World Development Vol. 95, pp. 15–26, 2017
0305-750X/© 2017 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/4.0/).
ELSEVIER
www.elsevier.com/locate/worlddev
CrossMark
http://dx.doi.org/10.1016/j.worlddev.2017.02.022

Estimating Smallholder Opportunity Costs of REDD+: A Pantropical Analysis from Households to Carbon and Back

AMY ICKOWITZ [a], ERIN SILLS [a,b] and CLAUDIO DE SASSI [a,*]
[a] *Center for International Forestry Research (CIFOR), Bogor, Indonesia*
[b] *North Carolina State University, Raleigh, USA*

Summary. — Compensating forest users for the opportunity costs of foregoing deforestation and degradation was one of the original distinguishing features of REDD+ (Reducing Emissions from Deforestation and Degradation). In the early days of REDD+, such costs for tropical smallholders were believed to be quite low, but this has increasingly been questioned. A decade after the concept was proposed, direct payments to forest stakeholders remain rare, while concerns about safeguarding livelihoods are increasing. Households facing restrictions on forest-based activities will have to be compensated, yet evidence on actual costs to households, their distribution, and implications for efficiency and equity is limited. We estimate smallholder opportunity costs of REDD+ in 17 sites in six countries across the tropics. We use household data collected from multiple sites in multiple countries using a uniform methodology. We find that opportunity costs per tCO_2 emissions from deforestation are less than the social costs of tCO_2 emissions ($36) in 16 of the 17 sites; in only six of the sites, however, are opportunity costs lower than the 2015 voluntary market price for tCO_2 ($3.30). While opportunity costs per tCO_2 are of interest from an efficiency perspective, it is opportunity costs per household that are relevant for safeguarding local peoples' income. We calculate opportunity costs per household and examine how these costs differ for households of different income groups within each site. We find that poorer households face lower opportunity costs from deforestation and forest degradation in all sites. In a system of direct conditional payments with no transactions costs to households, poorer households would earn the highest rents from a system of flat payments. Our findings highlight that heterogeneity and asymmetrical distribution of opportunity costs within and between communities bear important consequences on both equity and efficiency of REDD+ initiatives.

Keywords — REDD+, Deforestation, Degradation, Opportunity costs, Equity

1. INTRODUCTION

Reducing Emissions from Deforestation and Degradation (REDD+) was conceived as a conditional incentive program that would compensate forest users and governments for voluntary reductions in carbon emissions from deforestation and forest degradation. The hundreds of REDD+ initiatives implemented across the tropics have sought to encourage reductions in forest carbon emissions through many different forms of compensation (Sills *et al.*, 2014; Simonet *et al.*, 2015; Sunderlin *et al.*, 2015). However, there is a common expectation that REDD+ must at minimum cover the costs of those who are affected by its implementation (Luttrell *et al.*, 2013). Whether emissions are measured and verified at the national, regional, or village level, ultimately it is local actors in the land sector who bear the costs of generating the global good of reduced carbon emissions (Visseren-Hamakers, McDermott, Vijge, & Cashore, 2012).

In most tropical forest settings, a large share of those local actors are smallholders whose livelihoods depend on forest and land uses that generate carbon emissions. Foregoing or limiting those uses for REDD+ will impose opportunity costs on smallholders. Protecting their livelihoods has become a major focus of concern in REDD+ policy, e.g., as reflected in the "safeguards" adopted at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP16) in Cancun, Mexico in 2010 (Jagger *et al.*, 2014). Compensating households fairly for their opportunity costs is a necessary condition for safeguarding local livelihoods. Understanding potential impacts on the poorest members of local communities requires an understanding of both the level and distribution of opportunity costs across households.

There have been numerous efforts to estimate the opportunity costs of avoided deforestation and forest degradation, reflecting the central role of opportunity costs in the original concept of REDD+ (Grieg-Gran, 2008; Stern, 2006). Most studies report an average cost per tonne of avoided carbon emissions (or per tCO2e), with results that vary by location and methodology. We expand on this literature by estimating opportunity costs with household survey data from 130 rural communities located in and near sites selected for REDD+ initiatives in six countries (Sunderlin *et al.*, 2016). We show how cost per tonne of carbon and cost per household vary across sites, while holding methodology constant, addressing a major concern with previous literature. We estimate the opportunity costs of avoided degradation as well as avoided deforestation. Finally, we disaggregate cost per household

* This research is part of CIFOR's Global Comparative Study on REDD+ (www.cifor.org/gcs). The funding partners that have supported this research include the Norwegian Agency for Development Cooperation (Norad), the Australian Department of Foreign Affairs and Trade (DFAT), the European Commission (EC), the International Climate Initiative (IKI) of the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB), the United Kingdom Department for International Development (UKAID), and the CGIAR Research Program on Forests, Trees and Agroforestry (CRP-FTA), with financial support from the donors contributing to the CGIAR Fund. Final revision accepted: February 12, 2017.

within sites by income group to illustrate how the costs of REDD+ vary within communities.

In the following section, we review conceptual and methodological concerns with previous estimates of opportunity costs, noting which are caveats on our analysis. After describing our methods and presenting our estimates of opportunity costs, we use those estimates to assess the implications of different compensation schemes, which we conceptualize as direct conditional payments to households.

2. OPPORTUNITY COSTS AND REDD+: COMPLEXITIES AND CAVEATS

Early estimates of the opportunity costs that REDD+ would impose on smallholders were criticized as being unrealistically low (Dyer & Counsell, 2010; Fosci, 2013). For example, a well-known McKinsey & Co. study estimated that the costs of avoiding deforestation from slash and burn agriculture and cattle ranching were less than 2 Euros per tCO_2 (Nauclér & Enkvist, 2009). Attempts to improve on those early estimates have produced widely varying results, at least partly due to the use of different models and estimation methods (Gregersen, Lakany Karsen, & White, 2010; Wertz-Kanounnikoff, 2008). Phan, Brouwer, and Davidson (2014) review 32 primary studies of opportunity costs, which use different types of data, methods, and scales of analysis and report a very wide range of costs from \$0.15 to \$339 per tonne of carbon. They were not able to disentangle differences that are due to variation in actual opportunity costs related to site characteristics or local activities from those that are a by-product of methodological and data choices.

To understand potential impacts on households, it is important to use household level as opposed to national or sub-regional level data. Aggregate data are useful for predicting overall costs of REDD+, but not for understanding household participation patterns and equity implications. One study (Araya & Hofstad, 2014), published after the Phan *et al.* (2014) review, did use household data and employed the same methods to calculate opportunity costs across two sites in Tanzania in different agro-ecological zones, finding very large differences in opportunity costs.

Given concerns about the impact of REDD+ on equity and on the poor in particular (Gregersen *et al.*, 2010; Lawlor, Madeira, Blockhus, & Ganz, 2013; Mohammed, 2011), it is important to understand not only the average opportunity cost per tonne of carbon, per hectare of land, and per household, but also the distribution of those costs. For purposes of designing a compensation system, the key metric is opportunity costs per household, but there is very little empirical evidence on its distribution across households. One exception is Borrego and Skutsch (2014), who look at the distribution of opportunity costs across households by activity in communal areas in Jalisco, Mexico, and find that the poorer households would face lower opportunity costs from preventing degradation than richer households. In order to better understand likely impacts of REDD+ restrictions on the poorest income groups, more such empirical work is needed across a diversity of REDD+ sites.

One of the most controversial aspects of opportunity cost calculations is the question of who has "carbon rights" and thus whose opportunity costs are to be calculated (Luttrell, Sills, Aryani, Ekaputri, & Evinke, 2017). Because forest tenure in tropical countries is often contested and rarely recorded in a formal titling system, determining who should receive REDD+ compensation can be complicated (Palmer, 2011). If only private landholders with secure and formal tenure rights were recognized, many (if not most) smallholders in REDD+ countries would be ineligible (Larson *et al.*, 2013). However, opportunity cost calculations that exclude values to those smallholders would clearly be incomplete if they are engaged in deforesting or forest degrading activities (White *et al.*, 2011). In this study, we estimate opportunity costs based on land "used" by smallholders irrespective of formal ownership. This is consistent with the idea of REDD+ as inducing voluntary reductions in emissions by offering incentives to those who are currently deforesting and degrading forests, even if they do not have formal tenure. Land use agents can respond to conditional incentives as long as they can prevent outsiders from using the resource (Naughton-Treves & Wendland, 2014; Wunder, 2007). Legally enforceable exclusion rights are in many ways a prerequisite for conditional payments from a REDD+ proponents' perspective, and many REDD+ proponents have been working with communities to strengthen these rights (Larson *et al.*, 2013; Lawlor *et al.*, 2013; Sunderlin *et al.*, 2015).

