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Saunders Hall 542, 2424 Maile Way,  
Honolulu, HI 96822  
Phone: (808) 956 -8496  
[www.economics.hawaii.edu](http://www.economics.hawaii.edu)

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Rethinking Baselines: An Efficiency-based Approach  
to Better REDD+ Governance

By  
Majah-Leah V. Ravago  
James A. Roumasset

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# Rethinking Baselines: An Efficiency-based Approach to Better REDD+ Governance\*

Majah-Leah V. Ravago<sup>†</sup> and James A. Roumasset

University of the Philippines and University of Hawaii

## Abstract

We present an approach for determining dynamic baselines for Reducing Emissions from Deforestation and Degradation plus sequestration (REDD+) based on the efficient path of forest emissions absent carbon prices. We show that, unlike industrial emissions, baseline emission permits for forests should be negative. Positive entitlements for forest emissions are unnecessary and may be ineffective in the absence of additional governance mechanisms. A numerical illustration for the case of Indonesia shows that the potential gains from the efficiency-based approach are nearly twice those from conventional REDD+ proposals.

Keywords: Governance, REDD+, deforestation, carbon emissions, sequestration, climate change

JEL: Q23, Q28, Q54, Q57

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<sup>†</sup> Corresponding author: Majah-Leah V. Ravago | University of the Philippines School of Economics, Encarnacion Hall, Guerrero corner Osmeña St, Diliman, Quezon City, Philippines 1101 | Phone: 632-9279686 loc 316 | Fax: 632-9205465 | E-mail: [mvravago@econ.upd.edu.ph](mailto:mvravago@econ.upd.edu.ph)

## **Rethinking Baselines: An Efficiency-based Approach to Better REDD+ Governance**

### **1. Introduction**

Reducing Emissions from Deforestation and Degradation plus Conservation (REDD+) is viewed as a critical component of climate change mitigation that will incentivize developing countries to participate. The 19th session of the Conference of Parties (COP 19) to the UN Framework Convention on Climate Change (UNFCCC) adopted the Warsaw Framework for REDD+ in November 2013. This followed a series of proposals designed to incentivize countries to increase forest conservation, e.g., through payments for ecosystem services (PES), and stimulated still further proposals. The Warsaw framework provides guidelines for the development of reference levels by which future forest emissions would be judged. As with earlier proposals, REDD+ is currently envisioned to base payments according to each country's reduction in emissions relative to those occurring under historical deforestation.

The economic rationale for using historical baselines to determine positive entitlements may appear to follow from traditions regarding industrial emissions. As discussed below, this overlooks the fundamental difference between forest emissions and industrial emissions. While private industry tends to maximize profits, forests are plagued with open access problems, and historical levels cannot be taken to reflect what is privately efficient. If existing timber prices have not induced efficient forestry practices, why would small additional price incentives render forestry socially efficient, even with the addition of conditional grants? Furthermore, unlike industrial emissions, the efficient amount of forest emissions absent carbon may be negative.

The objective of this study is to develop and illustrate such an approach. We propose *Efficient Reforms for REDD+* (ERR), which provides for an efficient path of net forest emissions that constitutes a dynamic baseline for granting emission permits. Forest-emission permits are based on the amount of carbon that would be efficiently emitted in the absence of carbon pricing. The efficiency baseline provides appropriate incentives for reducing emissions of forest carbon while saving as much as \$1.1 trillion worldwide relative to calculating baselines according to historical emissions.

Since ERR is more cost effective, we provide a numerical illustration of the *potential* gains. The savings can be used to induce the participation of developing countries through financial and technical assistance in forest governance, instead of transfers without adequate provision for enforcing project conditionalities. If a coalition of developed countries has a comparative advantage in aspects of governance, e.g. through satellite-based monitoring systems, this promises to make cooperation both more attractive to developing countries and more affordable for developed countries.

The results also illustrate the tendency of well-managed forests to emit more carbon than they sequester. Positive entitlements for forest emissions are therefore unnecessary.

## 2. Conventional REDD+ proposals

The many REDD+ proposals submitted to the United Nations<sup>3</sup> differ primarily according to the baseline from which emission reduction should be reckoned. The majority of these proposals are based on historical emissions as a guide to what forest

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<sup>3</sup> Already thirty two proposals had been submitted since December 2009 (Parker et al., 2009).

emissions *would* have been in the absence of any carbon agreement.<sup>4</sup> The Warsaw Framework for REDD+ crafted at the Conference of Parties (COP) in 2013, while leaving enough flexibility for countries to develop their own proposals, largely adopted the principle of historical baselines. Under these proposals, hereafter referred to as “conventional REDD+” proposals, countries receive payments for emissions reductions but pay no penalties for increases in emissions nor for failing to achieve targets (Mollicone et al., 2007). In contrast, we propose estimating what emissions *should* have been, under an efficiency benchmark, thereby avoiding overly costly entitlements and possibly crowding out expenditures on forest governance.

Figure illustrates historical deforestation for the case of Indonesia, which has been deforested at the rate of 1.2 million hectares per year (FAO, 2010) over the reference period 1990-2010. The vertical axis in Figure 1 is the total emissions of carbon for a given year. Busch *et al.* (2010) estimated Indonesia’s net emissions for this reference period at 219 million tons of carbon emissions per year. This becomes the benchmark from which emissions reductions (shaded area) are measured during the illustrative crediting period, 2015 to 2030. A decrease in deforestation, say by 32 percent, results in an emissions reduction of 70 million tons of carbon by 2030. At the price of \$20, for example, earnings for the reduction in emissions would be \$1.4 billion in 2030.

## FIGURE 1 AROUND HERE

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<sup>4</sup> Another approach uses projected baselines, whereby future deforestation rates are forecast using econometric models that are based on socioeconomic or structural causes of deforestation. In consideration of potential changes in future causes of deforestation, the use of a development adjusted factor has also been suggested.

## **2.1 Should baselines be set according to historical emissions?**

Historical emission entitlements raise horizontal equity issues inasmuch as they discriminate against countries that have practiced forest conservation relative to countries that have inefficiently degraded their forests. In contrast, rewarding countries according to their existing stocks might punish deforested countries for profligate behavior, but would not serve as an effective basis for cooperation.

Forests are plagued with open access problems. Governments are either unable or unwilling to enforce efficient harvesting practices. Government and military officials may even collude with foresters (Obidzinskia and Kusters, 2015; Contreras-Hermosilla, 2002) to harvest faster than the socially efficient level. Granting forest emission permits on the basis of historical deforestation would reward overharvesting and result in unnecessary and inequitable transfers. Granting permits on the basis of what level of deforestation and/or degradation is efficient abstracts from actual behavior and would be less expensive.

## **2.2 Should forest emissions be positive or negative?**

Inasmuch as the concept of cap and trade arose in the context of industrial emissions, the presumption of positive emission entitlements is perhaps natural given that both the efficient level of emissions and historical emissions are positive. For the case of forests, however, carbon emissions can be negative. To see this, define gross carbon emissions as  $\alpha[(1 - \beta)q(t)]$ , gross sequestration from new growth as  $\alpha Q'(t)$ , and net forest emissions as the difference:

$$(1) \quad e = \alpha[(1 - \beta)q(t) - Q'(t)],$$

where  $q(t)$  and  $Q'(t)$  are the rates of harvest and tree growth (change in volume) of standing merchantable trees biomass growth;  $\alpha$  is the weight of carbon per unit

volume ( $\frac{tc}{m^3}$ ) of the tree species in question; and  $\beta$  is the "pickling rate," i.e. the percentage of carbon retained in lumber and other wood products (van Kooten et al. 1995; IPCC 1997, 2006b). Net emissions will be positive if and only if  $(1 - \beta)q(t) - Q'(t) > 0$ .

To illustrate, suppose that the forest is harvested (and replanted) sustainably such that new growth,  $Q'(t)$  and harvest,  $q(t)$ , are equal on average to  $\omega Q(t)$  (where  $\omega$  is a percentage). Emissions are now given by  $e = \alpha[(1 - \beta)\omega Q(t) - \omega Q(t)] = -\alpha\beta\omega Q(t)$ . For example if  $\alpha$  is 8 percent and both  $\beta$  and  $\omega$  are  $\frac{1}{2}$ , net emissions would be -2% of the biomass stock, i.e. net sequestration would be 2%. In order for emissions to be positive, the harvesting rate must be some multiple of  $\omega$ ,  $x$ , that satisfies  $(1 - \beta)\omega Q(t) - \omega Q(t) > 0$ . That is,  $x$  must be greater than  $1/(1-\beta)$ . For our example where the pickling rate is  $\frac{1}{2}$ , this means that the harvesting rate must be on average more than twice the growth rate. This would be satisfied for example if the area harvested were more than twice the area replanted, i.e. under rapid deforestation, which is likely to be inefficient as well as unsustainable.

