median offset price is US$3.90 per Mg CO_2 (interquartile range: US$3.20–US$5.50 per Mg CO_2; Fig. 3a; Supplementary Table S1). The variation across districts is large owing to the differences in agricultural crop choice (Supplementary Table S3), yield and variation in wood available for charcoal. Sensitivity analyses showed that the choice of discount rate had the greatest effect on the median offset price, but this always remained below US$6 per Mg CO_2 (Supplementary Fig. S2).

However, the opportunity-cost approach assumes that there are well-functioning commodity markets where communities limiting their conversion activity can buy food and other products foregone under conservation. Where this is true it may simply shift pressure for forest conversion elsewhere, so that carbon benefits are lost through leakage. Where it is not true (as in much of the developing world, including Tanzania, where those involved in conversion often have only limited access to imperfect markets[15]), preventing forest conversion may lead to increased poverty because food and fuel demands go unmet. For these reasons we therefore complemented our opportunity-cost calculations with a more practical approach, estimating instead the cost of implementing policies aimed at directly alleviating demand for forest conversion and degradation. We considered, for each district, the cost of boosting agricultural yield on existing farmland, and of decreasing charcoal demand by increasing the efficiency of charcoal cooking stoves, to match the food and charcoal that would have been produced through continued conversion. In principle this implementation cost approach thus estimates the costs of meeting demand for food and fuel sustainably and—when linked with forest protection—without leakage. Looking first at the cost of increasing farm yields, agricultural productivity is well below its potential in Tanzania and indeed across sub-Saharan Africa[16–18]. Tanzanian government statistics put the national yield of maize at $\sim$1 Mg ha^{-1} yr^{-1}, although census data suggests it is closer to 0.7 Mg ha^{-1} yr^{-1} (ref. 13). However, potential yields are closer to 5 Mg ha^{-1} yr^{-1} (refs 16–18). In the districts we studied, the use of chemical fertilizers and improved seed, and access to credit are all extremely low (employed on 8%, 17% and 7% of farms, respectively[13]). There is clearly considerable scope for yield increases[18].

We assumed that because yields are so low (weighted mean maize yield: 0.7 Mg ha^{-1} yr^{-1}) the marginal cost of increasing them is independent of current yield. We also assumed that the relationship between yield growth and avoided deforestation is imperfect[19,20], because yield increases are unlikely to reduce habitat conversion in situations where they generate capital, free up labour or increase demand[21]. Research has suggested a wide range of elasticities in developing countries between land spared and yield gained, from −0.15% across all developing countries[19] to 1.08% for sub-Saharan Africa[20]. However, where policies explicitly link yield gains with conservation, more marked land sparing has occurred[20]. Given that REDD+ payments will be conditional on verifiable emission reductions, we conservatively assumed that they will be at least 50% efficient in sparing forests from clearance, such that a 1% increase in yield leads to only a 0.5% decrease in forest conversion. We then used data from the Millennium Villages Project[17] to estimate the cost of implementing the necessary yield increase (see Methods).

Charcoal demand would also have to be reduced to ensure that the fuel production lost through carbon conservation is not simply replaced through leakage. As is the case for raising farming yields, reducing demand for charcoal is a widespread challenge across the tropics[22]. To avoid the conversion of one hectare, fuel demand would have to be reduced by an amount equal to the fuel that its conversion would yield. Here we estimated doing so by increasing the efficiency of charcoal-burning stoves. In Tanzania, and elsewhere in Africa, there are projects producing locally made fuel-efficient stoves that can increase cooking efficiency by 40–75% (ref. 23). However, as for interventions to increase

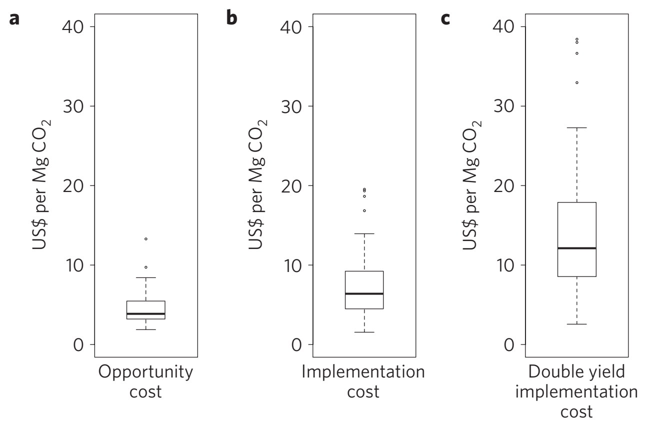

Figure 3 | Opportunity and implementation cost estimates for REDD+. District-level results for when carbon payments (US$ per Mg CO_2) offset **a**, the opportunity cost of conservation; **b**, the implementation cost of alleviating demand for the next hectare converted through gains in agricultural yield and stove efficiency (including monitoring costs); and **c**, the implementation cost of doubling agricultural yield, replacing demand for charcoal from the next hectare of forest converted, and associated monitoring. Dark bars represent median values, boxes represent interquartile ranges, whiskers equal 1.5 times the interquartile range.

