Comparing REDD mechanism design options with an open source economic model

Submitted for review, 20 February 2009

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Abstract

Discussions of policy options for Reducing Emissions from Deforestation and Forest Degradation (REDD) have risen to the forefront of international negotiations on climate change policy. Quantitative analysis of REDD policies is critical for designing a REDD mechanism that is effective, efficient, and equitable. In this paper we develop a partial-equilibrium model (the Open Source Impacts of REDD Incentives Spreadsheet; OSIRIS), which we use to compare carbon dioxide emissions reductions and economic impacts across seven proposed REDD incentive design options at global, regional, and national scales. Our results support the growing consensus that REDD can be a low cost component of an overall climate solution. Differences in emissions reductions across design options are small relative to the difference in emissions with or without a REDD mechanism. Excluding any country from REDD incentives shifts emissions from deforestation to those countries, undermining the overall effectiveness of the REDD mechanism. As a result, REDD design options which extend incentives to countries with historically low deforestation rates can result in greater emissions reductions overall than those options which provide incentives only to countries with historically high deforestation rates. Absolute estimates of emissions reductions under REDD depend critically on the elasticity of demand for agricultural commodities produced on the tropical forest frontier. This underscores the importance of pursuing strategies to meet agricultural needs outside of the forest frontier. As a transparent, flexible open source economic model, OSIRIS can be adapted by stakeholders to advance negotiations on REDD.

Keywords: Climate change, reduced emissions from deforestation and forest degradation (REDD), reference levels, economic modeling

Introduction

Tropical deforestation is responsible for approximately one fifth of recent greenhouse gas emissions (IPCC, 2007). Dangerous climate change can not be avoided without large-scale effective action on reducing emissions from deforestation and forest degradation (REDD) and on increasing carbon sequestration in land-based systems (Eliasch, 2008; Warren *et al*, in review). The literature has shown that in many forests the opportunity cost of avoiding deforestation is relatively low (Stern, 2006; Kindermann, 2008; Eliasch, 2008; Naucler and Enkvist, 2009). Therefore, including a REDD mechanism in a global climate agreement presents an opportunity to achieve stronger global emissions reductions targets more quickly and cheaply, while providing countries which choose to retain forest cover with a valuable economic development opportunity (Stern, 2006; Eliasch, 2008; Garnaut, 2008).

As part of a broader climate agreement, nations are expected to negotiate a REDD mechanism at the 15th Convention of Parties (COP 15) of the United Nations Framework Convention on Climate Change (UNFCCC) in December 2009. There is active discussion under the UNFCCC about whether the new mechanism will include the conservation of carbon stocks, agricultural and other soil carbon, and afforestation and reforestation, in addition to emissions from deforestation and degradation. The Subsidiary Body for Scientific and Technical Advice (SBSTA) of the UNFCCC is focusing on methodological issues that include reference levels of emissions from deforestation and degradation under REDD. The design of these reference levels will determine the effectiveness, efficiency, and equity (Stern, 2006; Angelsen, 2008) of the REDD mechanism.

Dozens of design options for setting national reference levels under REDD have been put forward by countries and non-governmental organizations (see Parker *et al*, 2008). As a result of differences in their design, these options would likely vary in terms of their impact on overall reductions in emissions from deforestation ("effectiveness"), reductions per dollar spent ("efficiency"), and distribution of REDD revenue across countries and regions ("equity"). It is of critical and urgent importance to the UNFCCC negotiation process that REDD stakeholders be able to quantitatively compare the likely impacts across REDD design options, using standardized data and consistent but flexible assumptions.

We have developed a publicly accessible economic model to enable quantitative comparison of REDD design options, in support of UNFCCC negotiations on REDD. The model is parameterized using the best currently available global data sets on factors relevant to REDD, including forest and soil carbon density, forest cover, and opportunity cost of forest for agriculture and timber. We have made this model and data set publicly available in the form of an open-source decision support tool, the Open Source Impacts of REDD Incentives Spreadsheet (OSIRIS).[1]

REDD design, reference levels, and incentives

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[1] OSIRIS, a free, accessible, transparent, and open-source Excel spreadsheet tool is available for download as a companion piece to this paper at <www.conservation.org/osiris>. Stakeholders to REDD negotiations can use OSIRIS to recreate the results of this paper, explore the impacts on effectiveness, efficiency, and equity of key economic parameters, and evaluate impacts of other published or user-generated REDD design options on their countries or regions.

In all proposed REDD designs, emissions reductions from participating countries would be measured relative to an agreed-upon reference level. Countries' actual emissions from deforestation would then be monitored and verified. Any country whose actual level of emissions from deforestation is less than its reference level would be eligible to credit this difference as an emissions reduction achievement. Proposed REDD designs are generally distinct from a cap-and-trade system in that countries would not be required to purchase credits to cover emissions above their reference level, though in some design proposals countries could be required to make up the balance in future time periods before becoming eligible to earn future payments for reductions.

REDD design options differ in the manner in which countries' reference levels are established, which in turn leads to differing incentives for countries to participate in a REDD program. In the simplest design option, a country's reference level is equal to its average national rate of emissions from deforestation over a recent historical period, as in one variant of the original compensated reduction design proposal (Santilli *et al*, 2005). When positive incentives are extended only to countries with historically high rates of deforestation, there is exacerbated throat of shifting, or "leakage," of deforestation activities to countries with historically low deforestation rates, including to the carbon-rich "high forest, low deforestation" (HFLD) countries (da Fonseca *et al*, 2007) at the top of the forest transition curve (Mather, 1992). Some design proposals address leakage by extending higher than historical reference levels to countries with historically low deforestation rates (Santilli *et al*, 2005; Mollicone *et al*, 2007). When the sum of nationals reference levels is greater than the global business as usual emissions rates, there is the possibility that there could be more credits generated than emissions reduced, compromising the UNFCCC principle of additionality. To maintain additionality, Strassburg *et al* (2009) have proposed a combined incentive mechanism which maintains the sum of national references levels equal to the global reference level through a flexible combination of higher reference levels for countries with historically low deforestation rates and lower reference levels for countries with historically high deforestation rates. As an alternative, Cattaneo (2008) has proposed withholding some fraction from the price paid for emissions reductions. The funds raised through the withholding would be distributed to forest countries in the form of payments for forest stocks. However, if a country exceeds historical emissions its stock payments would be reduced by the cost of offsetting the increase in its emissions elsewhere. Historical deforestation rates are an imperfect predictor of business as usual emissions and reference levels. Ashton *et al* (2008) have proposed a 'forward looking' reference level that can be predicted using a uniform fraction of the terrestrial carbon stock estimated to be 'at risk' into the future, based on biophysical, economic and legal considerations.

