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A ranking of net national contributions to climate change mitigation through tropical forest conservation

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ABSTRACT

Deforestation in tropical regions causes 15% of global anthropogenic carbon emissions and reduces the mitigation potential of carbon sequestration services. A global market failure occurs as the value of many ecosystem services provided by forests is not recognised by the markets. Identifying the contribution of individual countries to tropical carbon stocks and sequestration might help identify responsibilities and facilitate debate towards the correction of the market failure through international payments for ecosystem services. We compare and rank tropical countries' contributions by estimating carbon sequestration services vs. emissions disservices. The annual value of tropical carbon sequestration services in 2010 from 88 tropical countries was estimated to range from $2.8 to $30.7 billion, using market and social prices of carbon respectively. Democratic Republic of Congo, India and Sudan contribute the highest net carbon sequestration, whereas Brazil, Nigeria and Indonesia are the highest net emitters.

1. Introduction

Deforestation in tropical regions causes 15% of global anthropogenic carbon emissions (Van der Werf et al., 2009). Reduction of deforestation related emissions and mitigation through carbon sequestration have been identified as among the most cost-effective interventions to mitigate climate change (Stern, 2007). Carbon sequestration is a public good because it is nonrivalrous in consumption and nonexcludable (Stone, 1994). Public goods are associated with the tragedy of the commons and market failures as the market does not capture the actual value of the service, leading to an undesirable shortage of supply. In this case, as the value of standing forests is not recognised, excessive deforestation occurs and causes a shortage in supply of carbon sequestration services. International payments for ecosystem services (PES) such as carbon sequestration can correct this market failure by compensating countries responsible for generating the service (Bishop and Hill, 2014). Once payments are introduced and the service value internalized, service undersupply—avoided carbon emissions and carbon sequestration—is expected to be mitigated.

In 2005, at the eleventh Conference of the Parties in Montreal, a mechanism for reducing deforestation emissions in developing countries through PES was proposed and widely supported. This mechanism, abbreviated as REDD, was subsequently expanded to REDD + to include carbon stock enhancing activities, sustainable forest management and conservation (Peskett, 2008).

Technical limitations of historical and projected deforestation reference levels made REDD + controversial at the United Nations Framework Convention on Climate Change negotiations. Partly due to this controversy, REDD+ was prevented from joining other clean development mechanism projects—such as renewable energy introduction—as certified emission reduction credits (Grondard et al., 2008). Rather than the expected large-scale implementation of REDD + at the global and national level, which would have occurred if REDD + had joined global carbon credit markets, REDD+ is currently slowly growing, supported by project level international donors. There are currently over 300 subnational REDD + projects under implementation (Kshatriya et al., 2013) representing only 0.4% of the CO_2 traded in carbon markets globally in 2008. Given these circumstances, further international level discussions on international PES strategies for carbon services through conservation could be necessary to accelerate agreements on financial mechanisms and establish strong global carbon markets.

Quantifying the contributions from each country on carbon sequestration services could be an important first step to catalyse further discussion on international PES. For high-income countries, this clarifies which countries could be potentially compensated and how much, facilitating the generation of responsibilities and information. Information about the problem and potential solutions,

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in this case contributions to tropical forest preservation, are key to avoid global commons tragedies for tropical forests (Ostrom et al., 1999).

To this end, here we identify the carbon sequestration services and emissions from deforestation by tropical nations and rank net sequesters and emitters.

2. Methods

2.1. A ranking of contributions based on net carbon sequestration services

Contributions are based on the balance of CO_2 sequestered from forest stock and carbon emitted from deforestation and degradation activities. If a country has net carbon sequestration, potential compensation is calculated by multiplying net sequestration by the price of carbon sequestered, i.e. the country contributes the actual services provided in a given period of time and such contribution occurs when the services of carbon sequestration are greater than the disservices from emissions due to deforestation. If the country is a net emitter of carbon, the contribution is negative. The value of the net contributions is:

$$\text{value}_i = (S_i - E_i)p \tag{1}$$

where value$_i$ is the value of the net contribution by country i (USD/year); p is the carbon price (USD/tons of CO_2 emitted or sequestered); E_i is the annual emission from deforestation for country i (tons of CO_2 emitted); and S_i is the annual sequestration from forests for country i (tons of CO_2 sequestered).