Positive entitlements amount to a lump sum transfer in the amount of the difference between historically-based and efficient entitlements times the shadow price of carbon. The only possible benefit of excessive entitlements would be to induce a country that would not otherwise join the "climate club" (Nordhaus, 2015) to participate in a global agreement. As argued below however, international assistance in forest governance may be a more cost effective inducement.

## **2.3 Are two instruments required to regulate the stock of trees and the flow of emissions?**

Some observers have suggested that there are two potential targets of REDD incentives – the flow of emissions and the stock of trees -- prompting calls for two instruments of control such as payments for emission reduction and dividends for stock maintenance (e.g. Cattaneo, 2009). But since carbon stock is determined from carbon flux, there is only one control variable: the amount of carbon emitted (Tavoni et al., 2007). Changes in forest area and carbon density alter the amount of forest stocks. The underlying control is the amount of forest harvesting. In an efficient system, the forester is faced with the same price of carbon regardless of whether emissions are positive or negative.

## **3. Efficient reforms for REDD+ (ERR)**

Basing entitlements on the efficient level of net emissions absent carbon pricing offers an initial step toward improved forest governance. Once the baseline is in place, first-best efficiency calls for rewarding reductions of emissions below that level. If the efficient level of emissions is negative, then compensation would only be paid for reducing emissions even further below that level. Moreover, countries (or individual foresters) would be penalized for emissions above the benchmark.

Previous studies have shown that current levels of deforestation have been higher than optimal (Barbier and Burgess, 1997; Barbier, 2001; Amacher et al., 2008) due to incomplete property rights including tenure insecurity and open access problems. Deforestation has continued in recent history, even when forestry prices rose relative to agricultural prices. Since stocks are below their optimal levels, efficient management implies increasing stocks for some time through afforestation

and restoration, even if optimal forest cover is declining as more land is devoted to agriculture and urban uses. Inasmuch as a fully integrated land-use model with theoretic foundations for both forestry and agriculture has yet to be developed, we focus here on clarifying the conceptual issues regarding baselines from which emission permits should be established. We outline the potential gains from forest governance. Rather than assuming that forest area will increase due to price incentives and good governance, however, we make the more conservative assumption that deforestation is stopped but not reversed and focus our attention on the efficient management of existing forestlands.

Figure 2 illustrates a hypothetical implementation of ERR. Our illustrative country, Indonesia, has been emitting an average of 219 million tons of carbon per year compared to an efficient level of negative 5 million tons per year. Reforms begin to take effect in 2020, but full implementation is achieved in 2030, after which the country is paid the global shadow price of carbon for reduction in emissions below that level and is penalized at the same rate for emissions above the efficient baseline. Carbon-pricing from 2030 forward, then allows payments for the emissions as represented by the shaded area. In this way, efficient management renders the developing country a supplier of permits on the world market even though it starts with a negative quantity of emission permits. Efficient emissions are negative and any increase in emissions is penalized to incorporate the externalities associated with carbon emissions.

This leaves the question of what to do during the transition period, 2020-2030. One possibility is to implement a sliding baseline, starting from 219 tons in 2020 and decreasing linearly over 10 years until reaching the target of 5 million tons of net

emissions in 2030. In our illustration, we assume that the country meets the transitional target and is neither rewarded nor penalized. A shorter transition period may also be desired, e.g., five or even zero years.

## **FIGURE 2 AROUND HERE**

Faustmann (1849) provided the solution to the forest rotation problem -- when to cut trees in order to maximize present value of stream of profits. This formula has become the basis of a rich literature in forestry economics. Benefits from either timber only (Hyde, 1980; Chang, 1983) or both timber and non-timber products (Hartman, 1976; van Kooten et al., 1995) can be considered. The standard solution applies to a homogeneous forest of uniform age (e.g., Anderson, 1976). As shown e.g. by Amacher et al. (2009), the optimal age to cut trees in a heterogeneously-aged forest is that same Faustmann age.

In what follows, we model the evolution of the optimal biomass stock with and without carbon pricing. A social planner/forester maximizes producer-consumer surplus from harvesting timber given an initial forest stock and exogenous world prices. Taking demand curves as given, the planner arrives at the same harvest age as a competitive forester. Forest biomass is modeled as a function of age distribution of trees across stands, such that the solution to the optimal cutting problem corresponds to the evolution of the optimal biomass stock. Its implication on the evolution of carbon stored in tree biomass and the corresponding carbon emissions is illustrated.

### **3.1 A dynamic baseline: efficiency without carbon pricing**

We begin with the standard Faustmann (1849) problem. At time zero there is no stock of standing forest (e.g. it has just been cut). Given an exogenous world price of timber and costs of harvesting including any costs of replanting, the price net of

cost is  $p > 0$  per unit volume.<sup>5</sup> With a discount rate of  $\delta$ , the problem of the Faustmann forester is to determine when to cut the uniformly aged forest, i.e., find the rotation age ( $T$ ) that maximizes the infinite sequence of discounted profits  $\pi_F$  (expressed in \$/Ha), where the discounted profits in the future harvesting period are equal to current profits.<sup>6</sup>

The present value of profits for the first rotation is given by  $[pQ(T)]e^{-\delta T}$ , where  $Q = Q(t)$  is the volume of standing merchantable wood per hectare. After harvesting, a new rotation starts for the second  $T$  years, and the process is repeated infinitely, where trees are harvested every  $T$  years. The net present value of this infinite sequence of identical rotations is given by:

$$(2) \quad [pQ(T)]e^{-\delta T} + \{[pQ(T)]e^{-\delta T}\}e^{-\delta T} + \{[pQ(T)]e^{-\delta T}\}e^{-2\delta T} + \dots$$

After factoring out the present value of first period profits, we are left with an infinite sequence that reduces to  $(1 - e^{-\delta T})^{-1}$  i.e., the present value becomes  $[pQ(T)]e^{-\delta T}/(1 - e^{-\delta T})$ .<sup>7</sup> Leaving aside the external costs of carbon emissions both the planner's and the private harvester's problem is now to solve for the harvest age,  $T$ , that maximizes:

$$(3) \quad \pi_F = [pQ(T)]e^{-\delta T}/(1 - e^{-\delta T}) .$$

The solution is obtained by setting  $d\pi_F/dT = 0$ , which gives the Faustmann equation:

$$(4) \quad pQ'(T_F) = \delta[pQ(T_F)] + \delta\pi_F,$$

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<sup>5</sup> For notational convenience,  $p = P - c$  is net price with  $P$  and  $c$  as gross price and cost expressed in per unit volume.

<sup>6</sup> In the numerical illustrations (sections 4 and 5), the Faustmann principle is extended to a mixed-age forest. In that case present value is maximized by harvesting in each period all trees of Faustmann age or greater.

<sup>7</sup> See e.g. Conrad (2010) and Amacher et. al. (2009).

where  $T_F$  is the optimal harvesting age. The left-hand side (LHS) is the marginal value of delaying the harvest by one period. The right-hand side (RHS) is the corresponding marginal cost of delaying harvest and consists of two terms: the interest forgone by delaying harvest by one period and the implicit rental payment for keeping the land in its current use for an additional year. Equation (4) determines the first-best efficient rotation age ( $T_F$ ) in the absence of carbon price and serves as the efficient harvesting schedule. The corresponding emission levels then become the baseline emission entitlements on which emission payments in ERR are based. This, in turn, determines the efficient evolution of carbon stock on which emission entitlements are based.

### **3.2 Internalizing the carbon externality**

Forests are generally considered to be mostly overharvested due to externalities conferred on other potential harvesters and stock externalities associated with ecosystem services, including carbon sequestration. They provide both tangible (e.g., timber, panels, paper, and fuel wood) and non-tangible benefits (e.g., watershed control, protection of farmlands and livestock, and even cultural preservation) to society. These benefits increase when policy reforms arrest the extent of overharvesting.