The relevance of opportunity cost estimates to REDD+ has also been questioned on the grounds that they do not adequately represent the full costs of REDD+ to smallholders (Dyer & Counsell, 2010; Ekins, Kesicki, & Smith, 2011; Gregersen *et al.*, 2010). In cases where markets are thin or missing, the market values of food and materials that are affected by REDD+ restrictions may be poor indicators of their true replacement value because restrictions could affect prices as well as quantities (Dyer & Counsell, 2010). In some communities, restrictions on forest clearing could make current livelihood strategies obsolete. Shifting cultivation, for example, requires access to fallowed or forest land to remain a viable system (Ruthenberg, 1980). The opportunity cost of conserving all forest would be the entire production system. In such cases, it has been argued that the market value of current output does not fully capture the opportunity costs of restrictions (Gregersen *et al.*, 2010). This may be one of the reasons behind the tendency of REDD+ proponents to support alternative livelihood strategies rather than offer direct compensation to beneficiaries (Lawlor *et al.*, 2013; Mohammed, 2011; Sunderlin *et al.*, 2015), despite the poor track record of such strategies (Bauch, Sills, & Pattanayak, 2014; Clements, 2010). Even if a REDD+ initiative were to work successfully with communities to develop alternative livelihood options, this process takes time. In the interim, the short-run opportunity cost of forest conservation is best represented by current income from activities associated with deforestation and degradation.

Opportunity costs are only one component of the full costs of REDD+. Other costs, such as avoiding leakages, monitoring and verification of activities and emissions, and other transactions and implementation costs, are often borne by the government or other organization implementing REDD+ (Luttrell *et al.*, 2017), but may also be shared with local land use actors. Ensuring that the opportunity costs of REDD+ can be covered by carbon revenues does not necessarily imply that REDD+ is economically feasible. However, compensation of opportunity costs is the minimum requirement for REDD+ to be implemented as a voluntary program.

In sum, smallholder opportunity costs are one critical piece of information for designing and evaluating REDD+. We acknowledge that opportunity costs are not the only factor affecting willingness to participate in REDD+ and that they are not the only costs of REDD+. Thus compensating households for their opportunity costs is a necessary but not sufficient condition for REDD+ to "do no harm".

While safeguarding local wellbeing has been a central concern in both the UNFCCC negotiations and voluntary market standards such as CCB (Climate, Community, and Biodiversity), clearly not all organizations implementing REDD+ have been equally concerned. Accusations of "land grabbing", or evicting local people from their customary land, have been leveled at REDD+ initiatives (Fairhead, Leach, & Scoones, 2012; Larson *et al.*, 2013). This was part of the motivation for establishing safeguards (Chhatre *et al.*, 2012; Jagger *et al.*, 2014). Such safeguards do not guarantee that local stakeholders' interests will be respected by all REDD+ initiatives (Jagger *et al.*, 2014), because this depends on government commitment to enforcing the safeguards as well as the relative power of forest management authorities compared to civil society (Kashwan, 2015). The assumption that we use throughout the rest of the paper is that the REDD+ implementing institution is motivated to carry out REDD+ in a way that is both efficient and equitable. It is certainly legitimate to question whether this assumption reflects reality, but we believe that it is a good starting point to see whether and how such objectives might be achieved.

3. METHODS

(a) *Data*

We use data from CIFOR's Global Comparative Study on REDD+ (GCS-REDD) Module 2 on sub-national initiatives (http://www.cifor.org/gcs/modules/redd-subnational-initiatives) in Brazil, Peru, Cameroon, Tanzania, Indonesia, and Vietnam. GCS-REDD collected village and household-level baseline data during 2010–12, before REDD+ implementation. A comprehensive description of the study design and sampling methodology, aimed at providing a robust counterfactual design for impact assessment, is given in Sills et al. (In press); the study sites are described in terms of their geography, socioeconomics, initiative motivation, and strategy in Sills *et al.* (2014). For this manuscript, we use a subset of the full baseline sample, composed of the 17 sites as shown in Figure 1 for which household data are available.

In these 17 sites, the sample is composed of eight villages per site (with two exceptions explained in Appendix 3 of Sills *et al.* (2014)) and a target number of 30 smallholder households randomly selected in each village. The total number of households interviewed was 4183 (Sunderlin *et al.*, 2016). [1] For this study, twelve households were dropped after they were each identified as an "extreme income outlier", defined as an observation with income greater than the 75th percentile or smaller than the 25th percentile by an amount more than 10 times the inner quartile range (IQR), but without commensurate wealth and land endowments. Thus the actual sample used for our estimates consisted of 4,171 households. Detailed descriptions of each site and characteristics of their samples can be found in Sills *et al.* (2014). In the overall sample, about 90% of households were headed by males with a mean age of 46 years and an average of 5.5 years of education. Average household size was about five people.

The survey recorded household income over the last 12 months from all sources: crop production, animal husbandry and animal products, forest-based activities, wage labor, business, as well as other types of income such as government support and remittances. The full value of household production, for both sale and subsistence, is monetized, with market values imputed for products not traded in markets and purchased inputs deducted from that value. All monetary values are deflated to the year 2010 (2011 for two sites) and then converted to USD for ease of comparison. [2] The project design is fully described in Sunderlin *et al.* (2016) and the household questionnaire is available at http://www.cifor.org/library/3286/technical-guidelines-for-research-on-redd-project-sites-with-survey-instruments-and-code-book/.

To provide a sense of how the composition of the average household livelihood portfolio varies across sites, countries, and household income groups, Figure 2 shows average annual income (in USD) from all crops, all livestock, all forest-based activities, and all other income sources by income tercile (low, middle, and high income) averaged across the sites in each country. Income terciles are defined based on the total income of households in each site. Thus the "low-income" group in one site can only be compared with the "low-income" group in another site in the sense that they are the poorest in their respective communities, without implying any similarity in the absolute amount of their income. Note that average incomes differ substantially across the countries in our sample so that the scales of the *y*-axes in the figures are not the same. Thus, the figure is intended to illustrate variation across countries in the patterns of activities and variation across income terciles in the distribution of income from these activities.

Income from livestock was economically important in the REDD+ sites in Brazil and Tanzania and moderately important in Vietnam. In each of those countries, not only did the income from livestock of the "high-income" households vastly exceed that of "low-income" households, but the proportion of income from livestock was also substantially higher for the "high-income" households. For example, while in Brazil the poorest group actually earned negative income on average from livestock production in the year of the survey, almost 30% of the net income of the rich came from livestock production.