2.2. Application of the mechanism at the pantropical level to identify contributions

We are not aware of geographic information system (GIS) maps of changes in primary, secondary and plantation forests at the pantropical level. Instead, to distinguish different sequestration rates for different forest types, the Global Forest Resource Assessment 2010 (FAO, 2010) was employed. We used this as a source for the area changes in primary, secondary and planted tropical forests in each country in the years between 1990 and 2010.

We estimated potential emissions from carbon (E in Equation (1)) aboveground, belowground, in soil and in dead organic matter in each country. GIS maps of aboveground tropical forest biomass were obtained by overlaying maps from Ruesch and Gibbs (2008) with the distribution of tropical forests (Hansen et al., 2010). Biomass was transformed to tons of carbon per hectare, multiplying by a 0.49 carbon fraction of biomass (Feldpausch et al., 2004; IPCC, 2006). Belowground carbon was estimated using IPCC (2006) shoot-root ratios for tropical forests, applied to aboveground carbon maps. IPCC Tables 2.3 and 2.2 (Feldpausch et al., 2004; IPCC, 2006) were employed to derive estimates of carbon stored in soil and dead organic matter. All carbon estimates were expressed as tons of carbon dioxide per hectare and the maps were used to estimate the average emissions per hectare of tropical forest deforested for each country.

The exact size and location of carbon sinks is uncertain and depends on the type of forest and level of degradation (Pan et al., 2011). Given these limitations, we used a power law model of variation in the pools of living biomass, organic soil horizons, soil and coarse woody debris in tropical forests as a function of forest age (Pregitzer and Euskirchen, 2004) to estimate carbon sequestration (S in Equation (1)) for different types of forests. The model (MgC/ha $= 53.7 \cdot \text{age}^{0.26}$), derived through fitting existing literature estimates of carbon sequestration in the tropics, allowed prediction of carbon sequestration rates for different forest ages (Pregitzer and Euskirchen, 2004). We considered three different forest types consistent with the Global Forest Resource Assessment 2010 and used their expected average age to estimate sequestration rates: (i) *primary intact tropical forests* for which sequestration rates ranged from 0.46 Mg C/ha•year (for 100 year old forests) to 0.33 Mg C/ha•year (for 200 year old forests). Note that the equation was fitted to age stages of up to 200 years and was hence not used to extrapolate beyond that age. These results are conservative with respect to sequestration of 0.63 Mg C/ha•year (95% CI 0.22–0.94) in intact African forests (Lewis et al., 2009) and 0.62 ± 0.23 Mg C/ha•year in intact Amazon forests (Baker et al., 2004); (ii) *secondary forests* that were assumed to range between 30 and 90 years old with corresponding sequestration rates ranging from 1.1 to 0.5 Mg C/ha•year respectively. These estimates resemble biomass accumulation of 1–2 Mg C/ha year in forests greater than 60–80 years old (Lugo and Brown, 1992); and (iii) *planted forests* that were assumed to range between 5 and 20 years old with corresponding sequestration rates of 3.9 and 1.5 Mg C/ha•year. These estimates agree with sequestration rates of 1.9–7 Mg C/ha•year in 12–13 year old native tree plantations in Costa Rica (Redondo-Brenes and Montagnini, 2006).

We employed two carbon price scenarios (p in Equation (1)): (i) USD$2.31/tC, the average of the market settlement prices per tonne of carbon from 2003 to 2010 in the Chicago Climate Exchange (CCX, 2013); (ii) USD$25/tC, a social carbon price based on the certainty equivalent of the mode of peer-reviewed estimates with a 3% of pure rate of time preference, without equity weights and a risk premium (Tol, 2009). Countries included were low income, lower-middle income and upper-middle income countries (as classified by the World Bank in July 2013) where the majority of the country lies between the tropics of Cancer and Capricorn and information on primary, secondary and plantation forest were available, resulting in a total of 88 countries.