ERR involves pricing carbon to internalize sequestration services provided by forests. Amacher et al. (2009) provide a brief literature review, including van Kooten et al. (1995) and Plantinga and Birdsey (1994) who use Hartman's (1976) framework to include carbon sequestration. We follow the formulation in van Kooten et al. (1995), where the benefits from carbon sequestration are a function of the change in biomass and the amount of carbon per area.

Carbon pricing aligns the forester's incentives with the maximum social value function of the forester. The forester faces a penalty for harvesting and emitting

carbon above the benchmark and is rewarded at the same rate for emissions below that benchmark. In the following formalization, the forester pays the social cost of carbon times net emissions minus benchmark emissions. If actual emissions are less than the benchmark level, this tax is negative, i.e. is a subsidy for sequestration above the benchmark.

The model assumes that the amount of carbon in the forest is proportional to the biomass content of merchantable timber given its age. Trees sequester carbon as they grow, but growth eventually diminishes with age. Equation 3 is expanded to account for the shadow value of gross emissions when timber is harvested and the present value net benefits from carbon sequestration. The per-hectare maximization problem of the social planner can now be written as:

(5)

$$\max_T \pi_{ERR} = [p - v\alpha(1 - \beta)]Q(T)e^{-\delta T}/(1 - e^{-\delta T}) + \int_0^T v\alpha Q'(t)e^{-\delta t} dt /(1 - e^{-\delta T})$$

where  $v$  is the social cost of carbon (SCC, Nordhaus 2014).<sup>8</sup> The first term on the RHS of equation (5) is the value of timber adjusted for the shadow value of gross carbon emissions. The second term is the present value of the benefits obtained from net emissions over time. As shown by van Kooten et al. (1995), integration by parts can be applied to the numerator of the second term, allowing the maximization problem to be rewritten as:

(5')

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<sup>8</sup> The social cost of carbon in this case is regarded as constant for ease of exposition. A more accurate calculation would specify the SCC as an increasing function of time.

$$\begin{aligned}
\underset{T}{Max} \quad \pi_{ERR} = & [p - v\alpha(1 - \beta)]Q(T)e^{-\delta T}/(1 - e^{-\delta T}) \\
& + v\alpha \left[ Q(T)e^{-\delta T} + \delta \int_0^T Q(t)e^{-\delta t} dt \right] / (1 - e^{-\delta T})^9
\end{aligned}$$

Setting  $d\pi_{ERR}/dT = 0$ , the optimal rotation age (inclusive of the social cost of carbon emissions),  $T_{ERR}$ , satisfies the equation:

$$(6) \quad [(p + v\alpha\beta)Q'(T_{ERR}) + v\alpha Q(T_{ERR})] = \delta\pi_{ERR}$$

The LHS of equation (6) is the marginal benefit of delaying harvest, which is the summation of the value of harvested timber plus the value of net carbon sequestered.

The RHS is the opportunity cost of delaying harvest, which is the forgone rental payment including foregone sequestration benefits. This equation provides the condition for optimal harvesting decision, determined by the equality of the marginal benefits and the opportunity costs from delaying harvest.

This optimal solution can be implemented by taxing net emissions above the benchmark. This means that emission levels below the benchmark are subsidized.

There is no need for separate instruments or for a separate incentive for maintaining stock. There is only one control variable, the amount of harvest, and one instrument of control, a tax (subsidy) on net emissions above (below) the benchmark level. The optimal harvest corresponds to the harvest following optimal rotation age,  $T_{ERR}$ , when benefits from wood harvest and sequestration are considered.

#### 4. Numerical illustration: the Case of Indonesia

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<sup>9</sup> The units corresponding to equation (5') can be heuristically represented by:

$$\left[ \frac{\$}{m^3} - \left( \frac{\$}{tC} \right) \left( \frac{tC}{m^3} \right) (1 - \beta) \right] (m^3/ha) + (\$/tC)(tC/m^3)[m^3/ha + m^3/ha]$$

#### 4.1 Assumptions and parameters

We now turn to a numerical illustration of the principles developed in sections 2 and 3 based on parameters from the Indonesia case. We use an extended Faustmann (1849) model where we are given an initial distribution of trees (unrestricted by a requirement that all tree ages are less than or equal to the Faustmann optimum). We illustrate the dynamic baseline, the amount of transfers needed, and the potential gains from implementing ERR and harvesting according to an efficient schedule. As discussed in Section 3, the dynamic baseline is given by efficient harvesting before accounting for the social cost of carbon. For tractability and ease of exposition, the numerical exercise uses the discrete time analog of the model.<sup>10</sup>

A fixed area of forests is assumed corresponding to the conservative assumption that deforestation is simply stopped, rather than reversed. All forest lands are also assumed to be capable of regeneration.

We assume that the forest landscape is composed of a single representative species, mahogany (*Swietenia macrophylla*), with a given age distribution. Mahogany is a dominant tree in Southeast Asia. It grows relatively slow but is highly valued. The assumption of a representative tree species is coupled with a spatially independent tree growth.

In order to examine the role of the initial age distribution on emission entitlements, we consider the three age distributions representing a country's forest landscape as shown in Figure 3. The horizontal axis is the age of trees and the vertical axis is the percent of forest area covered by the corresponding age cohort. Panel (a)

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<sup>10</sup>Discrete time analysis often provides convenience for purposes of numerical analysis. Examples include Hellegers et al. (2001), Sun (1992), and Merton (1971).

and panel (c) represent the polar extremes of a completely degraded or deforested landscape and a mature forest landscape. Assume that harvest occurs only once a year and that the distribution is portrayed at harvest time. With regeneration, the completely degraded forest is now composed of trees all of age one. For simplicity the hypothetical mature forest is entirely composed of trees at Faustmann age. Between these two extremes, panel (b), is a case of a positively skewed age distribution, corresponding to a highly-degraded country-wide forest landscape (panel b) as commonly observed in Asia (Odoom, 2001).

### **FIGURE 3 AROUND HERE**

Standing trees are reckoned in units of merchantable volume.<sup>11</sup> This study employs the stand volume function estimated using samples of mahogany trees from the Philippines by Revilla et al. (1976) as cited in Galinato and Uchida (2011).

$$(7) \quad Q(t) = 10^{[1.7348 - (6.6721/T) + (0.53801 \times SI) - (0.78406 - SI/t)]}$$

In equation (7),  $Q(t)$  is the volume of standing timber in cubic meters on a representative hectare. The variable  $t$  is the age of tree in years, and SI is the site index, referring to the height of tree at a base age. The average SI height (in meters) at base age of 40 years is used.

The parameters used in the numerical exercise are summarized in Table 1.

Table 1: Parameter values

Description	Variable	Mahogany
Price of timber per m <sup>3</sup>	$P$	171.47
Cost of harvesting per m <sup>3</sup>	$c_1$	35.23
Fixed cost of harvesting \$ per ha	$c_2$	803.97

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<sup>11</sup> Merchantable volume is defined as the amount of wood that has commercial value.

Site Index	<i>SI</i>	25
Wood density in ton dry matter (tdm) per m <sup>3</sup>	<i>WD</i>	0.53
Biomass expansion factor if $Q \times WD > 190$	<i>BEF</i>	1.74
Biomass expansion factor if $Q \times WD < 190$	<i>BEF</i>	Exp[3.213 - 0.506 x Ln(Q x WD)]
Root ratio: below ground to above ground	<i>R</i>	0.37
Carbon factor in ton of carbon (tC) per tdm	<i>CF</i>	0.47
Discount rate	$\delta$	5%
Pickling rate <sup>12</sup>	$\beta$	0.30
Price of carbon per tC	$v$	\$37
Forest area '000 Ha (Indonesia)		97,857

Sources: Timber price and site index are from Galinato and Uchida (2011). Costs are from Kosonen *et al.* (1997). *WD* and *BEF* are from Brown (1997). *CF* is from (IPCC 2006a) based on McGroddy *et al.*(2004). *R* is from Table 4.4 of IPCC (2006a). *R* is the ratio attributed to tropical rainforest. Forest area is from (FAO 2010b). Carbon price is set at \$37 following (Busch et al., 2010).