In this paper we quantitatively model and compare reductions in emissions from deforestation,[2] and REDD financial transfers per emissions reduction, across seven REDD design options[3]:

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[2] We examine only the impacts of the first 'D' in REDD, deforestation, and not the second 'D,' forest degradation. Yet, we refer to 'REDD' throughout the paper to be consistent with the name of the UNFCCC mechanism under negotiation.

[3] Note that we are examining here only those specific features of proposals that relate to the setting of national level incentives, rather than REDD design proposals in their entirety.

- "Without REDD" or "business as usual" – No REDD mechanism put in place (counterfactual)
- "National historical" – Reference levels equal to national historical rates for all countries (Santilli *et al*, 2005)
- "Higher than historical for low deforestation" – Reference levels equal to national historical rates for countries with historically high deforestation; reference levels higher than national historical rates for countries with historically low deforestation rates (Santilli *et al*, 2005; Mollicone *et al*, 2007)
- "Weighted average of national and global" – Reference levels weighted average of national and global historical rates (Strassburg *et al*, 2009)
- "Flow withholding and stock payment" – A percentage of payment for emissions reductions is withheld to fund payment for forest stock (Cattaneo, 2008)
- "Uniform fraction of qualified stock" – Some portion of national forest stock is assumed to be at-risk; reference level is a uniform fraction of at-risk forest stock (Ashton *et al*, 2008)[4]
- "Cap and trade for REDD" – Countries required to purchase credits for emissions above their reference level (as a benchmark scenario only)[5]

The formulae for calculating reference levels under each design option are displayed in Table 1. Most of these design options require the specification of a design-specific parameter, e.g. the weight placed on global average historical rates, or the percentage of flow payment withheld. For each design, a "best foot forward" design-specific parameter was selected for which the design achieved its maximum effectiveness and efficiency.

Analytical framework

The analytical framework for OSIRIS is a one-period global partial equilibrium market for a single commodity, adapted from Murray (2008). The commodity in the OSIRIS model is a composite index of agricultural output (including timber) produced on one hectare of land cleared from the tropical forest frontier ("frontier land agricultural output;" Figure 1). Expansion of the agricultural frontier is assumed to be wholly responsible for deforestation, and frontier land agricultural output is assumed to be perfectly substitutable geographically. Demand for frontier land agricultural output is global, with underlying national demand for agriculture and timber perfectly substitutable between domestic and imported agricultural production. In each of 79 tropical or developing countries thought to be potentially eligible for REDD, a national supply curve for frontier land agricultural output in the absence of REDD incentives is constructed from spatially explicit estimates of returns from agriculture and timber. National supply curves sum horizontally to determine a global supply curve for frontier land agricultural output. Global supply and demand curves intersect to determine the economic return to

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[4] Note that a number of defining elements of the Ashton *et al* (2008) proposal have not been modeled here, including variation in the portion of at-risk carbon stock across countries, the assumption of increasing deforestation rates into the future under business as usual, and carbon stocks outside of forests.

[5] Cap and trade for REDD has been discussed by Eliasch (2008), but has not been submitted to the UNFCCC by any parties or observers.

frontier land agricultural output and the quantity of annual deforestation. It is assumed that these economic returns determine the price of frontier agricultural land, which in turn determines national quantities of deforestation instantaneously, as each country simultaneously chooses a quantity of frontier agricultural land to maximize national surplus from agriculture and.REDD.

The impact of REDD incentives on deforestation is modeled by shifting national level supply curves inward, as return to frontier land agricultural output is diminished by the opportunity cost of obtaining REDD credits from standing forest. The inwardly shifted global supply curve intersects with the global demand curve to predict the global increase in the return to frontier land agricultural output, and the change in quantity of frontier land supplied by each country. With REDD, the quantity of frontier agricultural land supplied decreases in most countries as REDD provides sufficient incentives to retain standing forest (Figure 1, countries I and II). However, deforestation increases in countries where REDD incentives are weak or non-existent, because REDD incentives are outweighed by increased returns to agriculture, including timber (Figure 1, country III). Quantities of deforestation avoided by each country, along with estimates of average national forest carbon density, are used to calculate countries' reductions in emissions from deforestation and REDD revenue.

Real uncertainties exist about the market price of carbon, transaction and management costs, and the elasticity of demand for frontier land agricultural output. These and other uncertainties are treated transparently in OSIRIS through the use of flexible parameters which can be changed by users.

National supply curves without REDD incentives

National supply curves for frontier land agricultural output are constructed from national-level deforestation data and spatially explicit calculations of agricultural land rent, as well as timber returns. In every country $i \in 1:79$, there exists J_i hectares of forest land (Schmitt *et al*, 2008). For each hectare of forest of land h_{ij} in country i where $j \in 1:J_i$, a highest-return agricultural activity and productivity level, a_{ij}, is determined based on a map of global agro-ecological zones (Fischer *et al*, 2000). The highest-return economic activity and productivity level at each hectare j in each country i is converted to a maximum potential gross annual agricultural revenue, r_{ij}, excluding production costs, following Naidoo and Iwamura (2007) and Strassburg *et al* (2009).

Potential agricultural land rental price, p_{ij}, is deduced from maximum potential stream of annual agricultural revenue plus a one-time timber extraction value using the formula $p_j = (\pi \sum_{n=1}^{N} r_{ij}^{(1-\delta)^n}) + t_i$. Following Stern (2007), we specify a time horizon, N, of 30 years, a discount rate, δ, of 0.10, and a uniform profit margin, π, of 0.15 across all agricultural land. Spatial variation in transport and other costs is not captured in π. Parameter t_i represents the average national net present timber extraction value (Sohngen and Tennity, 2004). To form monotonically non-increasing agricultural rent curves across the entire forest estate, hectares of forest were rank-ordered in decreasing potential agricultural land rental price, such that in each country i, $p_{ij} \geq p_{ij'}\ \forall j < j'$.

In each country *i*, the without-REDD equilibrium quantity of annual deforestation, q_i*, is taken from self-reported actual historical national rates of deforestation from 2000-2005 (FAO, 2005).[6] The distribution of return to agricultural land across deforested hectares is assumed to be identical to the distribution of return to agricultural land across all forest hectares,[7] so that the curve of decreasing agricultural rent across deforested hectares is a linear transformation of the curve of decreasing agricultural rent across all forest hectares; i.e. $p_{iq} = p_{ij} \ \forall \ q/q_i{*}=j/J_i$.

Supply curves for frontier land agricultural output are constructed by building down from a global clearing price for agricultural land using return to agricultural land, rather than building up from the x-axis using cost of agricultural production (Figure 1, Country I). Changes in national quantities of frontier land agricultural output supplied are driven by shifts in return to agricultural land output, rather than absolute return. So without loss of generality, we can arbitrarily select the without-REDD global clearing price of frontier land agricultural output at equilibrium, $P*$, to be the global maximum return to agricultural land output from the data set, $max\{p_{ij}\}$. Now in every country *i*, the height of the supply curve at quantity *q*, S_{iq}, is equal to $P_i * - p_{iq}$, or global maximum frontier land agricultural output minus local frontier land agricultural output.