The relative contribution of crops to household income was highest in the REDD+ sites in Cameroon and Tanzania,

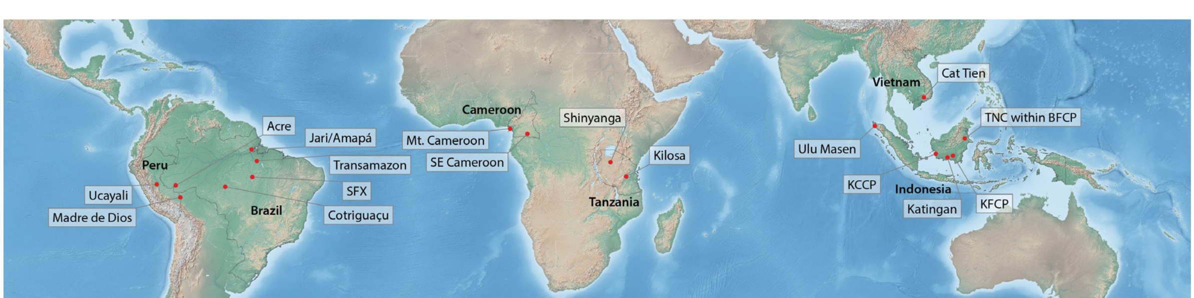

Figure 1. *Site map of GCS initiatives included in study.*

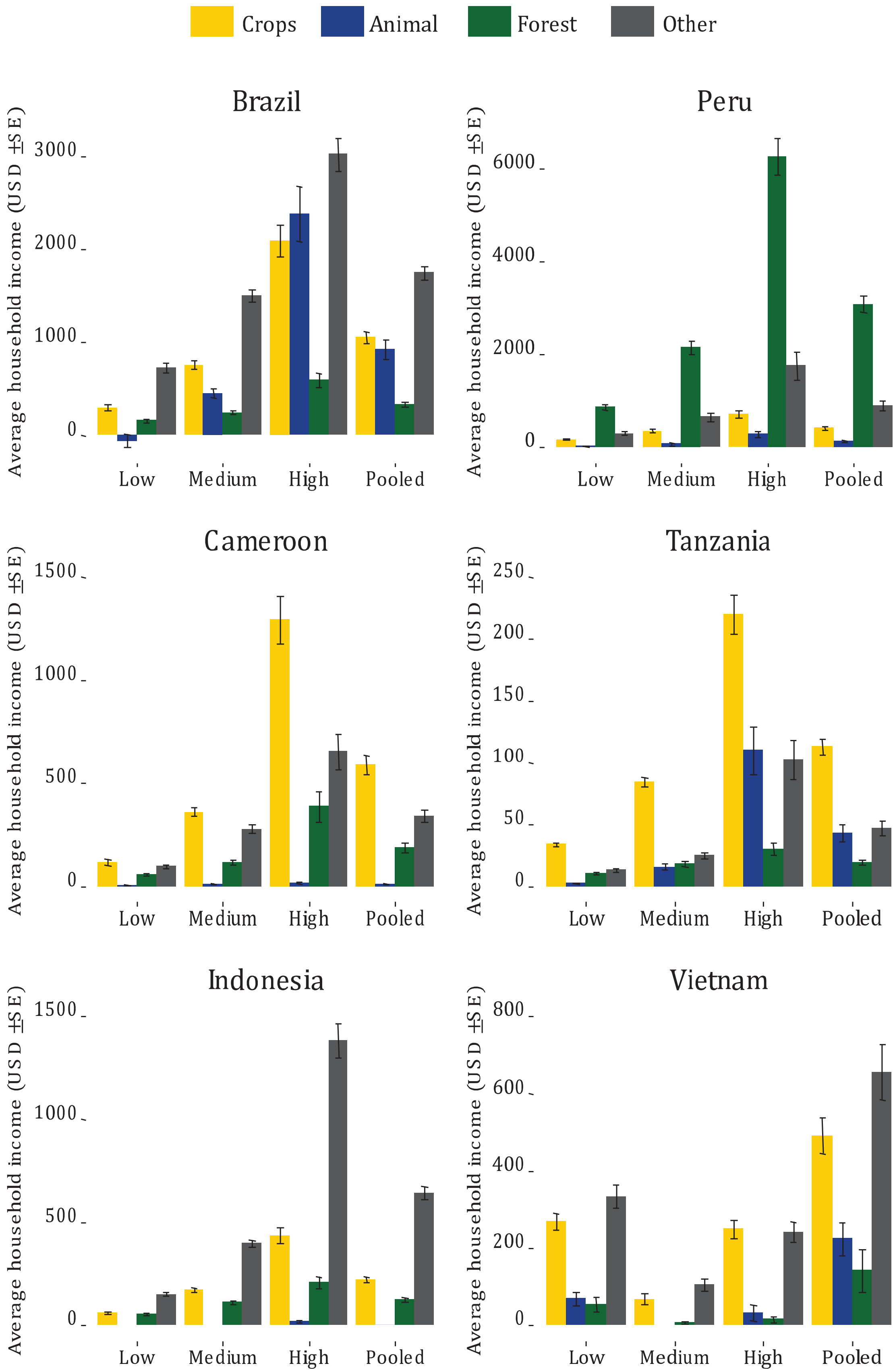

Figure 2. *Average income in GCS REDD+ sites from different activities by country and income group.*

where crops comprised about 50% of income across groups, and lowest in Peru where it contributed about 10% of income. The proportion of household income from crops was similar across income terciles, although absolute income earned from crop production was always highest for the rich.

Income from forest-based activities includes income from timber, charcoal, mining, hunting, and non-timber product collection. While the income from forest products in all countries was highest for the richest tercile in absolute terms, the proportion of total income earned from forest products was highest for the poor in the REDD+ sites in Brazil, Indonesia, Cameroon, and Tanzania. Similar patterns were found in the Poverty Environment Network's study of forest income across a large sample of tropical countries (Angelsen *et al.*, 2014). Peru stands out for a consistently high share of forest income across all income terciles. Vietnam is the only country in the sample where the rich earned a higher share of their income than the poor from forest-based activities.

(b) *Opportunity costs of avoided deforestation*

We first estimate opportunity cost per hectare by calculating each household's total income from crops and large livestock,[3] divided by the amount of land that is controlled and used by the household for agriculture and pasture (note that borrowed land and communal lands may be used, but not considered "controlled" by households), i.e., $OC_{HA} = Y/H$ where Y is the household's net annual income from agriculture and large livestock and H is land controlled and used for agriculture and pasture in hectares.[4] Tenure arrangements differ across sites both with respect to the type of ownership of forests (e.g., whether private or common property) and with respect to the security of access (Sunderlin, Ekaputri, *et al.*, 2014; Sunderlin, Larson, *et al.*, 2014; Larson, *et al.*, 2013). Thus land "used" is more relevant than land "owned" in most sites, since whether or not the household has formal rights of ownership to land, they clearly have use rights which would need to be compensated in order for the household to voluntarily accept restrictions.

(i) *Opportunity cost per tonne of carbon*

We calculate the annual opportunity cost of avoided deforestation per tonne of carbon at each site and also report these costs in present value terms, in order to make them comparable with other estimates in the literature. Specifically, we divide the opportunity cost per hectare by the carbon density per hectare of forests at each of the GCS sites using estimates from Avitabile *et al.* (2016). This recent study provides a pantropical carbon map at 1-km resolution using an independent reference dataset of field observations and locally calibrated high-resolution biomass maps. It integrates existing regional biomass maps and country-specific reference datasets (Avitabile *et al.*, 2016). The carbon density per hectare was calculated as half of the biomass per hectare, which in turn was calculated as the sum of above ground biomass (AGB) and below ground biomass (BGB) estimated using $BGB = 0.489 * AGB^{0.89}$ (Saatchi *et al.*, 2011).

Thus we calculate the cost of avoided deforestation per tonne of carbon at each site as:

$$CC = \frac{OC_{HA}}{C_{HA}} \tag{1}$$

where

CC, the annual cost of carbon to smallholders, is equal to the average annual opportunity cost per hectare across all households in a site, OC_{HA}, divided by C_{HA}, the average above and below ground stock of carbon per hectare of forest in that site.

In a direct payment scheme, proponents would likely make annual payments in order to ensure compliance (Wunder, Engel, & Pagiola, 2008). In order to compare with other studies and with carbon prices, however, we also calculate the PV of the annual opportunity cost of avoided deforestation per tonne of carbon over a 30-year time horizon with a 9% discount rate (based on common time horizons and discount rates used in the literature (Grieg-Gran, 2008; Phan *et al.*, 2014).