3. Results

3.1. Global carbon sequestration and emissions during 2005–2010

We estimate that a total of 1.2 billion tons of CO_2 were sequestered annually between 2005 and 2010 by forests in the 88 countries. In total, these 88 countries also emitted an annual average of 1.1 billion tons of CO_2 through deforestation in the same period. The average annual value of carbon sequestration services during this period were USD2.8 and USD30.7 billion for current market values of CO_2 and the social price of carbon respectively.

3.2. Contribution at the national level

Despite this global trend of greater sequestration than emissions, the comparison between emission and sequestration from deforestation is very different at the national level. In the proposed system, emitted tons of carbon carry the same weight as the service provided by tons sequestered. Under these conditions, most countries (66 of 88 countries) produce net contributions, i.e. their sequestration is greater than their emissions (see Supporting Information for a ranking of the countries per net contribution). Countries contributing the most are those with low deforestation rates and relatively large forest stocks which produce notable carbon sequestration services. For instance, the highest average annual contributors are the Democratic Republic of Congo (USD1.7 billion per year, Fig. 1) and India (USD1.7 billion per year, Fig. 2). The high contribution from India is due to a large forest stock, combining preserved primary forests and increasing planted forests (from 9.4 to 10.2 million hectares) which provide higher sequestration rates. In countries producing a net carbon contribution, reforestation is common, and

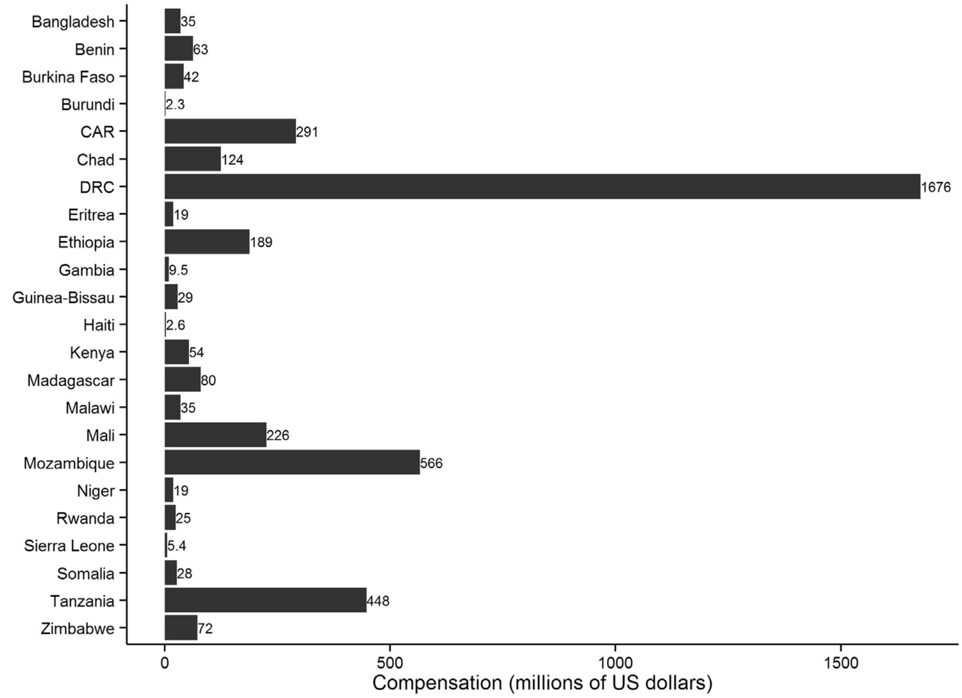

Fig. 1. Value of carbon sequestration contributions by low income countries which provide net carbon sequestration services for an average year between 2005 and 2010. Country income based on World Bank classification in July 2013. CAR = Central African Republic, DRC = Democratic Republic of Congo.

some countries with net deforestation of primary forests from 2005 to 2010, such as Malawi (17% deforestation of primary forest), are still net contributors due to increased planted forest (Fig. 1). Countries could also become net contributors by halting deforestation. For example, Colombia would contribute net sequestration valued at $678 million per year from 2005 to 2010 (Fig. 3). However the potential value of Colombia's contribution, if no deforestation occurred, is $1.1 billion per year when based on the 2010 forested area and the social price of carbon (Supporting Information, Table S1, “potential annual income from sequestration”).