The final step in constructing national supply curves is to extend the national supply curves to the right, beyond the without-REDD equilibrium quantity of annual deforestation, q_i* (Figure 1). Relative slopes of supply curve extensions across countries, β_i, were produced by running regression lines through each country's curve of agricultural land rental prices across all forest hectares in Excel, fixed to the origin. That is, for each country *i*, β_i solves the econometric equation $q_j = \beta_i h_{ij}$ across all $j \in 1 : J_i$. So, supply curve extensions are flatter in countries with more forest and more land with high agricultural rental price, and steeper in countries with less forest and less land with high agricultural rental price. Relative slopes of supply curve extensions were scaled linearly into absolute supply curve extensions using a flexible parameter *n*, such that $\forall \ q>q_i*$, $S_{iq} = P_i * + \beta_i (q - Q_i *)$. The default value of flexible parameter *n* is 0.10, arbitrarily chosen such that the slope of the global supply curve extensions beyond $Q*$ is roughly equivalent to the slope of the global supply curves leading up to $Q*$.[8]

Global demand curve

The global demand curve for frontier land agricultural output determines the extent to which a decrease in the area of frontier agricultural land in one country causes an increase in the prices of the underlying commodities and a corresponding increase in

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[6] This is the "business as usual" reference scenario. Though we have assumed historical emissions rates for business as usual over the time period, the model can be adapted to include projected business as usual reference rates if and when such projections are developed. For more on the use of FAO Forest Resource Assessment deforestation rates, see Olander *et al* (2008).

[7] This assumption is consistent with an agricultural and timber frontier that is determined by proximity to transportation networks, where the spatial distribution of transportation networks is uncorrelated with the spatial distribution of agricultural and timber land rent.

[8] This assumption is consistent with a continuous distribution of agricultural and timber rental value across the intrinsic margin (barely profitable land) and extrinsic margin (barely unprofitable land), rather than a discontinuity in the distribution of agricultural and timber rental value at the margin.

the return to frontier land agricultural output elsewhere. This increased return to frontier land agricultural output in turn results in increased area of frontier agricultural land produced in other countries. This shifting of deforestation to other locations in response to reductions in deforestation is referred to as 'leakage' or 'international emissions displacement.'[9]

We specify an exponential global demand curve for frontier land agricultural output, whose default elasticity is an intermediate elasticity of 1.0 (implying that a 1% reduction in supply results in a 1% increase in price), and which is calibrated about the point of total observed annual deforestation (12.1 million Ha/yr) and estimated average agricultural return ($506/Ha); i.e. the demand curve is comprised of all points (p,q) such that $q = Q^*(p^*)^e(p-(S^*-p^*))^{-e}$. For the REDD design in which reference levels are based on national historic emissions rates, which has no feature in place to control leakage, these parameters for the demand curve generate leakage of 42%.[10]

National supply curves with REDD incentives

As REDD positive incentives increase the monetary value of standing forest relative to the return to agriculture, national supply curves for frontier land agricultural output shift upward and inward according to design-specific formulae (see Table 1). National supply curves with REDD incentives are determined by two steps—first by calculating the change in the per-hectare return to frontier land agricultural output, and then by determining the overall national quantity of frontier land agricultural output supplied at any price due to the incentive.

First, we calculate the magnitude of the per-hectare marginal incentive. For most design options, the per-hectare incentive to reduce deforestation emissions on one hectare in country i, R_i, is calculated using the formula $R_i=CD_i*3.66*PC*PERM-CM_i$. Here, CD_i is the carbon density in country i (tons C/Ha). The default carbon density is the national average forest carbon density (Ruesch and Gibbs, 2008; WCMC, 2008) plus a default value of 0.25 times the average national forest soil carbon density in the top 100 cm of forest soil (Global Soil Data Task Group, 2000). 3.66 is the atomic ratio between carbon dioxide and carbon (ton CO_2e/ton C). *PC* is the market price of a ton of carbon dioxide

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[9] For a complete discussion of leakage see Murray (2008) or Wunder (2008).

[10] Leakage calculated as $1-r_a/r_i$, where r_a is the percent reduction in deforestation with actual elasticity of demand (e=1), and r_i is the percent reduction in deforestation with hypothetical infinite elasticity of demand ($e=\infty$). We have simplified global demand by specifying demand for an aggregation of land across all agricultural commodities, rather than treating the elasticity of demand for land in each agricultural commodity separately. We are not aware of any empirical estimates of the price elasticity of demand for frontier agricultural land. While the elasticity of demand for food calories can not be distinguished from perfectly inelastic (Roberts and Schlenker, 2009), frontier agricultural land comprises only one available option for increasing the production of food. Nevertheless, Roberts and Schlenker also find a low elasticity of supply for the global production of food calories (about 0.106), suggesting that options for increasing supply are limited, at least in the short run. Their estimates imply that the demand elasticity might be closer to 0 than our default value of 1 and that leakage would thus be significantly higher than implied by our default parameters. Their estimates imply that a 1% reduction in calorie supply generates about a 7% increase in price. Our leakage estimate of 42% is comparable to leakage estimates of 34-50% within the developing world generated by a model of the international timber market (Gan and McCarl, 2007), though this paper examines a different market and employs different methods.

emission (\$/ton CO_2e). The default price of carbon is 2008 US\$5/ton CO_2e. *PERM* is a scaling factor applied to a payment for reduced emissions to ensure permanence. For discussion of insurance, buffers, and other permanence reductions, see Dutschke and Angelsen, 2008. The default permanence scaling factor is 1.00, assuming no permanence reduction. CM_i is the per hectare net present cost of management to ensure deforestation is avoided in country *i*. The default net present management cost of avoiding deforestation is \$40/Ha for all countries, corresponding to \$3.50/Ha/yr, the average cost per hectare of protected area management across developing countries (James, 2001). All costs were deflated to 2000 US\$ using for comparison http://data.bls.gov/cgi-bin/cpicalc.pl. All default parameters are flexible in OSIRIS. The national supply curve without REDD (thin black line in Figure 2) is shifted upward by the incentive to the left of a crediting reference level, q_{ref}, to determine the incentive-shifted supply curve (thin red line in Figure 2). That is, if $q \le q_{ref}$, then $S_{iq}^{withoutREDD} = S_{iq}^{withREDD} + R_i$; otherwise $S_{iq}^{withoutREDD} = S_{iq}^{withREDD}$.