(ii) *Opportunity cost per household*

To calculate the opportunity cost per household, we must decide the relevant quantity of land for which opportunities are foregone. There are several issues to consider. First, there is the question of "additionality": households may have no intention of clearing all of their forest land, and would not bear real opportunity costs if restricted from clearing some of the land controlled. This may be particularly relevant in the Amazon where households can control several hundreds of hectares of forest. Second, there is the issue of common property rights to forest. If all households "own" the forest together, then the most straightforward way to calculate the opportunity cost is to calculate the total area of forests and divide by number of households to find the opportunity cost per household. However, even under a common property regime, it is unlikely that all households have the same access to forest or the same propensity to clear it. Thus, we use a household's recent forest clearing behavior (H_{cl}) as a proxy for the amount of land that it is likely to clear in the future. Based on this assumption, we calculate annual household opportunity costs per household as:

$$Y^{hh}_{lb} = OC_{HA} * H_{cl} \tag{2}$$

where Y^{hh}_{lb} is the average household's lower bound opportunity cost of deforestation, and H_{cl} is the average number of hectares of forest cleared by the average household annually.[5] Both are averages by income tercile and site. That is, we estimate the average annual opportunity cost per household for foregoing clearing new land based on how much land households in a given tercile and site cleared per year in the recent past. We consider this a lower bound on the "equitable" compensation for households in a shifting cultivation type of system in which the productivity of cleared land declines over time. Continuous cropping on the same plot of land would reduce fertility over time driving net income toward zero. Similarly for free range livestock, new pasture needs to be cleared periodically in order to prevent overgrazing in current pastures. Eqn. (2) captures the opportunity cost of giving up income from clearing new land, but not the productivity declines on land already cleared. If the household is restricted from clearing new land, it would not only be giving up its income from this land (as expressed in Eqn. (2)), but also would face reductions of income from the crops and livestock it is growing on already cleared land as productivity declines.

This suggests the household's total annual income from agriculture and large livestock (Y) as a long-run upper bound on its opportunity costs from clearing land in a shifting cultivation or free-range ranching system. We calculate, Y^{hh}_{ub}, the average upper bound household opportunity cost of avoided deforestation for each income tercile at each site.

$$Y^{hh}_{ub} = Y \tag{3}$$

Costs and benefits are quite uneven over the years in a typical agricultural production cycle in tropical forest regions. For both crops and ranching, there are typically high upfront costs to clear forest followed by initial high soil fertility, and then further inputs and/or declining productivity over time (Mertz, 2002). Because households were at different stages in this production cycle in the survey year, some reported negative net incomes from crops or livestock, while others reported high net incomes. Since we have data from a random sample of smallholders in each village, the average annual income of those households is a good approximation of the fixed annual income (or annuity) with the same present value as the income flows over a smallholder's entire production cycle (averaged over different possible starting points in that production cycle).

(c) *Opportunity cost of ecologically sensitive forest based extraction*

To reduce degradation and capture biodiversity co-benefits, REDD+ interventions may seek to restrict forest extraction activities that REDD+ proponents consider degrading, such as harvest of fuelwood and charcoal (Dokken, Caplow, Angelesen, & Sunderlin, 2014) as well as minerals (Intarini, Resosudarmo, Komalasari, Ekaputri, & Agustavia, 2014) from forests. Hunting may also be restricted in order to conserve biodiversity, which is viewed by many proponents as a key co-benefit of REDD+ (De Barros *et al.*, 2014; Lin, Sills, & Cheshire, 2014). In a survey of 80 existing REDD+ projects, proponents identified hunting as the second most important threat to biodiversity at their sites (Panfil & Harvey, 2015). Some researchers also argue that hunting can result in increased longer term carbon emissions since large mammals that are commonly hunted play an important role in plant community dynamics by dispersing seeds of carbon-rich tree species (Hinsley, Entwistle, & Pio, 2015; Peres, Thaise, Schietti, Desmoulieres, & Levi, 2015). We sum income from these categories and label it as income from "ecologically sensitive extraction activities." This income can only be calculated per household (rather than per hectare) since these activities often take place on common forest lands and are difficult to tie directly to area.

In any given REDD+ initiative, only some of these activities may be restricted. For example, while fuelwood extraction is negligible at some of our study sites, it has been identified as a main driver of degradation in the sites in Tanzania (Sunderlin *et al.*, 2015). In these sites, REDD+ funds are being used to promote more efficient cookstoves and alternative fuels for cooking. Similarly, not all initiatives seek to restrict hunting, but reduced hunting is commonly associated with co-benefits of REDD+ (Mertz *et al.*, 2012; Phelps, Friess, & Webb, 2012), and interventions to address illegal hunting have been reported by many REDD+ initiatives (Panfil & Harvey, 2015). Thus, while REDD+ initiatives will not necessarily restrict all of these activities, they provide a useful starting point for exploring likely scenarios of REDD+ implementation.

4. RESULTS

(a) *Opportunity costs per tonne of carbon*

Opportunity costs per tonne of carbon are reported in Table 1 for each site in both annual terms and as the present value (PV) over 30 years.

While all of our 17 study sites had been selected for REDD + initiatives, they are not all located in areas with high carbon density. In particular, the sites located in Tanzania's dry

Table 1. *Opportunity costs (OC) of avoided deforestation per tonne of carbon in $US*[*] *(note that one tonne of carbon = 3.67 tones of carbon dioxide)*

I. Country	II. Initiative #	III. OC per ha in US$	IV. C-stock per ha in tonnes	V. Annual OC per tonne C in US$	VI. PV OC per tonne C in US$[^]	VII. Sample Size
Brazil	1	357.40	165	2.17	24.30	235
	2	142.42	146	0.98	10.97	231
	3	144.78	153	0.95	10.63	249
	4	814.02	145	5.61	62.83	224
	5	1,522.00	221	6.89	77.15	115
Peru	6	96.87	158	0.61	6.83	234
	7	904.54	153	5.91	66.18	224
Cameroon	8	487.24	283	1.72	19.26	274
	9	714.98	111	6.44	72.12	238
Tanzania	10	168.58	2	84.29	943.90	255
	11	287.83	30	9.59	107.40	168
Indonesia	12	232.17	229	1.01	11.31	247
	13	452.98	163	2.78	31.13	253
	14	100.20	106	0.95	10.63	243
	15	133.84	118	1.13	12.66	259
	16	190.73	246	0.78	8.73	267
Vietnam	17	403.07	208	1.94	21.72	229

[*] To construct this table, we excluded observations that are more than three standard deviations from the mean.
[^] PV is calculated over a 30 year period.

forests have much lower carbon density than the rest of the sites, which are all in the humid tropics (see Sills *et al.*, 2014 for further details on the sites). The low carbon densities at the sites in Tanzania result in very high annual opportunity costs for REDD+, especially in Initiative 10, which has an opportunity cost per ton more than ten times that of the next highest cost project. Excluding this initiative, annual opportunity costs per tonne of carbon range from a low of \$0.45 in Initiative 14 in Indonesia to a high of \$9.32 in Initiative 11 in Tanzania. After the two initiatives in Tanzania, the next most costly site is Initiative #5 in Brazil, which has relatively rich carbon stocks, but also high agricultural income per hectare. Annual opportunity costs averaged across sites, excluding the Tanzanian initiatives (because of their very low carbon stocks), were \$2.66 per tonne.

Column VI reports the present value of opportunity costs assuming a constant annual stream of income over 30 years and a real discount rate of 9%. The average PV of opportunity costs across initiatives, excluding the Tanzanian sites, was \$29.76.

(b) *Opportunity costs per household*

While the opportunity costs of avoided deforestation per tonne of carbon is the main variable of interest from an efficiency perspective, equity implications can only be understood at the household level. Table 2 reports the average annual lower and upper bound opportunity costs per household for each income tercile in each site.

Under both scenarios, in all cases, the opportunity costs of foregoing deforestation of relatively high income, or "rich", smallholders would exceed those of relatively low income, or "poor", smallholders. However, the magnitudes of these differences vary significantly across countries, across sites within countries, and between the two scenarios. For example, using the lower bound estimates, the rich earn about twice as much as the poor from agriculture and livestock in Initiative 12 in Indonesia, but rich households earn more than 11 times more from theses activities than that of the poor in Initiative 4 in Brazil. The differences in incomes across the terciles is even larger and varies even more widely across initiatives using the upper bound estimates of household opportunity costs. The smallest difference can be seen in initiative #6 in Peru where the average opportunity cost for the "high-income" groups is about three times the average opportunity cost of the "low-income" group. At the other end of the spectrum, the average income of the richest households from deforesting activities in initiative 2 in Brazil exceeds that of the poorest households by a factor of 26!