While the volume functions for the representative species were estimated using samples from the Philippines, mahogany is a dominant tree species in Southeast Asia (Odooom, 2001) and thus, the volume specification could serve as a good approximation when applied to other REDD+ countries in the region, such as Indonesia. These parameters are used in the numerical application of the model.

In order to investigate the implication of efficient harvesting and the corresponding net carbon-depletion, we consider the net change in carbon stock on a representative hectare. Merchantable volume, as measured in sawlog volume, is first augmented by non-merchantable biomass above and belowground. Aboveground biomass includes tree canopies, branches, twigs, and foliage. Belowground biomass consists of live roots. Further research is needed to determine the ratio between the

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<sup>12</sup> Pickling rate refers to the amount of carbon retained in harvested wood products (HWP). See van Kooten et al. (1995) and IPCC (1997, 2006b).

soil and biomass carbons under different circumstances. To date, estimates of soil carbon only introduces a tremendous amount of uncertainty in the estimates of forest stocks (Bottcher et al., 2009). For our illustration, we abstract from soil carbon and dead organic matter.

The total carbon stock in the forest is now obtained by converting the volume per hectare of live biomass of mahogany into its equivalent tonnage of carbon:

$$(8) \quad C_t = \alpha Q(t) \quad \text{where } \alpha = WD \times BEF \times (1 + R) \times CF$$

The determination of  $\alpha$  given by the discrete transformation factor of IPCC (2006a) and Brown (1997). The parameter  $\alpha$  converts green volume per hectare,  $m^3/ha$ , to carbon in  $tC/ha$ . The conversion factor  $\alpha$  is the product of wood density ( $WD$ ), biomass expansion factor ( $BEF$ ), root ratio factor ( $1 + R$ ), and carbon factor ( $CF$ ). The equivalent biomass in  $tdm/Ha$  units of green volume is obtained using  $WD$  (1 unit of oven-dry biomass per  $m^3$  green volume) and  $BEF$ .<sup>13</sup> The unit-less BEFs expand the dry weight of the biomass volume to account for the non-merchantable component of a tree. These BEFs vary with the volume of dry mass.<sup>14</sup> As a tree gets older, its capacity to sequester carbon decreases (Brown, 1997). To get the total biomass, the below-ground component is added by multiplying ( $1+R$ ). The tonnage of carbon per ha is then obtained using IPCC's default  $CF$  (in  $tC/tdm$ ). The pickling rate,  $\beta$ , is conventionally defined by the carbon sequestered in wood products. We abstract from an explicit specification of emission timing due to natural decay. Instead  $\beta$  is regarded

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<sup>13</sup> IPCC (2006a) discusses other methods including species-specific allometric equations and biomass regression functions.

<sup>14</sup> In the numerical exercise,  $\alpha$  varies with the volume of timber.

as approximating a lagged distribution of emissions, whereby distant decay is disregarded and near term decay is taken as instantaneous.<sup>15</sup>

#### 4.2 The dynamic baseline

The conventional Faustmann solution for the optimal harvest time is based on the assumption that the forest cycle begins with replanting a completely deforested plot of land. In the present case, however, we begin with a specific age distribution. Under the conditions set forth above, and assuming that the country is a price-taker in the world timber market, it can be shown that the rule for optimal harvesting of a mixed-age forest is to harvest each tree when it reaches the Faustmann age computed in the standard manner (Conrad, 1999; Amacher et al., 2009). Following Nordhaus (2008), we set  $\delta$  equal to 0.05. The solution to the forester's problem in equation (2) gives a Faustmann optimal cutting age of  $T_F = 31$  years for mahogany.

Figure 4 illustrates the effect of optimal harvesting on the evolution of the age distribution of mahogany trees for the case of the highly-degraded forest landscape from panel b of Figure 3. The vertical axis gives the percent of forest area covered by each age-cohort of trees. At *harvest year* = 0, trees of age 31 and older (0.94 per cent of total forest area) are cut resulting in the new age distribution shown in panel (a). Trees of age 1 to 30 remain standing and occupy the same area as in the initial distribution shown in Figure 3, panel (b). There is an immediate replanting after every harvest such that the new cohort emerges (age zero), covering the same area as the recently cut trees. Harvest occurs every year as each cohort of trees reaches its Faustmann age. Panel (b) shows the distribution at *harvest year* = 10. Trees that were

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<sup>15</sup> See discussions in Akao (2011).

initially one year old at *harvest year 0* are now 11 years old, such that 14 percent of the forest area is covered with 11-year-old trees. Panel (c) shows this cohort of trees to be 21 years old at *harvest year = 20*. At harvest year = 31 in panel (d), the distribution is back to the same distribution at the commencement of the efficient cutting rule. As in harvest year = 0, panel (d) shows that 14 percent of the forest area is covered with 1 year-old trees. Instead of converging to uniformity, the optimal cutting rule results in the initial age distribution reappearing every 31 years, whereupon an identical cycle begins again.

#### **FIGURE 4 AROUND HERE**

As discussed in section 3.1, using efficient emissions absent carbon pricing as the baseline means that aside from monitoring cost, the baseline entitlements would change every year as illustrated in Figure 5. When Faustmann-efficient emissions are positive (during times of heavy harvesting) the forester's emission entitlement would be positive. Otherwise, entitlements would be negative, and the forester would have to pay for (even negative) emissions above that level. Figure 5 illustrates that there is more sequestration than positive emissions over the cycle, regardless of the initial age-distribution. Depleted forests go through a period of regrowth, during which sequestration dominates, followed by a period of harvest, wherein net emissions are positive. The cycle is reversed for mature forests, but sequestration is again greater than gross emissions. Panel (a) shows net emissions corresponding to a completely degraded or deforested landscape. During the phase of sequestering, the country is building its stock of biomass and carbon. The greatest amount of harvesting takes place in 2045, after which the cycle repeats itself.

The highly degraded case of panel (b) is similar to the completely degraded case in that less than one per cent of trees are initially harvested. Accordingly net emissions are negative (positive sequestration). In panel (b), net sequestration troughs at year 2025. It then climbs, becoming positive in year 2036, with slightly more than 3.5 percent of forest area being harvested. In year 2045, the country harvests 14 percent of the forest area and net emissions peak at 13 tC/Ha. This cycle repeats itself every 31 years.

For the mature forest, the Faustmann rule requires immediate harvesting such that net forest emissions are positive during the first period. After the harvest, replanting takes place and the trees are left to grow until again reaching Faustmann age. The country sequesters forest carbon and builds its stock of biomass after the initial positive emissions. As before, the cycle repeats itself every 31 years.

#### **FIGURE 5 AROUND HERE**

Regardless of the initial age-distribution, average emission entitlements per cycle ( $S_F$ ) are negative. This means that sequestration is required, on average, to avoid paying a penalty. If sequestration is done at the higher efficient level implied by carbon prices, the country receives a bounty.<sup>16</sup> Under this scheme, countries would not be rewarded for reducing emissions below a historical baseline but rather for reducing emissions below their (negative) entitlement level.

#### **5. Comparing ERR and conventional REDD+ proposals**

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<sup>16</sup> To avoid the complication of having different entitlements for every period, the country can be given negative emission entitlements equivalent to the average of, say, two cycles (64 years). The country would then be allowed to bank and borrow permits to cover the deviations from the average.

Busch et al.(2010) estimated the effect of conventional REDD+ for Indonesia.<sup>17</sup>

Table 2 presents the reference levels for net emissions based on FAO estimates in 2010a. This reference year serves as the business-as-usual (BAU) scenario where net emission rates continue at 1.5 per cent of carbon stocks, with 0.7 per cent coming from deforestation (FAO, 2010a) and 0.8 per cent coming from forest degradation.<sup>18</sup>

Table 2 also presents the expected emissions under conventional REDD+ for Indonesia, relative to the BAU scenario. Busch et al. estimate that a conventional REDD+ policy with a carbon price of \$37/tC will reduce net carbon emissions from 1.5 to 1.1 per cent of the carbon stock.

Statistical data and the available conventional REDD+ studies use aggregate data to estimate the changes in stock due to degradation and deforestation. To facilitate comparison of conventional REDD+ and *ERR*, the projected total change in carbon stock resulting from BAU and conventional REDD+ is applied to the countrywide forest landscape presented in Figure 3. Specifically, the hypothetical degraded countrywide forest landscape given in panel (b) of Figure 3 is taken to simulate the percentage change in annual net emissions corresponding to BAU and conventional REDD+. The default assumption in conventional REDD+ proposals is that all carbon is oxidized upon harvest.