At any price, each country must choose between the quantity of deforestation on the original supply curve, without REDD, and quantity on the incentive-shifted supply curve, with REDD. At either quantity, the marginal benefit of supplying frontier agricultural land will be equal to the marginal cost. The default assumption in OSIRIS is that the country chooses the quantity of production which provides greater aggregate national welfare.[11] The set of chosen quantities at every price determines the with-REDD supply curve (heavy red line in Figure 2). It is assumed that all reductions in deforestation will have a buyer at a given price.[12]

Caveats

A number of limitations to the analysis should be noted. First and most importantly, OSIRIS is most useful for comparing impacts across design options and across countries, and is less useful for predicting the absolute magnitudes of impacts. This is because the model combines data sources of varying scale and quality, and because the absolute magnitude of impacts is sensitive to parameters such as transaction costs and elasticity of demand for frontier land agricultural output, whose values are uncertain.[13]

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[11] Since the tradeoff between opting into and opting out of REDD involves both winners and losers, we allow this assumption to be relaxed. We specify a parameter, *x*, which represents the social preference for agricultural surplus relative to REDD surplus, or the transaction costs in redistributing income from REDD to offset foregone surplus from agriculture. If REDD surplus from opting in to REDD (A+B in Figure 2) is greater than x times the foregone agricultural surplus from opting out of REDD (A+C in Figure 2), then a country chooses the quantity on the incentive-shifted supply curve (point m in Figure 2). Otherwise the country chooses the quantity on the without-REDD supply curve (point n in figure 2). The default value of *x* is 1, implying that a country will choose to participate in REDD if the REDD surplus outweighs the foregone agricultural surplus.

[12] When all reductions are purchased at a given price, REDD incentive price, based on carbon price, is the input to the model, and quantity of reductions is an output. However, OSIRIS has the capability to specify quantity of reductions as an input, with REDD incentive price as an output.

[13] Note for example that our predicted rate of business as usual emissions from deforestation, 8.2 billion tons CO_2e/yr, is slightly less than the IPCC estimate of 8.48 billion tons CO_2e of emissions from deforestation in 2004 (IPCC, 2007, Fig. SPM.3).

Second, following Stern (2007) and others, we have based the extent to which countries avoid deforestation on a comparison of per-hectare marginal benefits from agriculture and marginal benefits from REDD. While this opportunity cost framework offers a powerful starting point for impact comparison across design options and countries, it oversimplifies reality in two respects. First, countries' decisions to participate in REDD are likely to be more complex than is a simple comparison of earnings from agriculture and earnings from REDD. Objectives such as poverty alleviation, traditional values, ecological services, and biodiversity are likely to factor into countries' land use decisions. Second, some promising methods for reducing emissions from deforestation do not involve directly outcompeting opportunity cost at a site—notably, removal of perverse agricultural subsidies, moratoria on road construction, increased capacity to enforce forestry laws, and improved fire management.

Third, our single-period analysis compares short term but not long-term variation in incentives across REDD design options. By using 2000-2005 deforestation rates as our business as usual scenario, we compare the impacts if REDD had been in place during this period, rather than in future periods. Similarly, following the standard partial equilibrium model, we assume that countries' adoption of REDD policies, and price feedback to the price of agricultural land take place in a single period, in a perfect-information Nash equilibrium. In reality, it may take several years for information on prices and agricultural production to stabilize to a with-REDD equilibrium. Further, heterogeneous capacity between countries means that some countries will require external support or will risk falling behind on adoption of REDD.

Fourth, while OSIRIS allows for a rigorous in-depth analysis of one sector, the model excludes a number of other sectors important to climate change, land use and markets. The model considers the effects of carbon dioxide emissions but not other greenhouse gas emissions from deforestation, deforestation but not degradation, avoided deforestation but not afforestation and reforestation, and price feedbacks in the agricultural land market but not in the carbon market[14] or in specific agricultural subsectors.

Finally, we recognize that of the design of reference emission levels is just one important component of an efficient, effective, and equitable REDD mechanism. A REDD mechanism must also treat issues of permanence (Dutschke and Angelsen, 2008), monitoring (Olander *et al*, 2006), social and political viability, and the rights of indigenous peoples and communities (Seymour, 2008).

Results

All six scenarios in which a REDD mechanism is employed result in a significant decrease in emissions from deforestation relative to the scenario without a REDD mechanism. Under one set of illustrative conditions,[15] a REDD mechanism results in a

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[14] For more on price feedbacks of REDD in the carbon market, see Piris-Cabezas and Keohane (2008); Eliasch (2008).

[15] Results reported here are outputs of OSIRIS v2.0 using the following parameter values: carbon price = \$5/ton CO_2; permanence reduction scale = 1.00 (no permanence withholding); exponential demand with price elasticity = 1.00 (elasticity neither perfectly elastic nor perfectly inelastic); fraction of soil carbon eligible for REDD = 0.25; coefficient on slope of supply curve extensions = 0.10; Social preference for agricultural surplues parameter = 1.00; management and transaction cost = 2001 US\$3.50/Ha/yr; fraction of

58-76%[16] decrease in emissions from deforestation from business as usual (Figure 3). The difference between individual REDD design options is relatively small by comparison. Although a cap and trade system outperforms all other designs in both effectiveness and efficiency, this system is included as a benchmark rather than as a proposal. Caps on deforestation emissions for tropical countries which would require purchases of credits if exceeded have not been included in proposals to the UNFCCC.

Across all design options, emissions reductions are predicted to be greater in Asia (76-92% reductions relative to BAU) and Latin America (64-85%) than in Africa (4-53%),[15] as our data sets indicate that Asia and Latin America contain more land area on which carbon density is high and agricultural rent is low. In Africa, our model predicts that emissions reductions in high carbon density forests are largely offset by increased deforestation in lower carbon density forests in response to increased agricultural rental values.

When any country is excluded from REDD incentives, emissions from deforestation in that country increase due to leakage of frontier agriculture from REDD-incentivized countries. This is the case for countries with historically low-deforestation rates (deforestation rate below the global average deforestation rate of 0.22%/yr; FAO, 2005) in the national historical reference level design option. In the absence of incentives to maintain low emissions rates, countries with historically low deforestation rates undergo a fivefold increase in emissions from deforestation due to leakage from other countries (Figure 4).[15] Consequently, design options that provide REDD incentives to all countries can enable countries with historically low-deforestation rates to maintain low emissions rates, and make the REDD mechanism more effective and efficient overall (Figure 4).