The single greatest contributor to carbon sequestration services was Brazil, sequestering over 237 million tons of carbon per year. This was offset however, by over 392 million tons per year in carbon emissions from deforestation within Brazil (Fig. 4). Overall, net

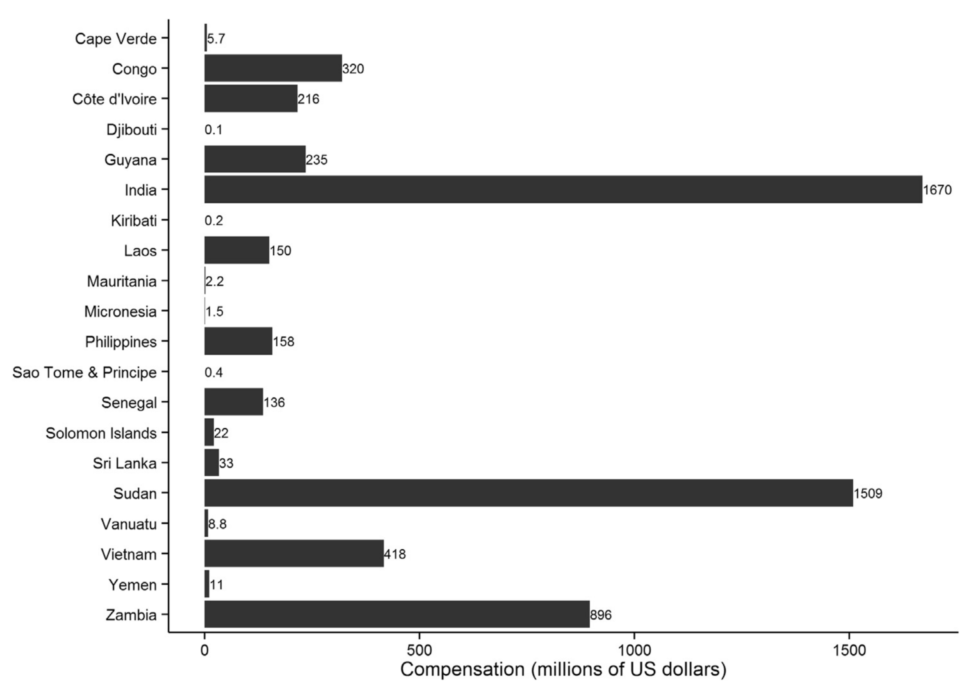

Fig. 2. Value of carbon sequestration contributions by lower middle income countries which provide net carbon sequestration services for an average year between 2005 and 2010. Country income based on World Bank classification in July 2013. Sudan includes both Sudan and Southern Sudan.