The same pattern of lower opportunity costs for the low-income group holds not only for opportunity costs per household, but for opportunity costs per hectare as well. Table 4 in the Appendix disaggregates the components of Scenario #1 in Table 2 to show both opportunity costs per hectare and amount of land cleared by income tercile. It is worth noting that in all sites except Vietnam, the rich cleared more land than the poor (although these differences are not always statistically significant).

(c) *Opportunity costs of restrictions on ecologically sensitive forest product extraction*

Table 3 presents household income from the collection of products that are commonly believed to result in either forest degradation or biodiversity loss.

The total income derived from collection of these products is substantially higher for the rich than the poor across all initiatives. While the poor in about half of the sites in our study derive a higher proportion of their income from ecologically sensitive forest product collection (calculations not shown), in absolute terms it is substantially less than the richer households.

The contribution of these activities to household income is quite substantial in many sites. The relative contribution compared with income from deforestation depends on whether we compare with the lower or upper bound estimates of the opportunity costs of foregone deforestation. Since scenario #1 only includes deforestation income from newly cleared land, the relative share of ecologically sensitive forest product extraction is much higher than under scenario #2 which

Table 2. *Average lower and upper bound estimates of household annual opportunity costs of avoided deforestation for income terciles by initiative in US\$*[*]

Country	Initiative #	Scenario 1 (SC1) : lower bound opportunity cost (OC_{ha} * H_{cl}) in US\$			Scenario 2 (SC2) : upper bound opportunity cost (Y) in US\$			
		Low income	Middle income	High income	Low income	Middle income	High income	Sample Size SC1/SC2
Brazil	1	159	229	550	1,401	2,543	5,024	234/230
	2	30	30	45	1168	3,741	11,971	231/231
	3	68	160	298	937	2,335	8,015	249/249
	4	56	337	761	913	2,669	11,018	221/239
	5	171	542	504	1079	2,963	7,735	116/117
Peru	6	22	59	73	393	759	1,277	237/238
	7	29	173	251	468	1,111	2,886	225/234
Cameroon	8	111	306	776	364	1,009	3,432	267/266
	9	29	68	253	398	1,384	4,862	236/240
Tanzania	10	1	3	12	105	335	1,366	258/243
	11	0	1	1	96	203	816	170/158
Indonesia	12	4	25	18	106	262	3,81	245/257
	13	4	27	72	297	1,184	2,415	256/253
	14	0	2	4	51	288	709	252/248
	15	1	1	9	31	176	780	258/256
	16	32	82	100	276	408	1,197	262/281
Vietnam	17	-2	0	3	170	793	1,663	154/227

[*] To construct this table, we have excluded observations that exceed three standard deviations from the mean.

Table 3. *Average household income in US $ from collection of ecologically sensitive forest products by income tercile*[*]

Country	Initiative #	Ecologically sensitive forest product income in US$			
		Low income	Middle income	High income	Sample Size
Brazil	1	540	710	1,182	233
	2	82	87	416	236
	3	149	170	444	250
	4	50	353	594	235
	5	249	918	1,161	118
Peru	6	309	2,139	4,294	237
	7	1,059	2,234	9,347	214
Cameroon	8	98	292	859	269
	9	60	61	91	243
Tanzania	10	23	59	62	258
	11	19	36	42	172
Indonesia	12	10	47	135	258
	13	7	12	23	259
	14	280	628	831	252
	15	108	89	208	252
	16	163	366	446	284
Vietnam	17	1	5	94	230

[*] To construct this table, we have excluded observations that exceed three standard deviations from the mean.

includes income from all agricultural activities. Income from extraction of "ecologically sensitive" products exceeds income from deforestation using scenario #1 estimates for at least one income group in all sites. Even comparing with the higher values from scenario #2, income from forest extraction activities that could be restricted under REDD+ is substantial compared with deforestation income; it is on average 85% of deforestation income for the lowest income group and 57% of deforestation income for the high-income group.

5. DISCUSSION

The claim that tropical forest conservation has low costs relative to other options for reducing net carbon emissions has been one of the key arguments in favor of REDD+, but has also been the subject of vigorous debate (Butler, Koh, & Ghazoul, 2009; Dyer & Counsell, 2010; Ekins *et al.*, 2011; Phan *et al.*, 2014). One cause of the controversy has been the different concepts and methods used to develop estimates of opportunity costs. Furthermore, many estimates have been based on coarse national data. In this study we use detailed household data to estimate opportunity costs to smallholders in multiple sites across the tropics using the same methodology, finding a mean opportunity cost of $29.76 per tonne.[6] This is similar to the mean of $30 per tonne from previous studies at the local level reported by Phan *et al.* (2014).

We find substantial variation in opportunity costs per tonne of carbon across sites, which we compare to various benchmark prices. Using the relatively low voluntary market price in 2015 of $3.30 per tCO_2, which is the equivalent of a price of $12.11 per tC (one unit of carbon equals 3.67 units of CO_2), we see that the opportunity cost to smallholders in only six out of the 17 initiatives in our study falls below this price (see column VI of Table 1). If we use the average historical price of $5.9 per tCO_2 (Peters-Stanley, Gonzalez, Goldstein, & Hamrick, 2014), eight of the sites are competitive. And finally, if we compare with the U.S. Environmental Protection Agency's estimate for the global social cost of CO_2 of $36 per tCO_2 (Interagency Working Group on Social Cost of Carbon, 2015), compensating households to reduce emissions makes economic sense from a global perspective in all but one of the Tanzanian sites.

The eight projects that are affordable at historical carbon prices (in terms of opportunity cost compensation only) are dispersed among four of the countries in our sample: Brazil, Peru, Indonesia, and Cameroon. Each of these countries has at least one other site in the study where the costs would exceed the historical carbon price. This highlights the importance of using household-level data to estimated opportunity costs rather than relying on national data.

Even if it were affordable to implement REDD+ in all sites, this does not imply that it makes equal economic sense to implement REDD+ in all sites. The large variation in opportunity costs per tonne of carbon is striking and clearly not due to differences in methodology. Even excluding the two dry forest sites in Tanzania, the highest cost site (initiative 5 in Brazil) is more than 16 times as expensive as the lowest cost site (initiative 14 in Indonesia). If the sole objective of REDD+ initiatives were to offset the most carbon emissions at the least cost, it would appear irrational to invest in sites that have a much higher opportunity cost per tonne of carbon compared to other sites. Clearly, sites for REDD+ initiatives have been selected based on other factors such as national interests (e.g., inclusion of forest-based climate change mitigation in the national submissions of Intended Nationally Determined Contribution (INDC)), trans-national agreements such as the Acre-California partnership under the Governor's Climate and Forest Taskforce (Roessing Neto, 2015), and potential to generate non-carbon benefits such as biodiversity conservation and watershed protection (Murray, Grenyer, Wunder, Raes, & Jones, 2015; Phelps *et al.*, 2012). The initiatives in our sample reflect the diversity of objectives and actors involved, some aiming to sell carbon credits on voluntary markets, others intending to enhance pre-existing activities with REDD+ funds, and others (like the two sites in Tanzania) intended to serve as demonstration pilots for REDD+ (Mustalahti, Bolin, Boyd, & Paavola, 2012).

The variation across sites in opportunity costs per tonne of carbon is important from an efficiency perspective, but to understand the implications of REDD+ for equity, we need to look at opportunity costs per household. Table 2 shows how household opportunity costs are distributed across income groups within sites both in the short run (lower bound estimates) and in the long run (upper bound estimates). Clearly the lower bound estimates will necessarily be below those of the upper bound estimates, but the magnitude of the difference is striking in some sites. This is largely because households in those sites do not report clearing very much land (see Appendix Table 4). If they actually clear very little land, that would call into question whether these are appropriate sites for REDD+. It is also possible, however, that some households underreport the amount of land that they clear either because it is illegal or because they believe the interviewers have a negative view of forest clearing. Where this is the case, the values reported for opportunity costs under scenario #1 will be underestimated.