REDD effectiveness and efficiency depend critically on the elasticity of demand for frontier land agricultural output, with greater elasticity implying greater emissions reductions (Figure 5). When elasticity is at its theoretical maximum, any frontier agricultural land can be taken out of production without bringing additional frontier agricultural land into production elsewhere. In this case, leakage is not a consideration, and nearly all emissions from deforestation can be avoided (Figure 5; e=inf.). When elasticity is at its theoretical minimum, every hectare of frontier agricultural land that is taken out of agricultural production in one place is replaced by a hectare of agricultural production elsewhere. It is worth noting that even in this extreme case, a REDD mechanism decreases emissions from deforestation, as deforestation activity is pushed from high carbon density to low carbon density forests (Figure 5; e=0). The true elasticity likely lies between these two extremes, though its exact value is uncertain (Figure 5; e=0.5, e=1.0; e=2.0).[17] In general, when elasticity is lower and leakage is greater, there is a greater difference in emissions reductions between the national historical design and the cap and trade design, representing greater potential gains to

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national average timber rent included = 1.00. Furthermore, the following design-specific parameters are assumed: reference level for countries with low deforestation rates = 0.003; weight on national historic rates = 0.40; flow withholding = 0.30; fraction of forest and other terrestrial carbon land protected = 0.20; reference level as fraction of unprotected land = 0.01.

[16] We report results in terms of percentage reductions rather than absolute reductions, as these results are less sensitive to parameter assumptions.

[17] Recent empirical analysis suggests that the relevant elasticity may well lie near the lower end of the range considered, at least in the short term (Roberts and Schlenker 2009).

designs features that prevent leakage. Elasticity can be influenced; the more agricultural needs can be supplied through expanded and intensified agricultural production outside of the forest frontier, the greater elasticity will be for frontier land agricultural output, and the more effective and efficient REDD is likely to be.

Discussion

A number of robust conclusions can be drawn across REDD design options, despite uncertainty about the absolute magnitude of emissions reductions under REDD. First, all REDD scenarios modeled yield substantial emissions reductions relative to the absence of REDD. Relative to the substantial difference in emissions levels with and without REDD, the difference in emissions reductions among particular reference level design is minor. This suggests that the implementation of a REDD mechanism, regardless of which design option is chosen, can significantly reduce emissions from deforestation and significantly contribute to mitigating climate change.

Second, excluding any countries from REDD incentives results in leakage of deforestation emissions to those countries. For example, when reference levels are set using national historical deforestation rates, deforestation increases in countries with historically low deforestation rates. To address this avoidable loss in efficiency and effectiveness, the REDD mechanism should include positive incentives for all countries, including those which currently have low deforestation rates. A higher than historical reference level for countries with historically low deforestation rates can make the REDD mechanism more effective and efficient overall.

Third, the effectiveness and efficiency of REDD is dependent upon the elasticity of demand for frontier land agricultural output. Strategies to provide for world agricultural needs through expanded and intensified agricultural production outside of the tropical forest frontier could reduced leakage of deforestation and contribute to greater emissions reductions under REDD.

A key next step for REDD incentives research is to work with UNFCCC negotiators to compare impacts of additional design options which negotiators consider to be likely or politically feasible. Analysis can also be extended to designs which combine component features of proposals. Research can be extended to compare the impacts of long-term REDD methodological incentives by integrating OSIRIS with a spatially explicit and dynamic projection of land use change (Kindermann *et al*, 2006). OSIRIS can also be integrated with more detailed national-level data sets to analyze sub-national land use implications. Finally, the accuracy of OSIRIS can be continually improved by integrating more accurate and finer scale data as these become available.

Conclusion

The results of this analysis add to a growing consensus (Pacala and Socolow, 2004; Stern, 2006; Eliasch 2008) that a well designed REDD mechanism can be an effective component of an overall agreement to avoid dangerous climate change. Quantitative economic models such as OSIRIS can help climate negotiators design a REDD mechanism that is effective, efficient, and equitable.

Acknowledgments

We are grateful for support from the Gordon and Betty Moore Foundation and a private donor to Conservation International. Valuable comments on this research were contributed by Arild Angelsen, Anna Creed, Celia Harvey, Fiona McKenzie, and event participants at the World Bank Forest Carbon Partnership Facility, International Institute for Applied Systems Analysis, Conservation International, and the UNFCCC COP 14 in Poznan, Poland.

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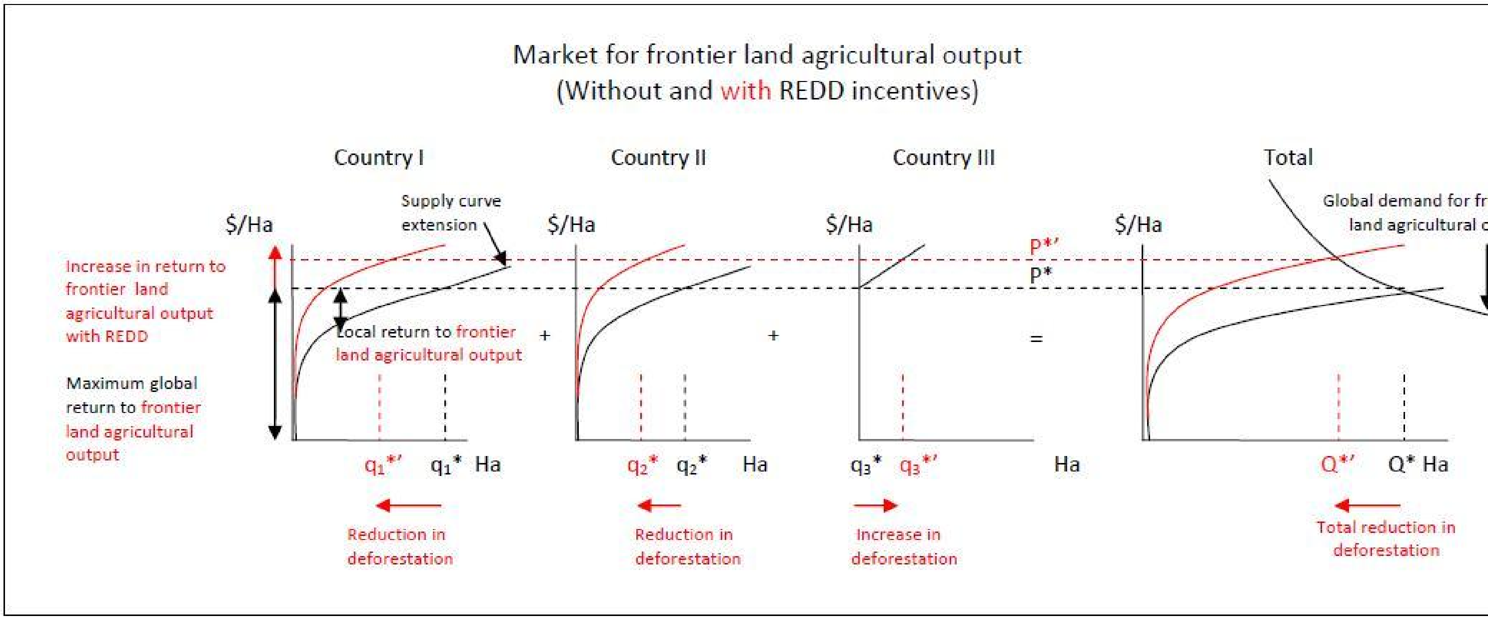

Figure 1 – Annual market for frontier land agricultural output. In this example, REDD incentives for countries I and II shift the supply curves for frontier land agricultural output upward. These countries reduce the quantity of frontier land agricultural output supplied. The slope of the global demand for frontier land agricultural output determines the extent of the global increase in the return to agricultural land output, which causes Country III, which does not receive REDD incentives, to increase frontier agricultural production. Countries' rate of deforestation with REDD are used to calculate emissions from deforestation and REDD financial flows.