yields, fuel-efficient stove projects in the tropics face multiple problems, such that they have been only partially effective owing to cost, cultural norms, personal preferences and rebound effects[24] (although it is now better understood how implementation and adoption rates can be improved, such as through the free distribution of stoves and follow-up technical visits (see ref. 22)). Evidence from sub-Saharan Africa suggests an elasticity of 0.58, where a 1% gain in fuel efficiency means a 0.58% decrease in fuel demand[24]. To be conservative we therefore estimated the number of fuel-efficient stoves needed to offset charcoal demand assuming a stove efficiency gain of 50% and an inelastic response at −0.5%. We then added the purchase price of fuel-efficient stoves and the cost of training people in their use (see Methods).

By adding this cost of reducing fuel demand to that of increasing crop yields plus monitoring REDD+ we estimated the total implementation cost in each of the 53 districts of meeting the demand that would otherwise have been met through converting one additional hectare of the district's remaining forest. Variation in crop yield, forest class and the availability of wood for charcoal produce a total cost that differs across districts with an interquartile range of US$4.60–US$9.40 per Mg CO_2 and a median value of US$6.50 per Mg CO_2 (Fig. 3b; Supplementary Table S1; sensitivity analyses show that these cost estimates are reasonably robust and remain below US$8 per Mg CO_2 across a wide range of parameter values; Supplementary Fig. S3). Furthermore, crop yields are so low in Tanzania that even a doubling of yields in each district would cost only ∼US$12.30 per Mg CO_2 (median value; including all stove-efficiency and forest-monitoring costs; interquartile range: US$8.70–US$18.10 per Mg CO_2; Fig. 3c; Supplementary Table S1).

Costs of ∼US$12 per Mg CO_2 are well below the European Union's Emmission Trading Scheme price point for CO_2 (currently ∼US$24 per Mg CO_2), and more realistic than REDD+ cost estimates that ignore important opportunity costs, such as foregone charcoal production, and neglect the critical issue of how and where the shortfall in food and fuel production will be met. Moreover, we assumed that a REDD+ mechanism would only be 50% efficient in reducing demand for forest conversion, but because REDD+ payments will likely be performance-based and therefore linked to verifiable emissions reductions[1] this assumption and our results are likely to be conservative. This assumed inefficiency also suggests that the amount of crop produced in the region and the amount of usable energy derived from its charcoal would be greater if rising demand is met, as we suggest, through yield and fuel-efficiency increases rather than through continued land conversion. These gains could be seen as additional benefits of the implementation of such a programme.

Recent analyses suggest that, at continental scales, large increases in carbon emissions have been associated with only small increases in food production[25,26]. This trade-off seems to be most severe in the tropics[26]. Here we show that it may be possible to obtain large increases in food production (with attendant human welfare benefits) and conserve forest carbon (with attendant biodiversity conservation benefits) for a relatively small economic cost. Although we use just one approach to calculate implementation costs (that is, increasing crop yields through using more fertilizer and improved seeds, plus more efficient fuel use), other approaches (such as intensifying agriculture with legume cover crops or tree fallows[27], subsidizing alternative cooking fuels (for example liquid fuels), or developing plantations for charcoal fuel) might be more cost-effective or practical.

In comparison with less-focused REDD+ interventions, those that directly target the local drivers of deforestation will be far less prone to within-country and cross-border leakage, and hence will be more likely to lead to sustained emission reductions and hence greater carbon, biodiversity and social benefits. Such targeted interventions could be considered Smart-REDD. The scope and apparent cost-effectiveness of boosting farm yields and increasing the efficiency of fuel use imply that Smart-REDD interventions may have merit not just in Tanzania, but also in other REDD-eligible countries where subsistence agriculture and fuelwood extraction drive forest clearance and degradation.

However, this conclusion is subject to two final but important caveats. First, because implementation costs exceed opportunity costs, if levels of REDD+ financing are based on opportunity-cost calculations they may be insufficient for effective carbon conservation. Policymakers need to be aware of this when devising REDD+ budgets. Second, although we show that the approaches we explore for Smart-REDD implementation are economically feasible they will face practical impediments (such as enhancing the capacity of institutions to enforce property rights). We suggest one valuable next step would be to establish randomized trials[28] to assess the delivery of Smart-REDD on the ground. Building implementation concerns into the design and funding of REDD+ from the outset is vital if this bold global ecosystem service payment scheme is to succeed.