The large differences in opportunity costs under the two scenarios make clear that proponents need to consider carefully the relevant land areas over which households should be compensated. If compensation is based on land likely to be cleared and the households continue to farm on their existing plots, the costs per hectare faced by the household will likely increase. If the compensation scheme is not re-evaluated periodically, over the long run, households would then be undercompensated.

Disaggregating opportunity costs by income group allows us to investigate the distributional implications of different compensation systems, which here we discuss in terms of direct conditional payments to households. The variability of opportunity cost per household suggests that some form of price discrimination could increase the efficiency of emissions reductions. However, many proponents of REDD+ are just as interested in equity as efficiency, and in particular, concerned about the potential impact of REDD+ interventions on the poorest households. Our estimations confirm that flat per household payments for participation in REDD+ would be progressive in all of the sites included in our study in the sense that the lowest income households would capture the greatest rents. This is because in our sites, the "low-income" households consistently have the lowest opportunity costs from deforestation and degradation activities (cf., Borrego & Skutsch, 2014).

If households were offered a flat payment equivalent to the mean opportunity cost (either per household or per hectare) at a site for voluntary participation in REDD+, most high-income households would opt not to participate, since the payment would not fully compensate them for the costs of expected changes in land use activities. Thus, this payment method would induce the most participation by low-income households, meaning that the poorest households would be the ones generating most of the reductions in emissions. This would be pro-poor in that the payment would exceed the deforestation and degradation income foregone by "low-income" households, and thus they would capture the "rents", or the excess of payments over opportunity costs, from REDD+.

In order to maximize participation under a flat payment scheme, compensation would have to be set at the highest opportunity cost in the site. This would further increase the rents of the poor and likely elicit high participation rates, but it would also be rather inefficient since all but the richest households would receive payments that exceed their opportunity costs. The other way to maximize participation theoretically would be to offer differentiated payments to households based on their costs. Practically this would be difficult to carry out because of the information asymmetry: households know their own opportunity costs, but these are not easy for the implementing organization to observe. Procurement auctions have been suggested to overcome this difficulty. However, because differentiated payments would mean reduced rents for the poor, this system might not appeal to proponents who see reducing poverty as a key co-benefit of REDD+.

While this study is focused on economic opportunity costs as measured by foregone income, there could be other factors that affect household's perceived opportunity costs that are more difficult to measure (Gregersen *et al.*, 2010). For example, if shifting cultivation no longer becomes possible without access to new land (as in scenario #2), it would not only be the value of a household's output that is lost, but a whole way of life. Both cultural non-monetary values of current practices as well as uncertainty of alternative livelihood strategies would mean that compensation based simply on opportunity costs of foregone income using current production and price information would be insufficient.

Much less research has been done on the opportunity costs of degradation than on deforestation perhaps because degradation is much more difficult to measure both from a biophysical perspective (Herold *et al.*, 2011; Morales-Barquero *et al.*, 2014) as well as from a socioeconomic perspective (Angelsen *et al.*, 2014). Unlike our estimates for deforestation, we are not able to estimate the opportunity costs per tonne of carbon or even per hectare for restrictions on ecologically sensitive forest product extraction. In addition to the difficulties of measuring the biophysical relationships between the different extractive activities and carbon emissions, it is much more difficult to disentangle the property rights issues for extraction. Much of the forest where extraction occurs is held as common property. Thus neither extraction income nor degradation of specific areas can be tied to particular households. Even if we know a particular household extracted forest products from a site, it is quite possible that other households did the same since more than one household can, for example, hunt or mine in the same area.

Despite these complexities, it is important to understand the livelihood implications of such restrictions on households. The results in Table 3 show that income from forest extraction activities is quite high and in most sites, exceeds income from deforestation using lower bound estimates of deforestation costs. This suggests that more effort needs to be dedicated to measuring and capturing the benefits of reduced degradation since loss of access can have substantial negative welfare effects on local smallholders. These results underscore the importance of recognizing complexity and the difficulties in getting accurate estimates. While collecting fine-grain household-level data is expensive, using coarser data carries the risk of underestimating important income streams, which in turn can undermine equity and legitimacy of entire initiatives. The distributional effect of compensation for restrictions on ecologically sensitive product extraction using flat payments to households is similar to that for deforestation since in all cases the "low-income" households had lower opportunity costs than the "high-income" households.

6. CONCLUSIONS

The concept of REDD+ as a way to compensate actors for foregoing income-generating activities that involve deforestation and degradation has changed the public discourse on conservation and the way national policy makers view their natural assets. However, the complexities of putting this basic idea into practice are gradually being uncovered. Although much of the discussion in policy circles and in the media is on conditional payments at the national and regional level (e.g., agreements between Norway and several tropical countries), ultimately households and firms will need to change their behavior in order for REDD+ to work (Di Gregorio *et al.*, 2013). For this to happen while safeguarding local well-being, smallholders will need to be compensated for their opportunity costs of changing behavior and practices.

Early estimates of the opportunity costs of REDD+ for smallholder farmers in the tropics were quite low (Dyer & Counsell, 2010). The most influential estimate by McKinsey & Co. put the average cost of 2 Euros per tCO_2 emissions for shifting cultivation and cattle ranching throughout the tropics.[7] Only three of the initiatives in our sample had an opportunity cost at or below this cost with two others quite close. The opportunity costs for smallholders at the majority of initiatives far exceeded this cost. Further, the costs of REDD+ would be higher than the opportunity costs reported here since they would also have to include transaction, implementation, and monitoring costs. On the other hand, the opportunity costs to smallholders in all but one of the sites are less than the social cost of carbon as calculated by the U.S. E.P.A. (Interagency Working Group on Social Cost of Carbon, 2015). Thus compensating smallholders to reduce carbon emissions would generate net global benefits.

Using our pan-tropical dataset, we found high variability of opportunity costs at all scales: across countries, across sites in the same country, and across income groups within sites. Although heterogeneity of livelihood activities and income in rural communities is well documented (e.g., Ruben & Pender, 2004), the implications for REDD+ benefit sharing remain largely unexplored. In the presence of such heterogeneity, information on the distribution of costs is critical for understanding how the design of REDD+ interventions, including what is restricted and how compensation is structured, will affect equity. We explore some of the conceptual and practical challenges in defining compensation amounts and designing mechanisms to fairly compensate households.

The impracticality of implementing detailed household surveys at each and every site where REDD+ will be implemented increases the value of the dataset analyzed here, which was collected in a wide range of sites across the tropics using uniform methods. This allows us to assess how different design choices for REDD+ interact with the heterogeneity of household livelihoods and income to affect efficiency and equity on the ground. Strikingly, although crop, livestock, and forest income represent varying percentages of total household income (as shown in Figure 2), the highest income group consistently earned more than the poorest income group from deforesting and ecologically sensitive product extraction across all of our 17 sites both per household and per hectare. This implies that flat payments would be "pro-poor" in the sense that the poorer households would earn higher rents from REDD+ payments, as long as any differences in transactions costs do not outweigh the difference in opportunity costs. If participation is voluntary, it also implies that richer households would be unlikely to participate in generating reductions in emissions from deforestation and degradation. Understanding how the unequal distribution of income from deforestation and forest degradation interacts with compensation systems is one key factor in designing effective REDD+ systems that safeguard local livelihoods.

NOTES

1. Sunderlin *et al*. report 4184, but one observation was a duplicate.

2. We used 2010 market exchange rates from http://data.worldbank.org/indicator/PA.NUS.FCRF.

3. Large livestock excludes husbandry of pigs, chickens, goats, and sheep, all of which are common in the sample.

4. We did not include households with positive deforestation income who reported zero land controlled for this calculation.

5. Note that we are comparing market prices with the present value of opportunity costs over 30 years as reported in Table 1, because prices are for "permanent" emissions reduction, monitored over a contract period that may be 30 years.

6. This mean excludes the Tanzanian sites which have very low stocks of carbon.

7. Using 2009 Euro: USD exchange rates and converting CO_2 to carbon equivalent gives a price of $10.57 per tonne of carbon.

REFERENCES

Angelsen, A., Jagger, P., Babigumira, R., Belcher, B., Hogarth, N. J., Bauch, S., *et al.* (2014). Environmental income and rural livelihoods: A global-comparative analysis. *World Development, 64*, S12–S28.