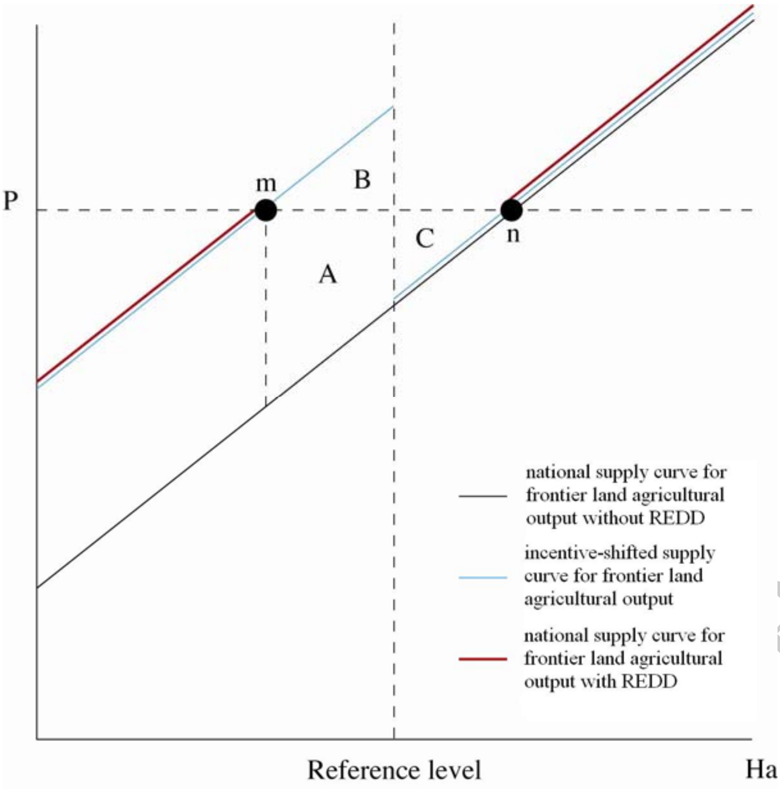

Figure 2 – National supply curves. National supply curve for frontier land agricultural output without REDD (black) is shifted upward to the left of the reference level by the magnitude of the per-hectare incentive payment to form the REDD incentive-shifted supply curve for frontier land agricultural output with REDD (blue). The national supply curve for frontier land agricultural output with REDD (red) is composed of the points along the incentive-shifted supply curve for which at a given price REDD surplus exceeds agricultural surplus. In the figure, when A+B=*x*(A+C), the surplus from participating in REDD (A+B) is just enough to offset foregone agricultural surplus (A+C) at the value of *x*, the parameter describing social preference for agricultural surplus to REDD surplus. REDD surplus is potentially large enough to distribute such that all land users are at least as well off with REDD as without REDD. Thus the government is ambivalent about participating in REDD (point m) and opting out of REDD (point n). When P is lower than $P^{\#}$, national REDD surplus would be more than enough to compensate all land users for lost agricultural surplus, so the government chooses to participate in REDD. When P is higher than $P^{\#}$, national REDD surplus is insufficient to compensate all land users for lost agricultural surplus, so the government chooses not to participate in REDD. The default value of the social preference for agriculture parameter *x* in OSIRIS is 1.0.

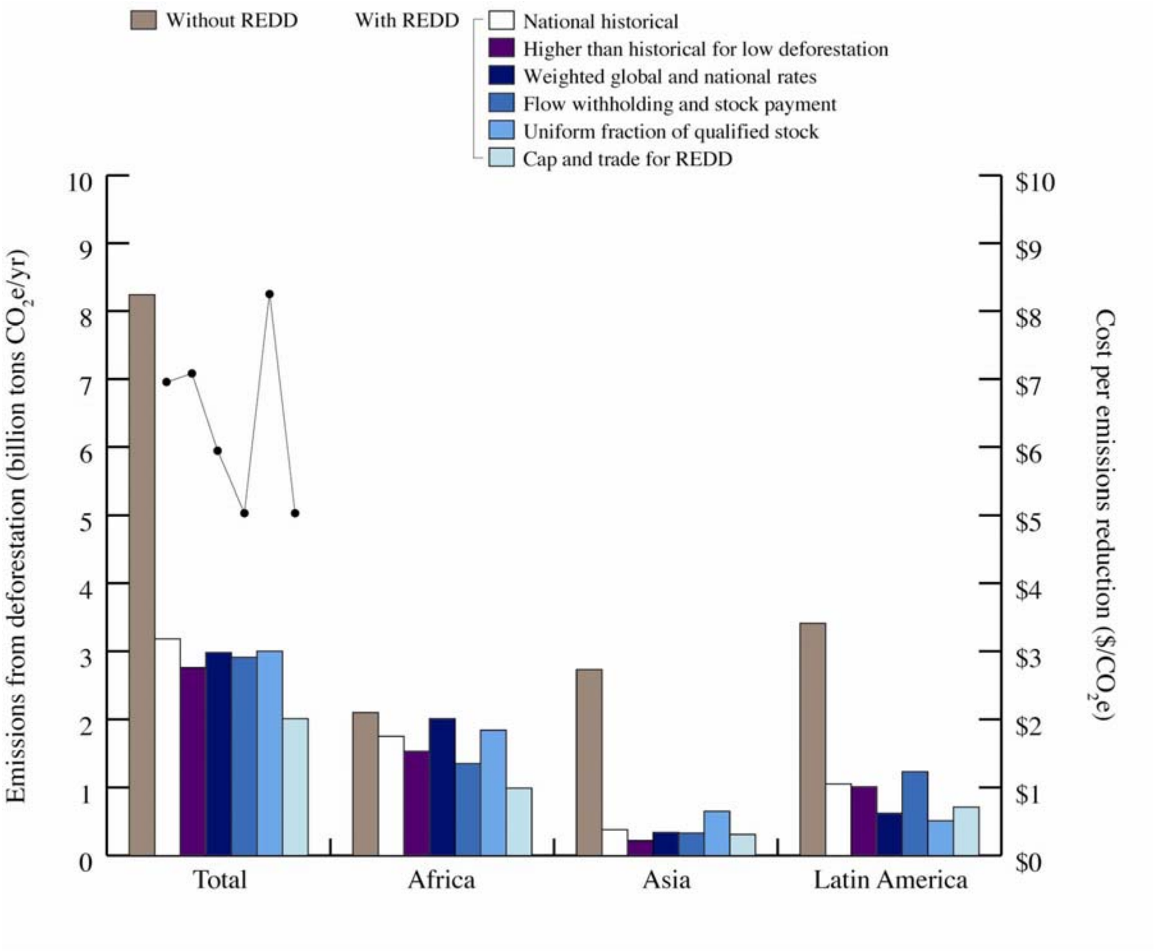

Figure 3 – Emissions from deforestation under seven REDD design options, by region