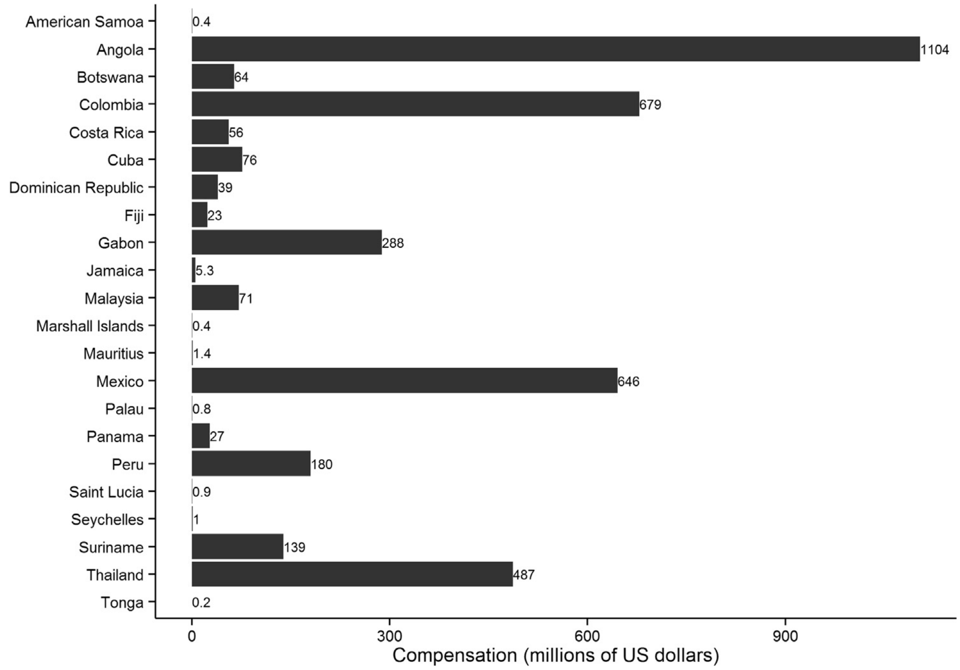

Fig. 3. Value of carbon sequestration contributions by upper middle income countries which provide net carbon sequestration services for an average year between 2005 and 2010. Country income based on World Bank classification in July 2013. Maldives and Tuvalu not shown – the value of their contribution is in both cases USD 20,000.

carbon emissions from 2005 to 2010 are associated with large areas of deforestation: Brazil (2 million hectares deforested and net 155 million tC emitted per year), Indonesia (0.7 million ha deforested and net 64 million tC emitted per year), and Nigeria (0.4 million ha deforested and net 68 million tC emitted per year) (Fig. 4).

3.3. *Potential incentives*

If the market failure was corrected through international PES for net carbon emitters, potential incentives for countries to reduce deforestation would be substantial. Based on 2010 forest levels,

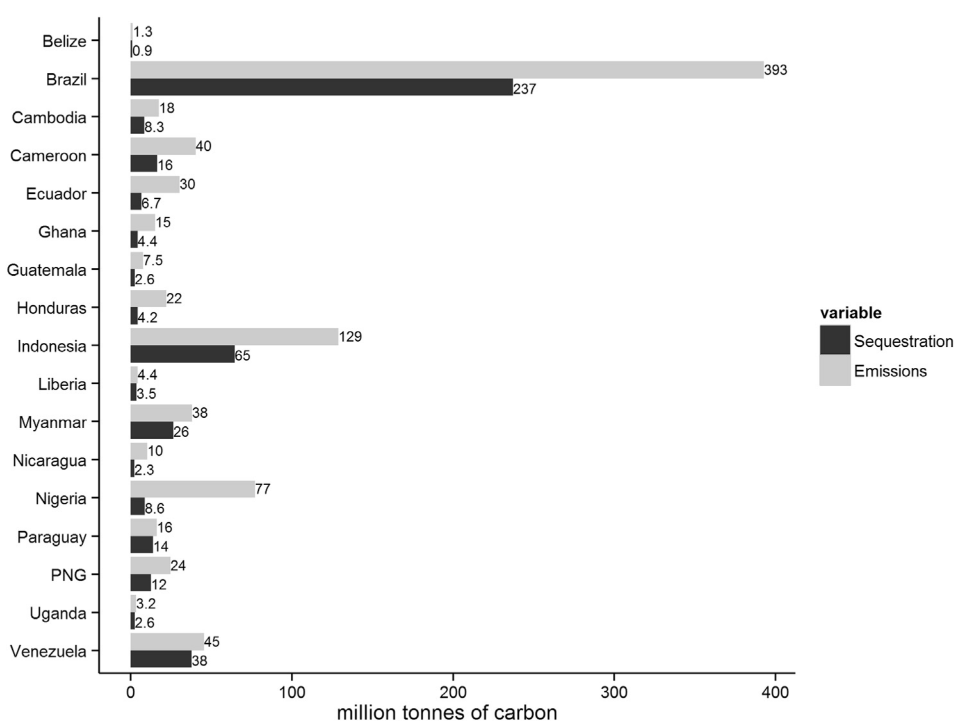

Fig. 4. Carbon sequestration and emissions by all net emitters with more than 1 million hectares of forest. Excluded net carbon emitters are The Comoros Islands, Timor-Leste, Togo and El Salvador, which have less than 1 million hectares of forest. PNG=Papua New Guinea.