Araya, M. M., & Hofstad, O. (2014). Monetary incentives to avoid deforestation under the Reducing emissions from deforestation and degradation (REDD)+ climate change mitigation scheme in Tanzania. *Mitigation and Adaptation Strategies for Global Change, 21*(3), 421–443.

Avitabile, V., Herold, M., Heuvelink, G., Lewis, S. L., Phillips, O. L., Asner, G. P., *et al.* (2016). An integrated pan-tropical biomass maps using multiple reference datasets. *Global Change Biology, 22*, 1406–1420. http://dx.doi.org/10.1111/gcb.13139.

Bauch, S. C., Sills, E. O., & Pattanayak, S. K. (2014). Have we managed to integrate conservation and development? ICDP impacts in the Brazilian Amazon. *World Development, 64*, S135–S148. http://dx.doi.org/10.1016/j.worlddev.2014.03.009.

Borrego, A., & Skutsch, M. (2014). Estimating the opportunity costs of activities that cause degradation in tropical dry forest: Implications for REDD. *Ecological Economics, 101*, 1–9. http://dx.doi.org/10.1016/j.ecolecon.2014.02.005.

Butler, R. A., Koh, L. P., & Ghazoul, J. (2009). REDD in the red: Palm oil could undermine carbon payment schemes. *Conservation Letters, 2*, 67–73.

Chhatre, A., Lakhanpal, S., Larson, A. M., Nelson, F., Ojha, H., & Rao, J. (2012). Social safeguards and co-benefits in REDD+: A review of the adjacent possible. *Current Opinion in Environmental Sustainability, 4*(6), 654–660. http://dx.doi.org/10.1016/j.cosust.2012.08.006.

Clements, T. (2010). Reduced expectations: The political and institutional challenges of REDD. *Oryx, 44*(3), 309–310. http://dx.doi.org/10.1017/S0030605310000712.

De Barros, A. E., Macdonald, E. A., Matsumoto, M. H., Paula, R. C., Nijhawan, S., Malhi, Y., *et al.* (2014). Identification of areas in Brazil that optimize conservation of forest carbon, jaguars, and biodiversity. *Conservation Biology, 28*(2), 580–593. http://dx.doi.org/10.1111/cobi.12202.

Di Gregorio, M., Brockhaus, M., Cronin, T., Muharrom, E., Santoso, L., Mardiah, S., *et al.* (2013). Equity and REDD plus in the media: a comparative analysis of policy discourses. *Ecology and Society, 18*(2). http://dx.doi.org/10.5751/ES-05694-180239, art39.

Dokken, T., Caplow, S., Angelesen, A., & Sunderlin, W. (2014). Tenure issues in REDD+ pilot projects in Tanzania. *Forests, 5*(2), 234–255.

Dyer, A., & Counsell, S. (2010). Briefing McREDD : How McKinsey "cost-curves" are distorting REDD. *Climate and Forests Policy Brief* (November), 12. Retrieved from http://www.redd-monitor.org/wp-content/uploads/2010/11/McRedd-English.pdf.

Ekins, P., Kesicki, F., & Smith, A. Z. (2011). *Marginal abatement cost curves: A call for caution*. London: University College Energy Institute, https://www.bartlett.ucl.ac.uk/energy/news/documents/einews-290611-macc.pdf.

Fairhead, J., Leach, M., & Scoones, I. (2012). Green grabbing: A new appropriation of nature?. *The Journal of Peasant Studies, 39*(2), 237–261. http://dx.doi.org/10.1080/03066150.2012.671770.

Fosci, M. (2013). Balance sheet in the REDD+: Are global estimates measuring the wrong costs?. *Ecological Economics*.

Gregersen, H., Lakany Karsen, H. El., & White, A. (2010). *Does the opportunity cost approach indicate the real cost of REDD+? Rights and realities of paying for REDD+*. , Washington DC. Retrieved from http://www.forestforclimate.org/attachments/1068_doc_1555.pdf.

Grieg-Gran, M. (2008). *The cost of avoiding deforestation: Update of the report prepared for the Stern Review of the Economics of Climate Change*. Paper commissioned by the Office of Climate Change as background work to its report Climate Change: Financing Global Forests (The El. London, UK.

Herold, M., Román-Cuesta, R. M., Mollicone, D., Hirata, Y., Van Laake, P., Asner, G. P., *et al.* (2011). Options for monitoring and estimating historical carbon emissions from forest degradation in the context of REDD+. *Carbon Balance and Management, 6*(1), 13. http://dx.doi.org/10.1186/1750-0680-6-13.

Hinsley, A., Entwistle, A., & Pio, D. V. (2015). Does the long-term success of REDD+ also depend on biodiversity?. *Oryx, 49*(02), 216–221, Retrieved from http://dx.doi.org/10.1017/S0030605314000507.

Intarini, D. Y., Resosudarmo, I., Komalasari, M., Ekaputri, A. D., & Agustavia, M. (2014). Ketapang community carbon pools, West Kalimantan, Indonesia. In E. O. Sills, S. Atmadja, C. de Sassi, A. E. Duchelle, D. Kweka, & I. A. P. Resosudarmo, *et al.* (Eds.), *REDD+ on the ground: A case book of subnational initiatives across the globe* (pp. 420–439). Bogor, Indonesia: Center for International Forestry Research.

Interagency Working Group on Social Cost of Carbon (2010). Technical support document : Social cost of carbon for regulatory impact analysis under executive order 12866. *Journal on the Theory of Ordered Sets and its Applications*.

Jagger, P., Brockhaus, M., Duchelle, A. E., Gebara, M. F., Lawlor, K., Resosudarmo, I. A. P., *et al.* (2014). Multi-level policy dialogues, processes, and actions: Challenges and opportunities for national REDD+ safeguards measurement, reporting, and verification (MRV). *Forests, 5*(9), 2136–2162. http://dx.doi.org/10.3390/f5092136.

Kashwan, P. (2015). Forest policy, institutions, and REDD+ in India, Tanzania, and Mexico. *Global Environmental Politics, 15*(3), 46–64.

Larson, A. M., Brockhaus, M., Sunderlin, W. D., Duchelle, A., Babon, A., Dokken, T., *et al.* (2013). Land tenure and REDD+: The good, the bad and the ugly. *Global Environmental Change, 23*, 678–689.

Lawlor, K., Madeira, E. M., Blockhus, J., & Ganz, D. J. (2013). Community participation and benefits in REDD+: A review of initial outcomes and lessons. *Forests, 4*(2), 296–318. http://dx.doi.org/10.3390/f4020296.

Lin, L., Sills, E., & Cheshire, H. (2014). Targeting areas for Reducing Emissions from Deforestation and forest Degradation (REDD+) projects in Tanzania. *Global Environmental Change, 24*, 277–286. http://dx.doi.org/10.1016/j.gloenvcha.2013.12.003.

Luttrell, C., Loft, L., Fernanda Gebara, M., Kweka, D., Brockhaus, M., Angelsen, A., *et al.* (2013). Who should benefit from REDD+? Rationales and realities. *Ecology and Society, 18*(4). http://dx.doi.org/10.5751/ES-05834-180452, art52.

Luttrell, C., Sills, E. O., Aryani, R., Ekaputri, A. D., & Evinke, M. F. (2017). Beyond opportunity costs: who bears the implementation costs of reducing emissions from deforestation and degradation?. *Mitig Adapt Strateg Glob Change*.

Mertz, O. (2002). The relationship between length of fallow and crop yields in shifting cultivation: A rethinking. *Agroforestry Systems*.

Mertz, O., Müller, D., Sikor, T., Hett, C., Heinimann, A., Castella, J.-C., *et al.* (2012). The forgotten D: Challenges of addressing forest degradation in complex mosaic landscapes under REDD+. *Geografisk Tidsskrift-Danish Journal of Geography, 112*(1), 63–76. http://dx.doi.org/10.1080/00167223.2012.709678.

Mohammed, E. Y. (2011). *Pro-poor benefit distribution in REDD+: Who gets what and why does it matter?* REDD+ Working Paper. London: IIED.