Results are outputs of OSIRIS v2.0 using the following parameter values: carbon price = \$5/ton CO_2; permanence reduction scale = 1.00 (no permanence withholding); exponential demand with price elasticity = 1.00 (elasticity neither perfectly elastic nor perfectly inelastic); fraction of soil carbon eligible for REDD = 0.25; coefficient on slope of supply curve extensions = 0.10; Social preference for agricultural surplus parameter = 1.00; management and transaction cost = 2001 US\$3.50/Ha/yr; fraction of national average timber rent included = 1.00. Furthermore, the following design-specific parameters are assumed: reference level for countries with low deforestation rates = 0.003; weight on national historic rates = 0.40; flow withholding = 0.30; fraction of forest and other terrestrial carbon land protected = 0.20; reference level as fraction of unprotected land = 0.01.

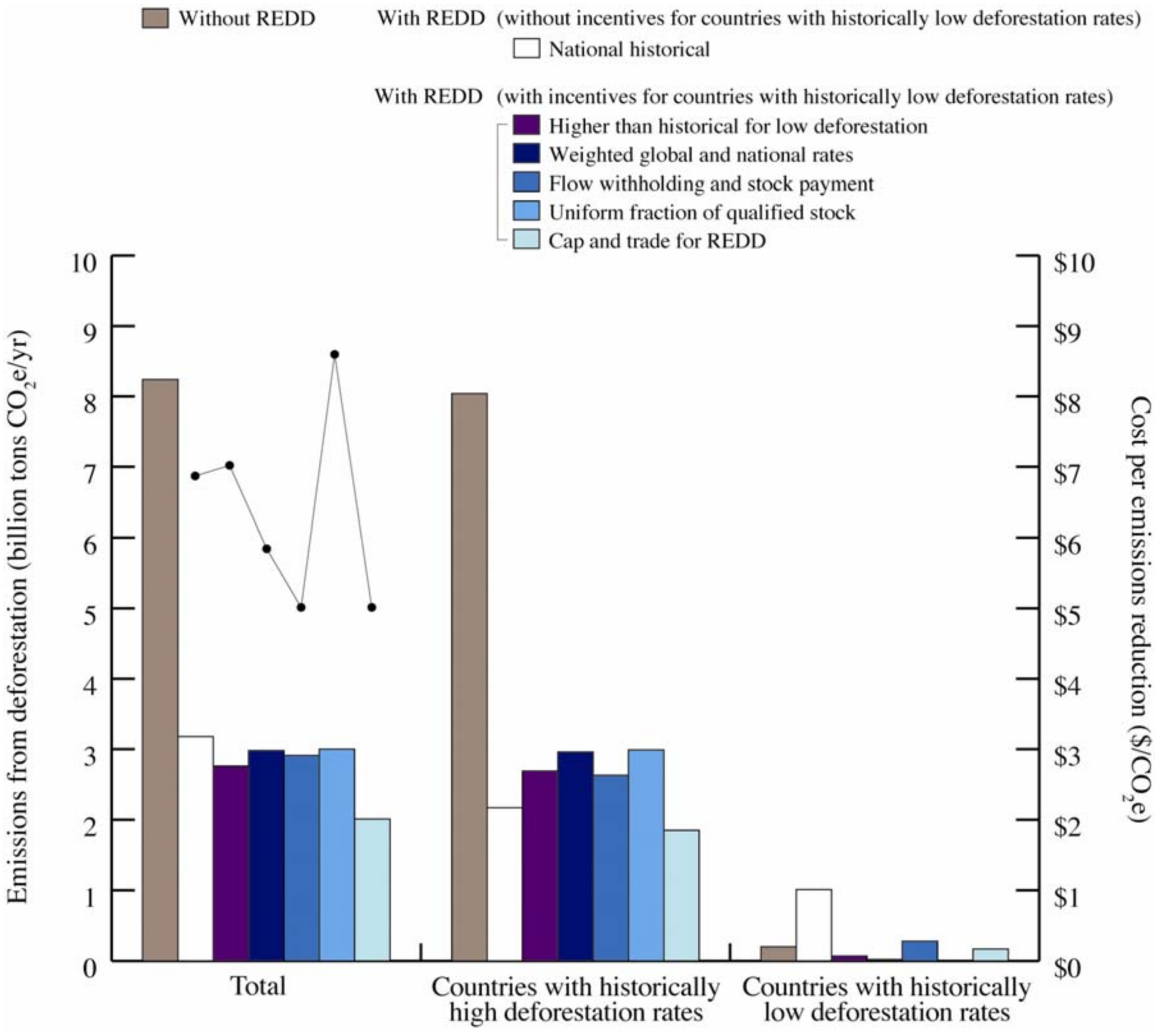

Figure 4 – Emissions from deforestation under seven REDD design options, by historical deforestation rate

Results are outputs of OSIRIS v2.0 using the following parameter values: carbon price = \$5/ton CO_2; permanence reduction scale = 1.00 (no permanence withholding); exponential demand with price elasticity = 1.00 (elasticity neither perfectly elastic nor perfectly inelastic); fraction of soil carbon eligible for REDD = 0.25; coefficient on slope of supply curve extensions = 0.10; Social preference for agricultural surplus parameter = 1.00; management and transaction cost = 2001 US\$3.50/Ha/yr; fraction of national average timber rent included = 1.00. Furthermore, the following design-specific parameters are assumed: reference level for countries with low deforestation rates = 0.003; weight on national historic rates = 0.40; flow withholding = 0.30; fraction of forest and other terrestrial carbon land protected = 0.20; reference level as fraction of unprotected land = 0.01.