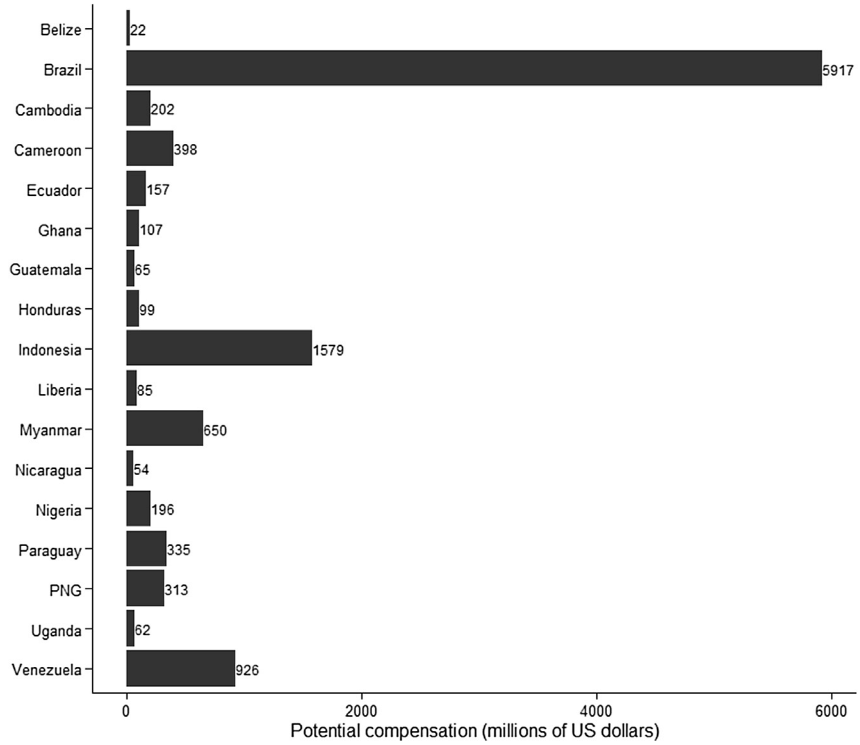

Fig. 5. Value of contributions for net carbon emitters if all deforestation were immediately halted, based on 2010 forested area. Excluded net emitters are The Comoros Islands, Timor-Leste, Togo and El Salvador, which have less than 1 million hectares of forest. PNG=Papua New Guinea.

Indonesia could receive up to $1.6 billion per year if all deforestation stopped and the social price of carbon were used (Fig. 5). This is considerable, particularly considering this is 50% more than the $1 billion moratorium Norway gave Indonesia to postpone new concession licenses in primary and peatland forests for two years (Murdiyarso et al., 2011). Annual payments of USD$5.9 billion for Brazil, and USD$0.9 billion for Venezuela would be generated if no further deforestation occurred. Given the large difference between the social price of carbon (USD$25/tC) and the actual market price (USD$2.31/tC), these payments would however be lowered ten-fold if the current market price of carbon is considered when estimating the value of sequestration services.

4. Discussion

Tropical forests house the richest biodiversity on Earth and act both as carbon stocks and carbon sinks. Their management is fundamental for climate change mitigation (Stern, 2007), yet they are threatened by habitat destruction (Laurance et al., 2012). This situation represents a market failure as the services provided by tropical forests in terms of carbon sequestration and storage are not captured by global markets. As these services have not traditionally been paid for, countries with tropical forests cannot meet the increasing opportunity costs of this land for other uses such as agriculture, e.g. palm oil can generate substantial benefits that are captured by markets (Koh and Wilcove, 2008).