Table 2: Expected carbon emissions under conventional REDD+.

BAU (Indonesia)	Conventional REDD+ at \$37/tC
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17 The study used a spreadsheet and mapping tool called OSIRI-Indonesia developed by Conservation International, the Environmental Defense Fund, and World Resources Institute, in collaboration with Indonesia DNPI and Ministry of Forestry. The

18 Denote carbon intensity or carbon per hectare by  $d$ , hectares of land by  $H$ , and the stock of carbon by  $S$ , such that  $d \times H = S$ . Decomposing the change in stock gives us  $\Delta S/S = \Delta d/d + \Delta H/H$ . The negative of the LHS is the net emissions rate while the negative of the RHS is the sum of degradation and deforestation rates.

Carbon stock (Mn tC/yr)	Net emissions in Mn tC/yr (rate/yr)	Net emissions in Mn tC/yr (rate/yr)
14,299	219	158
	(1.5%)	(1.1%)

Source: Busch *et al.*(2010). The reported units of tCO<sub>2</sub>e/yr were converted using 1tC = 3.667 tCO<sub>2</sub>e . The carbon price in Busch *et al.*(2010) is \$10/tCO<sub>2</sub>e, which is converted to \$37/tC. Source of carbon stock is (FAO, 2010a).

In our conventional REDD+ simulation, we also assumed that the forester follows the cutting rule of first-in-first-out (*oldest tree cut first*), such that carbon emissions rate are maintained at 1.5 per cent annually under BAU. Adherence to this cutting rule overstates the benefits of conventional REDD+ by assuming efficiency in selecting which trees to harvest. In that sense, our calculation of the present value of REDD+ can be taken as an estimate of the maximum present value.

**Result 1** *There is an enormous potential for countries to increase forest biomass, even without carbon subsidies.*

Crediting period of ERR starts in 2030. In order to estimate the potential gains from using an efficiency baseline instead of a historical baseline, we abstract from any transitional issues identified in section 2. To facilitate the comparison of the evolution of the different strategies, Figure 6 shows two cycles of ERR beginning in 2030 and extending to 2092. The evolution of the socially efficient ERR carbon stock is calculated for the case of an initially highly-degraded forest landscape. By comparison, the average carbon stock under BAU is 12.86 tC/ha. The conventional REDD+ regime increases the carbon stock to 14.33 tC/ha or by 11 percent above the BAU level for a carbon price of \$37/tC. Carbon stock under BAU and conventional REDD+ decrease over time, but the rate of decline under conventional REDD+ is slightly slower than BAU. After year 2065, carbon stock and emissions stabilize.

## **FIGURE 6 AROUND HERE**

In contrast, Faustmann management significantly increases carbon stock to 55.27 tC/ha, which is 328 per cent above BAU. Following efficient forestry practices, even aside from the social cost of carbon, the country would initially build its stock of biomass and carbon, reaching peak levels in 2051, and then deplete those stocks until year 2061. During the initial period, the country is building its stock of carbon, i.e. harvesting a relatively small area of mature trees, given the initial distribution. At year 2051, trees covering 4 to 14 per cent of the total area are nearing Faustmann age. After this point, the country starts harvesting a larger area of economically mature trees, such that the stock of carbon in the forest declines. The country builds its current carbon stock in the short term (while demand for forest products is still growing) to compensate for the fact that past inefficient policies have resulted in excess deforestation/degradation. This cycle repeats itself every 31 years, which characterizes the long-run equilibrium of the carbon stock.

Rotation age under ERR is higher at 31 years and carbon stock increases more than that under Faustmann management. If the carbon price is set at \$37/tC carbon stock increases by 356 per cent above BAU level. Rotation age under ERR is only a little bit higher than the Faustmann age and carbon stock increases correspondingly by only 6 per cent above the Faustmann efficient baseline.

From Figure 6, we can deduce the corresponding net emissions under the different regimes. Under conventional REDD+, the reductions in emissions, albeit still positive, constitute payments to the country valued at the respective carbon prices. In contrast, there is a long series of sequestration under the Faustmann and ERR regime followed by carbon emissions toward the end of the forest cycle. With

carbon pricing, sequestration increases and the country still receives carbon payments even though entitlements are negative under ERR.

## **6. Backstopping efficient national forestry policies for better governance**

### **Result 2 *Potential gains from ERR are greater than conventional REDD+***

Once countries are committed to abide by a forest-carbon trading regime, the initial endowment of carbon permits does not affect incentives regarding deforestation and degradation. In this case, granting entitlements on the basis of historical carbon emissions is unnecessary. It is an expensive proposition, given that induced sequestration is likely to be relatively small, even according to conventional REDD+ proponents (section 5 above). Table 3 shows the present value net benefits of alternative strategies for Indonesia and the world. The per-hectare present values of net benefits per hectare were obtained by summing the annual discounted net proceeds from today to infinity. Taking the initial age distribution of the highly-degraded forest landscape, harvesting starts immediately at time zero.<sup>19</sup> In the BAU scenario, proceeds from the sale of timber yield a present value of \$4,601 per hectare. When applied to all of Indonesia's forests, the total present value under BAU is \$450 billion.

Table 3: Present values of alternative strategies: Indonesia and the rest of the world

		BAU	Conventional REDD+	Faustmann	ERR
<i>Indonesia</i>					
(a)	Average entitlements (tC/ha)		0.17		-0.78
(b)	Average emissions (tC/ha)		0.13		-0.74

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<sup>19</sup> This is in contrast to calculation of present values starting at time zero with bare land as in the Faustmann formula.

(c)	Per hectare land value (\$/ha)	4,601	5,038	9,908	10,039
(d)	Total land value (\$Bn)	450	493	970	982
<i>Rest of the world (ROW)</i>					
(e)	Cost of entitlements (\$Bn)		160		0
(f)	Payments for reducing carbon (\$Bn)		4		2
(g)	Benefits for reduced carbon (\$Bn)		4		172
(h)	ROW net gain/loss (\$Bn): g - f - e		-160		169
World (d) + (h)			333		1,152

Note: Calculation for conventional REDD+ and ERR are made under price policy of \$37/tC (Busch et al., 2010). Total value is computed for Indonesia's forest with an area 97.857 Mn ha in 2005 (FAO, 2010a). Net emissions entitlements are computed based on Figure 6.

Rows (a) and (b) of Table 3 show average annual emission entitlements and average annual emissions under the various policy scenarios. Emission entitlements under conventional REDD+ are the emissions that would prevail under BAU scenario (i.e., historical baselines). The present values under conventional REDD+ and ERR include the net proceeds from carbon emission reduction as well as the net revenues from timber sales. Net proceeds from carbon are the payments received by Indonesia for any reduction in carbon emissions beyond their entitlements. If the country adopts conventional REDD+ under the carbon price policy of \$37/tC, the corresponding total present value net benefit with carbon is \$493 billion. This is 10 per cent higher than that under BAU. In contrast, if the country adopts ERR under a carbon price policy of \$37/tC, the total present value net benefit with carbon is \$982 billion or 118 per cent above BAU. Moreover, the potential gains from ERR even after imposing a penalty for any carbon emissions is significantly larger than conventional REDD+. In

summary, Indonesia stands to gain up to about half a trillion dollars in present value by adopting ERR instead of the more conventional approach to REDD+.

A tenable agreement must be acceptable to the rest of the world (ROW) as well as developing countries. Rows (e) through (h) provide the ROW benefits and costs in present value terms under the alternative policy scenarios. Relative to the efficiency benchmark, positive entitlements are equivalent to a lump sum transfer to the receiving country from the rest of the world. Valued at a carbon price of \$37/tC, the cost of excess entitlements under conventional REDD+ is \$160 billion as given in row (e) of Table 3. It is zero for ERR since entitlements are at the level of efficient Faustmann emissions. The other part of the gain/loss from the rest of the world perspective is the benefits and costs of reducing carbon given in rows (f) and (g).