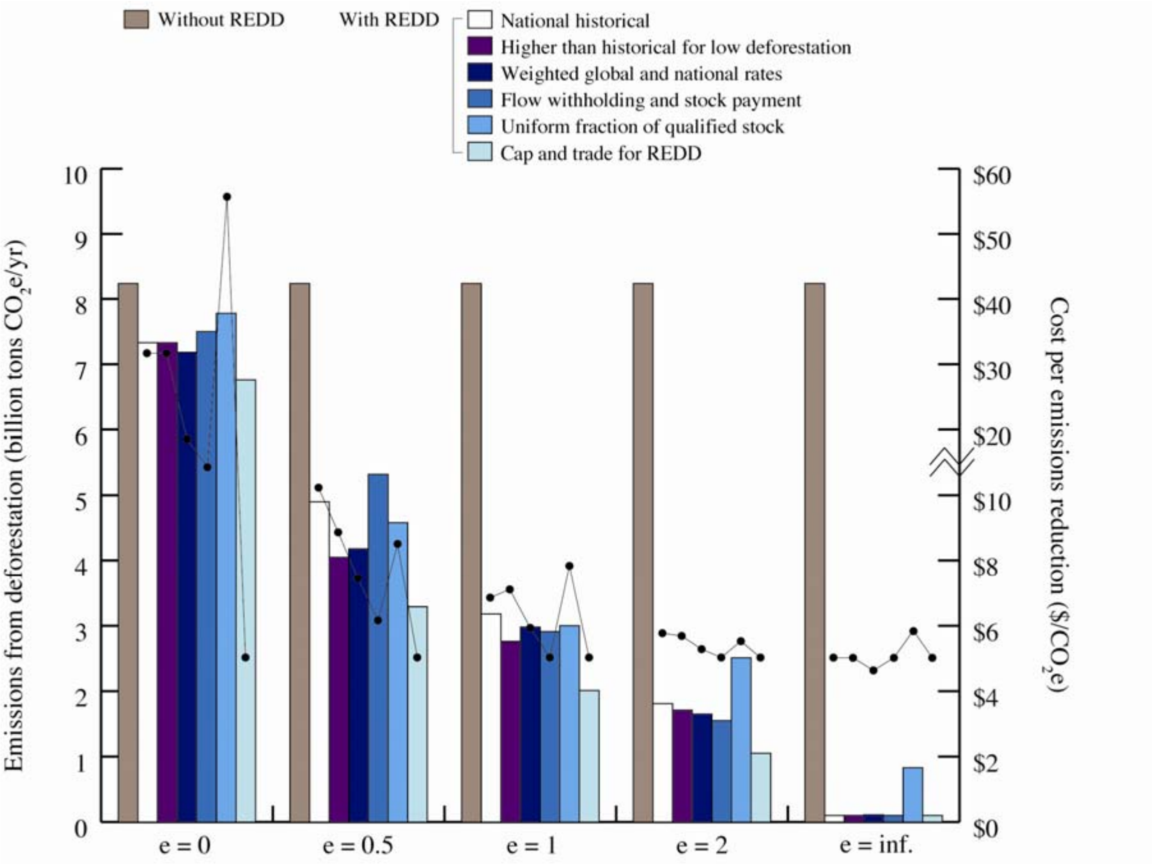

Figure 5 – Emissions from deforestation under seven REDD design options, at varying elasticity of demand for frontier land agricultural output. Higher elasticity results in greater emissions reductions underscoring the importance of strategies to provide for agricultural needs outside of the forest frontier.

Results are outputs of OSIRIS v2.0 using the following parameter values: carbon price = \$5/ton CO$_2$; permanence reduction scale = 1.00 (no permanence withholding); exponential demand; fraction of soil carbon eligible for REDD = 0.25; coefficient on slope of supply curve extensions = 0.10; Social preference for agricultural surplus parameter = 1.00; management and transaction cost = 2001 US\$3.50/Ha/yr; fraction of national average timber rent included = 1.00. Furthermore, the following design-specific parameters are assumed when elasticity = (0; 0.5; 1.0; 2.0; ∞): reference level for countries with low deforestation rates = (0; 0.0035; 0.003; 0.001; 0); weight on national historic rates = (0.45; 0.70; 0.40; 0.70; 0.60); flow withholding = (0.50; 0.35; 0.30; 0.15; 0); fraction of forest and other terrestrial carbon land protected = 0.20; reference level as fraction of unprotected land = (0.0075; 0.0075; 0.0100; 0.0068; 0.0088).

Table 1 – Design-specific reference level formulae

Design option	Formulae for reference levels and REDD payments[18]
National historical reference levels (Santilli *et al*, 2005)	For all countries, $B_i = H_i$ $REDD_i = \max\ \{0, (B_i - E_i)*P\}$
Higher than historical reference levels for countries with historically low deforestation rates (Santilli *et al*, 2005; Mollicone *et al*, 2007)	If $D_i > D$, then $B_i = H_i$. Otherwise, $B_i = D_i . * CD_i * 3.66$ $REDD_i = \max\ \{0, (B_i - E_i)*P\}$
Reference level is weighted average of national and global historical rates (Strassburg *et al*, 2009)	For all countries, $B_i = [\alpha\, D_i . + (1 - \alpha\,)GAD] * CD_i * 3.66$ $REDD_i = \max\ \{0, (B_i - E_i)*P\}$
Percentage of payment for emissions reductions withheld to fund payment for forest stock (Cattaneo, 2008)	For all countries, $B_i = H_i$ $REDD\_FLOW_i = \max\ \{0, (B_i - E_i)*P*\mathrm{w}\}$ $STOCK = \max\ \{0, \sum_i\ (B_i - E_i)*P - \sum_i\ REDD\_FLOW_i\}$ $REDD\_STOCK_i = \max\ \{0, (\frac{s_i}{\sum_i s_i})*STOCK - \max\ \{0, E_i - B_i\}*P\ \}$ $REDD_i = REDD\_FLOW_i + REDD\_STOCK_i$
Reference level is uniform fraction of qualified stock (Ashton *et al*, 2008)	For all countries, $B_i = f * Q_i$ $REDD_i = \max\ \{0, (B_i - E_i)*P\}$
Cap and trade for REDD	For all countries, $B_i = H_i$ $REDD_i = (B_i - E_i)*P$

B_i = reference emission level (baseline) for country i (ton CO_2e)
H_i = historical emission level (business as usual) for country i (ton CO_2e)
E_i = emission level for country i (ton CO_2e)
$REDD_i$ = REDD payment to country i (\$/yr)
P = carbon price (\$/ton CO_2e)
D_i = historical deforestation rate for country i (Ha/yr)
D = cut-off deforestation rate (Ha/yr)
CD_i = carbon density for country i (ton C/Ha)
3.66 = atomic ratio of carbon dioxide to carbon (ton CO_2e/ton C)
GAD = global average deforestation rate (Ha/yr)
α = weight placed on national historical deforestation rate
$REDD\_FLOW_i$ = flow payment to country i (\$/yr)
w = percentage of flow payment withheld to fund stock payment
$STOCK$ = global stock payment
$REDD\_STOCK_i$ = stock payment to country i (\$/yr)
s_i = forest carbon stock in country i (ton CO_2e)
QS_i = qualified forest carbon stock in country i (ton CO_2e)
f = fraction of forest carbon stock eligible for REDD

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[18] These formulae do not include dynamic payment incentive effects. For example, in many designs emissions above reference levels in one year are deducted from creditable emissions reductions in subsequent years.