Because carbon sequestration is a service that would generate payments through time, countries have a strong incentive to preserve forests if payments can be guaranteed. Past deforestation would effectively forgo a stream of benefits. For instance, if the mechanism were implemented using the social price of carbon, based on forest levels of 2010, Indonesia would forgo USD$15.8 billion of compensation from carbon sequestration services as a result of deforestation greater than sequestration in the next ten years alone. Brazil would forgo USD$59 billion, Nigeria USD$2 billion, and Ecuador USD$1.6 billion in the same period.

Correcting the market failure of carbon sequestration would mean countries with large forest stocks and low deforestation rates would receive immediate payments for carbon sequestration services, allowing them to develop economically while preserving their natural capital. This could lead to countries which develop economically by specializing in provision of ecosystem services. As our scheme is based on market failure correction with respect to only carbon-related ecosystem services—carbon sequestration and avoided carbon emissions—natural extensions of the proposed mechanism include payment for other global relevant ecosystem services, such as the existence of forests and their biodiversity, or prospective pharmaceutical plant use. The spatial valuation and quantification of these ecosystem services is however less established and more complex than the valuation of carbon sequestration (Bishop and Hill, 2014).

An international PES scheme for carbon services at the national level could also have implications for poverty alleviation depending on payment allocation. Synergistic implications that could alleviate poverty would require national payments are distributed to poor natural resource managers. Potential adverse effects could occur if land tenure is insecure or payments encourage less labour-intensive practices (Pagiola et al., 2005). Other negative impacts on poverty could include displacement of poor people from the ecosystem service benefits obtained from areas which sequester carbon, or reduction of food supply from agriculture if forests are not converted. Potential solutions include the development of community-based wildlife management areas to support local livelihoods or translate payments into alternative livelihoods for poorer communities (Agrawal and Redford, 2006). However, win–win solutions will be difficult to obtain (Wunder, 2001).

Our estimate of the total value of contributions is clearly dependent on carbon prices. Using the social price of carbon indicates consideration of the marginal costs of climate change damage on societal welfare. We use the mode of a meta-analyses for our value of the social price of carbon (Tol, 2009). Current prices per ton of CO_2 in exchange markets do not necessarily reflect the true value of marginal costs due to climate change. Using the social price of carbon, the overall annual services provided by carbon sequestration are $30.7 billion globally. Under current carbon market prices however, the value of carbon sequestration is only $2.8 billion which may be insufficient to meet opportunity costs of other land uses. These values cannot however be directly compared with the opportunity costs of agriculture. They would need to be corrected with the transaction costs of program implementation and costs associated with developing alternative food production solutions to meet the demand of land-users that stop deforestation (Cacho et al., 2005; Gregersen et al., 2010).

Our estimation of carbon emissions and sequestration presents some limitations due to technical difficulties such as a lack of spatially explicit maps of carbon sequestration or uncertainty about timber destinations and how rapidly carbon stored in timber will be emitted as carbon dioxide. Further problems are the difficulty of detecting forest degradation using solely remote sensing methods (Pelletier et al., 2011) and the lack of capacity for most countries to report forest cover loss, epitomized by the uncertainty attached to the estimates from the FAO Forest Resource Assessment (Grainger, 2008). Further complexities would arise from spatially determining the distribution of carbon sequestration services from different types of forests (e.g. peat swamp soil carbon was not included leading to an underestimation of emissions in countries like Indonesia) and interventions (e.g. stock enhancement projects, plantations). Related to this, due to paucity of large-scale maps on tree species distributions, we could not use species-specific conversion rates from biomass into carbon or species-specific carbon sequestration rates. Finally, although we did not account for it, countries might appear as increasing net forest cover at the expense of indirectly inflicting deforestation to other countries through the timber trade; this is an area of intense current research (Weinzettel et al., 2013).

Despite these limitations, ranking net national contributions to climate change mitigation through tropical forest conservation could help identify responsibilities and contributors to climate change. Identifying responsibilities could be a first step to scale-up to international PES, moving beyond small scale projects to internationally-based payments. The alternative is to let tropical forest conversion outside local PES projects continue without considering the value of the ecosystem services that tropical forests provide.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2014.08.016.

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