Under conventional REDD+, the cost paid by ROW to Indonesia is equal to the reduction measured against the BAU scenario and valued at the carbon price. Reduction in carbon benefits of ROW is valued at the same carbon price. Thus, ROW accrues equal value of benefits and costs at \$4 billion with a carbon price of \$37/tC. On the other hand, under ERR, carbon payments are based on the reduction in carbon measured beyond Indonesia's negative entitlements (i.e., the country sequesters carbon). ROW's payment to Indonesia would be \$2 billion if the carbon price is \$37/tC. The benefit from carbon reduction is measured against the BAU obtaining a value of \$172. In summary, the rest of the world could lose up to \$160 billion under conventional REDD+ but could gain up to \$169 billion under ERR. Moreover, the world could potentially gain up to \$1.1 trillion, 245 per cent higher than under conventional REDD+.

In a sense, these results exaggerate the benefits of conventional REDD+ because it provides no penalty for countries that increase emissions. Due to the resulting moral hazard, countries may initially cooperate with REDD+ programs to garner the generous payments during the final program period only to increase emissions in the following period. On the other hand, the figures for ERR are based on the first-best optimal forest management, which represent the maximum potential gains available to the country. In practice, however, the best that countries can achieve are second-best profits – that is, profits net of governance costs. The potential first best profits for the world presented in Table 3 leaves out two important costs: the governance costs and the shortfall between first best potential profits and feasible profits. Second best profits are thus obtained by netting out this shortfall plus explicit governance costs. Maximizing the second best profits is equivalent to minimizing the sum of the shortfall and the explicit governance costs. We do not attempt to estimate feasible profits nor the size and form of governance expenditures here. Rather the estimates of the maximum potential gains serve only as a metric for comparing strategies. The conventional REDD+ proposals should be subject to similar adjustments.

## 7. Conclusions

Conventional REDD+ proposals appear to be based on an inappropriate analogy. It is thought that forest emissions should be treated analogously with industrial emissions and that countries and/or foresters should be subsidized for lowering emissions below some historically-determined, positive quantity. We

suggest an alternative, basing taxes or subsidies on what efficient forest emissions would be in the absence of carbon prices. For land that remain in forestry and are harvested efficiently, average gross emissions will be a fraction of gross sequestration, the fraction given by one minus the pickling rate, reflecting the preservation of wood products. For modest pickling rates, such as the 30% figure used here, this means that positive emissions would only be obtained if fairly rapid deforestation were efficient. But to the extent that forests have been overharvested, reforestation would be indicated.

To further illustrate this result, we conducted simulations for a mixed-age forest, given the conservative assumption that moving to efficiency would halt deforestation but not reverse it. This allows us to focus on the effects of efficient harvesting practices on the intensive margin. The simulations confirm the result that efficient forestry practices without carbon prices are congruent with negative emission permits, i.e. a sequestration requirement. By contrasting the polar extremes of a mature forest with one that is completely degraded, we see that this result is not dependent on the initial distribution.

Instead of granting positive emission entitlements as inducements to reduce forest emissions, developing countries whose emissions remain positive would have to buy permits to cover both the actual emissions and the shortfall from the efficient baseline level of sequestration. The savings from lower grants of emission permits could be used, all or in part, on improving governance for more efficient forestry practices. This leaves the question of whether the developing countries' costs of participation (accepting the sequestration requirement) would be outweighed by their

gains from improved forest management obtained by both financial and technical assistance in improved forestry governance.

The numerical exercise for Indonesia, which compares ERR with conventional REDD+, reveals that the developing country's potential gains from ERR (\$982 Bn) are nearly twice those of conventional REDD+ (\$493 Bn). And while the costs of conventional REDD+ strategies are greater than benefits, ERR yields positive net benefits. Moreover, potential gains to the world under ERR are three times larger than under conventional REDD+. These results suggest that world cooperation on forest emissions is potentially feasible under ERR. The savings generated could be channeled to investments in policy reforms and governance institutions such as satellite based monitoring and corresponding enforcement.

The results presented here can be modified for different parameter values. A higher pickling coefficient,  $\beta$ , e.g. 0.7 results in a shorter optimal rotation period. For example, the optimal rotation period in Japan is shorter than in other countries growing similar species due to Japan's propensity for less waste (Akao 2011). As discussed in section 2 however, this simply increases the ratio of gross emissions to gross sequestration for a given area of forestland. It would only be efficient for net emissions to be positive at the country level if the efficient rate of deforestation were high enough to more than offset the efficient rate of sequestration on the areas remaining in forestry. Using a different carbon price, e.g. the "high" figure of \$74/tC in Busch et al. 2010, yields similar figures for the carbon emission estimates in Sections 4 and 5, however the costs of conventional REDD+ almost double.

There are political and institutional reasons for poor performance in the forestry sector, and the conditional payments envisioned in conventional proposals

may be insufficient. Incentivizing efficient management without excessive transfers can afford the financial, technical, and administrative assistance to facilitate policy and governance reforms whose in-country benefits serve as substitutes for the conventional lump-sum inducements to join the international coalition of mitigating countries. These principles should be advanced as a possible alternative to the prominent REDD+ proposals currently circulating.

One possible extension of the model is to link it with models of the agriculture sector such that land-use decisions are endogenous (see e.g. Rosegrant et al., 2002; Angelsen, 1999; Pagiola, 2011; Chakravorty et al., 2011 for possible approaches). Another important extension would be to model resource governance explicitly by specifying response functions according to levels and types of governance. This would allow a more comprehensive assessment of the benefits and costs of ERR.<sup>20</sup> How close equilibrium deforestation and degradation is to the first-best optimum depends on monitoring, bonding, and other governance mechanisms and to the responsiveness of foresters and agriculturalists to those mechanisms.

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<sup>20</sup> Copeland and Taylor (2009) provide some insights into this line of research, but restrict their attention to the steady state properties of a theoretical model.

## References

- Akao, K.-I. (2011). Optimum forest program when the carbon sequestration service of a forest has value. *Environmental Economics and Policy Studies*, 13, pp. 323-343.
- Amacher, G.S., M. Ollikainen, and E. Koskela (2008). Deforestation and Land Use Under Insecure Property Rights. *Environment and Development Economics*, 14, pp.281-303
- Amacher, G.S., M. Ollikainen, and E. Koskela (2009). *Economics of Forest Resources*. United States of America.
- Anderson, F.J. (1976). Control Theory and the Optimum Timber Rotation. *Forest Science*, 22, pp. 242-246.
- Angelsen, A. (1999). Agricultural expansion and deforestation: modelling the impact of population, market forces and property rights. *Journal of Development Economics*, 58, pp. 185-218.
- Barbier, E.B. (2001). The Economics of Tropical Deforestation and Land Use: An Introduction to the Special Issue. *Land Economics*, 77, pp. 155-171.
- Barbier, E.B. and J.C. Burgess (1997). The Economics of Tropical Forest Land Use Options. *Land Economics*, 73, pp.174-195.
- Bottcher, H., K. Eisbrenner, S. Fritz, G. Kindermann, F. Kraxner, I. McCallum, and M. Obersteiner (2009). An assessment of monitoring requirements and costs of 'Reduced Emissions from Deforestation and Degradation'. *Carbon Balance and Management*, 4, p. 7.
- Brown, S. (1997). *Estimating Biomass and Biomass Change of Tropical Forests: a Primer*. Rome, Italy
- Busch, J., F. Godoy, W. Turner, and C. Harvey (2010). Biodiversity co-benefits of reducing emissions from deforestation under alternative reference levels and levels of finance. *Conservation Letters*, 4, pp.101-115.
- Busch, J., M. Farid, F. Boltz, F. Helmy, D. Sukadri, and R. Lubowski (2010). Economic Incentive Policies for REDD+ in Indonesia: Findings from the OSIRIS Model. *Policy Memo 02*.
- Cattaneo, A. (2009). A Revised Stock-Flow Mechanism to Distribute REDD Incentive Payments Across Countries. Submission to the United Nations