Morales-Barquero, L., Skutsch, M., Jardel-Pelaez, E. J., Ghilardi, A., Kleinn, C., & Healey, J. R. (2014). Operationalizing the definition of forest degradation for REDDplus, with application to Mexico. *Forests, 5*(7), 1653–1681. http://dx.doi.org/10.3390/f5071653.

Murray, J. P., Grenyer, R., Wunder, S., Raes, N., & Jones, J. P. G. (2015). Spatial patterns of carbon, biodiversity, deforestation threat, and REDD+ projects in Indonesia. *Conservation Biology*. http://dx.doi.org/10.1111/cobi.12500.

Mustalahti, I., Bolin, A., Boyd, E., & Paavola, J. (2012). Can REDD plus reconcile local priorities and needs with global mitigation benefits? Lessons from Angai Forest, Tanzania. *Ecology and Society, 17*(1). http://dx.doi.org/10.5751/ES-04498-170116, art16.

Nauclér, T., & Enkvist, P. A. (2009). *Pathways to a low-carbon economy – Version 2 of the global greenhouse gas abatement cost curve*. McKinsey & Company.

Naughton-Treves, L., & Wendland, K. (2014). Land tenure and tropical forest management. *World Development, 55*, 1–6.

Palmer, C. (2011). Property rights and liability for deforestation under REDD+: Implications for "permanence" in policy design. *Ecological Economics, 70*(4), 571–576. http://dx.doi.org/10.1016/j.ecolecon.2010.10.011.

Panfil, S. N., & Harvey, C. A. (2015). REDD+ and biodiversity conservation: A review of the biodiversity goals, monitoring methods and impacts of 80 REDD+ projects. *Conservation Letters, 0*(Unfccc 2010), http://doi.org/10.1111/conl.12188.

Peres, C. A., Thaise, E., Schietti, J., Desmoulieres, S. J. M., & Levi, T. (2015). Dispersal limitation induces long-term biomass collapse in overhunted Amazonian forests. *Proceedings of the National Academy of Sciences of the United States of America, 113*(4), 892–897.

Peters-Stanley, M., Gonzalez, G., Goldstein, A., & Hamrick, K. (2014). *Sharing the stage: State of the voluntary carbon markets 2014, Executive report. State of the voluntary carbon markets*.

Phan, T.-H. D., Brouwer, R., & Davidson, M. (2014). The economic costs of avoided deforestation in the developing world: A meta-analysis. *Journal of Forest Economics, 20*(1), 1–16. http://dx.doi.org/10.1016/j.jfe.2013.06.004.

Phelps, J., Friess, D. A., & Webb, E. L. (2012). Win–win REDD+ approaches belie carbon–biodiversity trade-offs. *Biological Conservation, 154*(2012), 53–60. http://dx.doi.org/10.1016/j.biocon.2011.12.031.

Roessing Neto, E. (2015). Linking subnational climate change policies: A commentary on the California-Acre process. *Transnational Environmental Law, 4*(02), 425–437, Retrieved from http://www.journals.cambridge.org/abstract_S2047102515000138.

Ruben, R., & Pender, J. (2004). Rural diversity and heterogeneity in less-favoured areas: The quest for policy targeting. *Food Policy, 29*(4 SPEC.ISS.), 303–320.

Ruthenberg, H. (1980). *Farming systems in the tropics*. Oxford, UK: Clarendon Press.

Saatchi, S. S., Harris, N. L., Brown, S., Lefsky, M., Mitchard, E. T. A., Salas, W., *et al.* (2011). Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences of the United States of America, 108*, 9899–9904.

Sills, E., C. de Sassi, P. Jagger, K. Lawlor, D. Miteva, S. Pattanayak, and W. Sunderlin. In press. Building the evidence base for REDD+: Study design and methods for evaluating the impacts of conservation interventions on local well-being. *Global Environmental Change*.

Sills, E. O., Atmadja, S., de Sassi, C., Duchelle, A. E., Kweka, D., & Resosudarmo, I. A. P.et al.], *et al.*] (Eds.) (2014). *REDD+ on the ground: A case book of subnational initiatives across the globe. REDD+ on the ground: A case book of subnational initiatives across the globe*. http://dx.doi.org/10.17528/cifor/005202.

Simonet, G., Karsenty, A., Newton, P., De, C., Schaap, B., Seyller, C., *et al.* (2015). *REDD+ projects in 2014: An overview based on a new database and typology*. Pari.

Stern, N. (2006). Stern review: The economics of climate change executive summary. *October*, *30*(3), 27. http://dx.doi.org/10.1378/chest.128.5.

Sunderlin, W., Ekaputri, A., Sills, E., Duchelle, A. E., Kweka, D., Diprose, R., *et al.* (2014). *The challenge of establishing REDD+ on the* *ground: Insights from 23 subnational initiatives in six countries*. Bogor, Indonesia: Centre for International Forestry Research.

Sunderlin, W. D., Larson, A. M., Duchelle, A. E., Resosudarmo, I. A. P., Huynh, T. B., Awono, A., *et al.* (2014). How are REDD plus proponents addressing tenure problems? Evidence from Brazil, Cameroon, Tanzania, Indonesia, and Vietnam. *World Development, 55*(SI), 37–52. http://dx.doi.org/10.1016/j.worlddev.2013.01.013.

Sunderlin, W. D., Larson, A. M., Duchelle, A. E., Sills, E., Luttrell, C., Jagger, P., *et al.* (2016). *Technical guidelines for research on REDD+ subnational initiatives* Bogor, Indonesia. .

Sunderlin, W. D., Sills, E. O., Duchelle, A. E., Ekaputri, A. D., Kweka, D., Toniolo, M. A., *et al.* (2015). REDD+ at a critical juncture: Assessing the limits of polycentric governance for achieving climate change mitigation. *International Forestry Review, 17*(4), 400–413. http://dx.doi.org/10.1505/146554815817476468.

Visseren-Hamakers, I. J., McDermott, C., Vijge, M. J., & Cashore, B. (2012). Trade-offs, co-benefits and safeguards: current debates on the breadth of REDD+. *Current Opinion in Environmental Sustainability, 4*(6), 646–653. http://dx.doi.org/10.1016/j.cosust.2012.10.005.

Wertz-Kanounnikoff, S. (2008). *Estimating the costs of reducing forest emissions: a review of methods (No. 42)* Bogor, Indonesia. .

White, D., Minang, P. A., Agus, F., Borner, J., Hairiah, K., & Gockowski, J. (2011). *Estimating the opportunity costs of REDD+: A training manual* Washington DC. .

Wunder, S. (2007). The efficiency of payments for environmental services in tropical conservation: Essays. *Conservation Biology*.

Wunder, S., Engel, S., & Pagiola, S. (2008). Taking stock: A comparative analysis of payments for environmental services programs in developed and developing countries. *Ecological Economics, 65*(4), 834–852.

APPENDIX

Table 4. *Disaggregation of Scenario #1 from Table 2*

Country	Initiative #	Opportunity costs per hectare in $			Land cleared annually in hectares		
		Low income	Middle income	High income	Low income	Middle income	High income
Brazil	1	189	363	536	0.81	0.84	1.06
	2	39	128	248	0.5	0.49	0.62
	3	64	145	228	1.27	1.35	2.07
	4	165	1,073	1,220	0.62	1.11	1.25
	5	774	1,795	2,235	0.42	0.35	0.44
Peru	6	71	106	100	0.28	0.72	0.57
	7	307	800	1,331	0.11	0.27	0.26
Cameroon	8	178	381	851	0.73	1.12	1.3
	9	101	214	663	0.23	0.31	0.46
Tanzania	10	101	128	376	0.04	0.09	0.09
	11	105	156	578	0	0.02	0.02
Indonesia	12	191	336	390	0.06	0.12	0.08
	13	316	480	534	0.04	0.11	0.23
	14	16	37	91	0.04	0.06	0.53
	15	57	101	274	0.03	0.03	0.09
	16	121	90	234	0.37	0.5	0.54
Vietnam	17	242	463	512	0.03	0.05	0.02