Methods

For each district we used the top five crops planted by area (representing ∼85% of all planted area), mean yields, regional market prices and the cost of seeds, land, fertilizer, labour and transportation to market, to obtain a net present value (discounted at 10% for 30 yr) for an area-weighted 'average hectare' of smallholder farm in a given district (see Supplementary Equations S1, S2, Table S1). The choice of discount rate reflects the median rate of lending by the Bank of Tanzania (2007–2010; 10.8%). Discount rates of 5% and 15% were applied for sensitivity analyses, but have limited impact (Supplementary Fig. S2). In the absence of spatially explicit predictions of future crop composition, this 'average hectare' represents the most likely composition of agriculture on the next hectare of converted forest.

We estimated the amount of charcoal that can be produced and sold before farming the land, using statistical relationships between above-ground biomass and yield of wood available for charcoal in each of our nine forest cover classes in all 53 districts, based on published field studies from Tanzania (Supplementary Equation S3). We then used published kiln efficiencies for converting biomass into charcoal in Tanzania and profit data from charcoal supply chain analyses to calculate the net rent of charcoal production from converting the next 'average hectare' in a given district (Supplementary Equation S4).

Using the Food and Agriculture Organization definition of forest (which includes both closed-canopy or tropical moist forest and open forest, known locally as miombo or woody savanna), we identified nine forest classes in our study area (open woodland, closed woodland, forest mosaic, sub-montane forest, montane forest, upper montane forest, mangrove forest, lowland forest, woodland with scattered crops). For each of these we derived carbon values for four of the Intergovernmental Panel on Climate Change's five carbon pools—above-ground live tree carbon, coarse woody debris (necromass or dead tree carbon), litter carbon (dead leaves), and below-ground live carbon (roots)—from published values, the grey literature and forest inventory data available to the authors (above-ground live carbon only); data on the fifth pool—soil carbon—were derived from the SOTOR database (Supplementary Table S2). We then used the sum of all five pools for a given forest class to derive an area-weighted average carbon value for each district's forest, which, given the lack of spatially-explicit deforestation information, we therefore took to be the carbon storage of that district's next-converted hectare (Supplementary Equation S5). Finally, we used the same sources to estimate total carbon storage under agriculture, and subtracted this from each district's area-weighted forest average to estimate the net change in storage from the next hectare of conversion (Supplementary Equation S6 and Table S1).

For implementation cost calculations we assumed that the average next-converted hectare for each district would grow maize only (which represents 46% of all farmed area). We used the current mean yield in each district as the yield that would be lost on a hectare that, because of REDD+, would now not be converted. We next took data from the Millennium Villages Project (MVP; ref. 17) which recorded the costs of improving maize yields by 1 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ over the 12 African Millennium Villages. We then calculated the cost of replacing the lost maize by boosting yields on existing farmland through improved seed, increased fertilizer use and extension training (Supplementary Equation S7 and Table S1).

To estimate the implementation cost of sparing the charcoal for which production would be forfeited as a result of forest conservation we first calculated the amount of charcoal that needs to be spared in each district (Supplementary Equation S8). We then calculated the amount of fuel spared by replacing an inefficient charcoal stove with a high efficiency stove over its lifetime, based on household charcoal demand from district-level household data (Supplementary Equation S9). From this we could calculate the number of efficient stoves needed to offset the amount of charcoal that one hectare of forest in a given district could produce (Supplementary Equation S10 and Table S1), and therefore the implementation cost of offsetting the lost charcoal production (Supplementary Equation S11) based on the cost of the stove and associated training and distribution. We doubled the number of stoves, to be conservative and to reflect the elasticity (0.5) discussed above and shown in the literature[24].

Last, we included in our implementation cost the estimated costs of delivering and monitoring a REDD+ mechanism: establishing baselines, and monitoring and verifying carbon stocks over time. We used an estimate taken from 12 forest-monitoring assessments in Tanzania of \$2.95 $\mathrm{ha^{-1}\,yr^{-1}}$ (ref. 29). This cost is in line with several other estimates (Supplementary Table S4), and was extended over 30 years and discounted at 10% $\mathrm{yr^{-1}}$.

All prices and costs have been standardized to 2010 US\$.

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Author contributions

B.F. and A.B. conceived the study. B.F., A.B., S.L.L., N.D.B. and R.K.T. designed the study. B.F., S.L.L., R.E.M., P.K.M. and S.W. collected data. B.F., A.B., S.L.L., R.D.S., R.E.M., P.K.M. and S.W. analysed the data. B.F., A.B. and S.L.L. wrote the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to B.F.