- Framework Convention on Climate Change regarding AWG-LCA FCCC/AWGLCA/2008/L.7, Woods Hole Research Center.
- Chakravorty, U., M.-H. Hubert, M. Moreaux, and L. Nøstbakken (2011). Will Biofuel Mandates Raise Food Prices? Department of Economics, University of Alberta, Working Paper No. 2011-01. Accessed on July 2014: [http://www.researchgate.net/publication/228759931\\_Will\\_Biofuel\\_Mandates\\_Raise\\_Food\\_Prices](http://www.researchgate.net/publication/228759931_Will_Biofuel_Mandates_Raise_Food_Prices)
- Chang, S.J. (1983). Rotation Age, Management Intensity, and the Economic Factors of Timber Production: Do Changes in Stumpage Price, Interest Rate, Regeneration Cost, and Forest Taxation Matter? *Forest Science*, 29, pp. 267-277.
- Conrad, J. (2010). Resource economics. New York.
- Contreras-Hermosilla, A. (2002). Law Compliance in the Forestry Sector, An Overview. World Bank Institute Working Paper, Stock No. 37205. Accessed on July 2014: <http://siteresources.worldbank.org/WBI/Resources/wbi37205.pdf>
- Copeland, M.S. and B. Taylor. (2009). Trade, Tragedy, and the Commons. *American Economic Review*, 99, pp. 725-49.
- FAO (2010a). Global Forest Resource Assessment 2010. Rome, Italy.
- FAO (2010b). Key Findings Global Forest Resources Assessment. Accessed on July 2014: <http://foris.fao.org/static/data/fra2010/KeyFindings-en.pdf> -- no place of publication specified in the document, so I put the url instead
- Galinato, G.I. and S. Uchida (2011). The Effect of Temporary Certified Emission Reductions on Forest Rotations and Carbon Supply. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroéconomie*, 59, pp.145-164.
- Hartman, R. (1976). The Harvesting Decision when a Standing Forest has a Value. *Economic Inquiry*, 14, pp. 52-58.
- Hartwick, J., N. Van Long, and H. Tian (2001). Deforestation and Development in a Small Open Economy. *Journal of Environmental Economics and Management*, 41, pp. 235-251.
- Hellegers, P., D. Zilberman, and E. van Ierland (2001). Dynamics of agricultural groundwater extraction. *Ecological Economics*, 37, pp.303-311.
- Hyde, W. (1980). Timber supply, land allocation, and economic efficiency. Baltimore.

- IPCC (1997). Revised 1996 IPCC Guidelines for National Greenhouse Inventories. Paris, France: IPCC/OECD/IEA.
- IPCC (2000). IPCC Special Report: Land use, Land-use Change, and Forestry.
- IPCC (2006a). Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme. Japan.
- IPCC (2006b). Harvested Wood Products. IPCC Guidelines for National Greenhouse Gas Inventories. Japan.
- McGroddy, M., T. Daufresne, and L. Hedin (2004). Scaling Of Stoichiometry In Forests Worldwide: Implications Of Terrestrial Redfield-Type Ratios. *Ecology*, 85, pp. 2390-2401.
- Merton, R.C. (1971). Optimum consumption and portfolio rules in a continuous-time model. *Journal of Economic Theory*, 3, pp. 373-413.
- Mollicone, D., F. Achard, S. Federici, H. Eva, G. Grassi, A. Belward, F. Raes, G. Seufert, H.-J Stibig., G. Matteucci, and E.-D Schulze. (2007). An incentive mechanism for reducing emissions from conversion of intact and non-intact forests. *Climatic Change*, 83, pp. 477-493.
- Nordhaus, W. (2008). A Question of Balance Weighing the Options on Global Warming Policies, United States of America
- Nordhaus, W. (2014). Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches. *Journal of the Association of Environmental and Resource Economists*, 1, pp. 273-312
- Nordhaus, W. (2015). Climate Clubs: Overcoming Free-Riding in International Climate Policy. *American Economic Review*, 105, pp. 1339-70.
- Odooom, F.K. (2001). Promotion of Valuable Hardwood Plantations in the Tropics: A global overview. In Mead D.J. (ed), *Forest Plantations Thematic Papers*. Rome, Italy
- Obidzinskia , K. and K. Kustersb (2015). Formalizing the Logging Sector in Indonesia: Historical Dynamics and Lessons for Current Policy Initiatives. *Society & Natural Resources: An International Journal*, 28, pp. 530-542.
- Pagiola, S. (2011). Using PES to implement REDD. World Bank, Washington, DC  
<https://openknowledge.worldbank.org/handle/10986/17892>. Accessed on July 2014:

- Parker, C., A. Mitchell, M. Trivedi, and N. Mardas (2009). Little REDD Book. United Kingdom.
- Plantinga, A.J. and R.A. Birdsey (1994). Optimal forest stand management when benefits are derived from carbon. *Natural Resource Modeling*, 8, pp. 373–387.
- Revilla, A.V., Jr., M. Bonita, and L. Dimapilis (1976). Tree volume functions for *Swietenia macrophylla* King. *The Pterocarpus: A Philippine Science Journal of Forestry*, 2, pp. 1-7.
- Rosegrant, M., X. Cai, and S. Cline (2002). *World Water and Food to 2025: Dealing with Scarcity*. Washington D.C.
- Sun, T.-S. (1992). Real and Nominal Interest Rates: A Discrete-Time moel and its Continuous-Time Limit. *Review of Financial Studies*, 5, pp. 581-612.
- Tavoni, M., B. Sohngen, and V. Bosetti (2007). Forestry and the carbon market response to stabilize climate. *Energy Policy*, 35, pp. 5346-5353.
- van Kooten, G.C., C.S. Binkley, and G. Delcourt (1995). Effect of Carbon Taxes and Subsidies on Optimal Forest Rotation Age and Supply of Carbon Services. *American Journal of Agricultural Economics*, 77, pp. 365-374.

Figure 1. Conventional REDD+ proposal using historical baselines

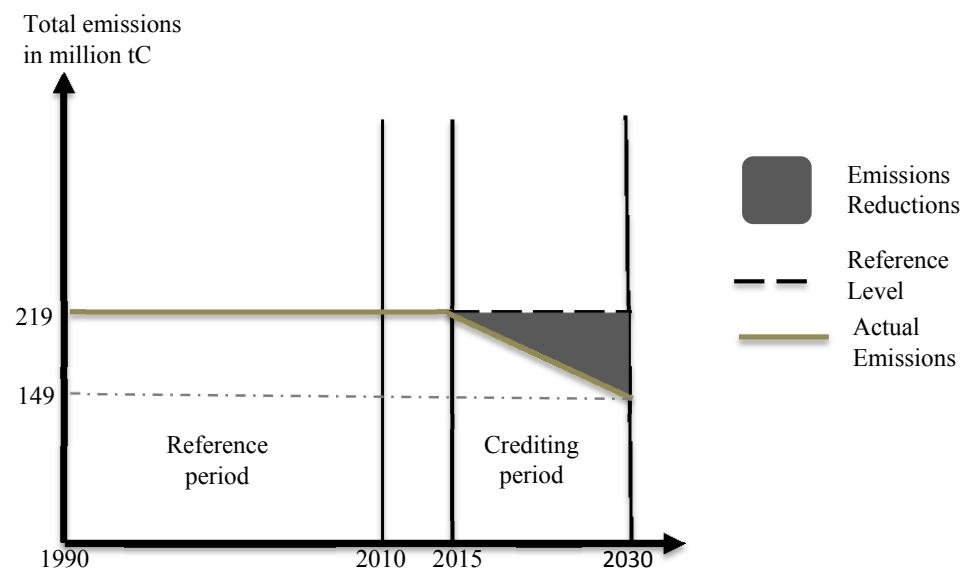


Figure 2. Efficient REDD+ reforms require negative emission permits

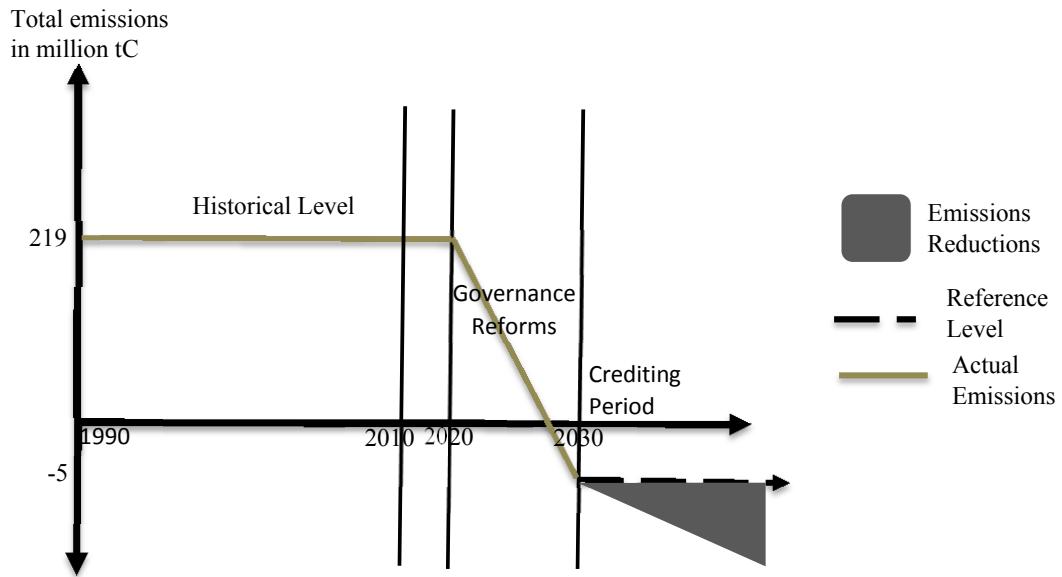


Figure 3. Three country-wide initial age-distributions

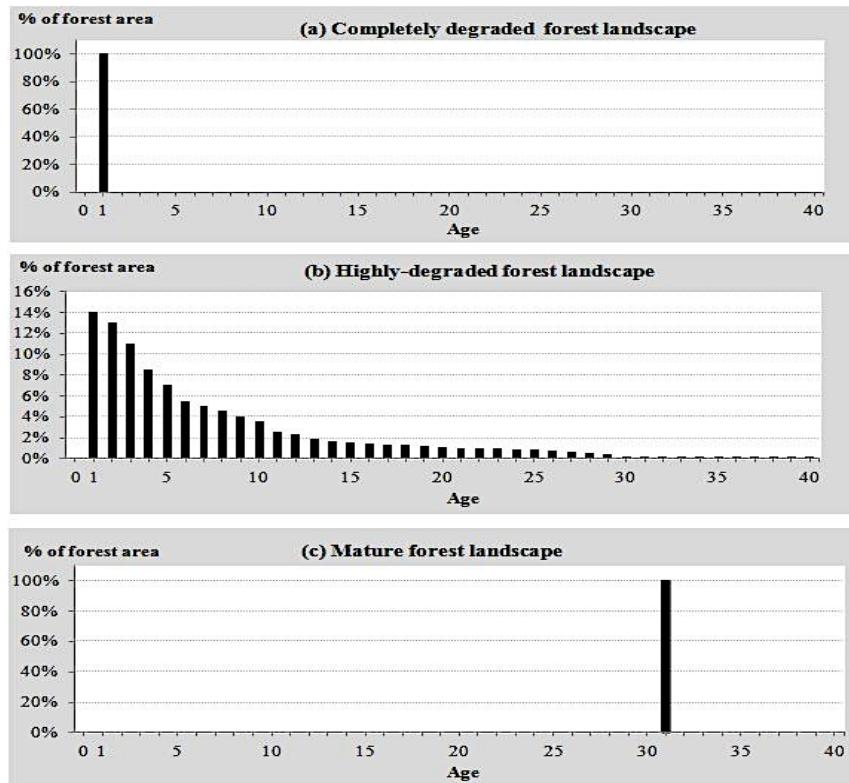


Figure 4. Forest cycles: evolution of age distributions for Faustmann = 31

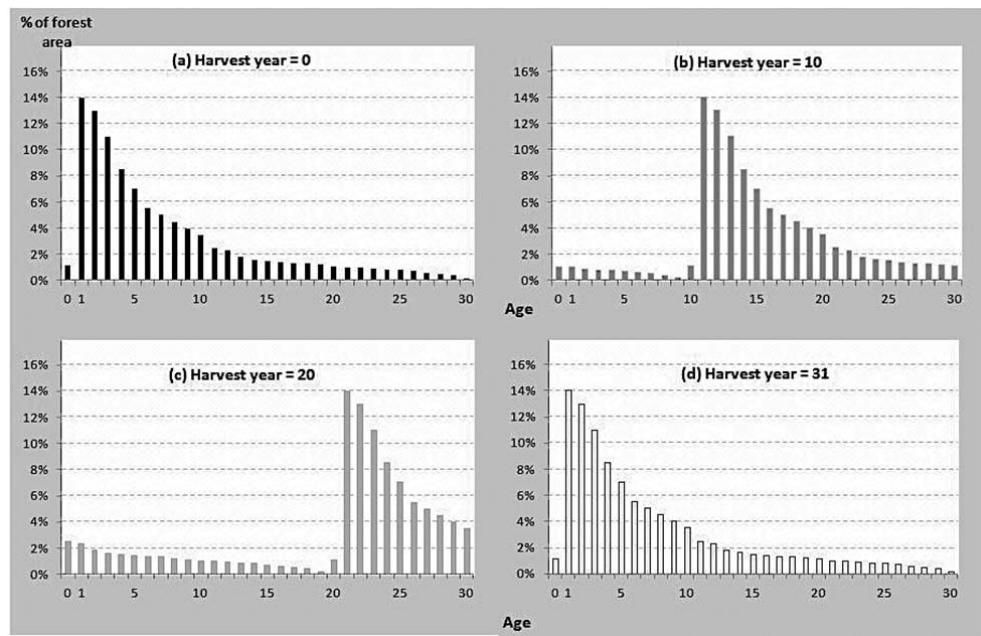
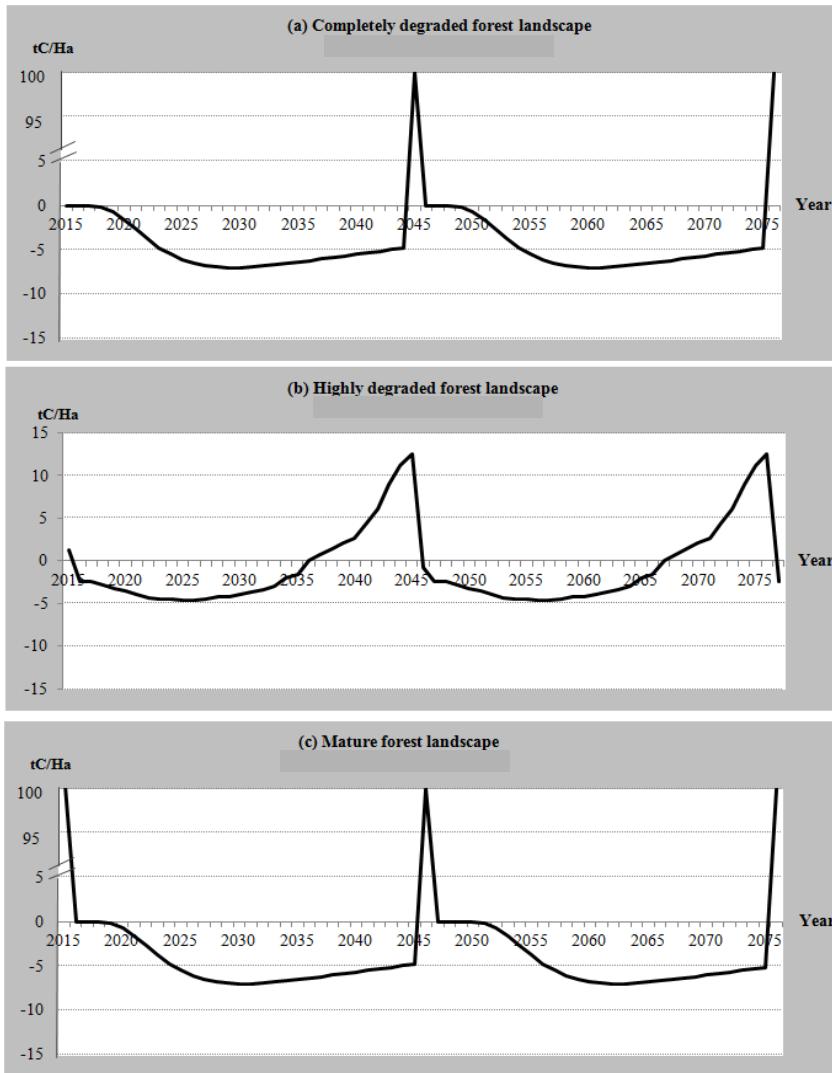
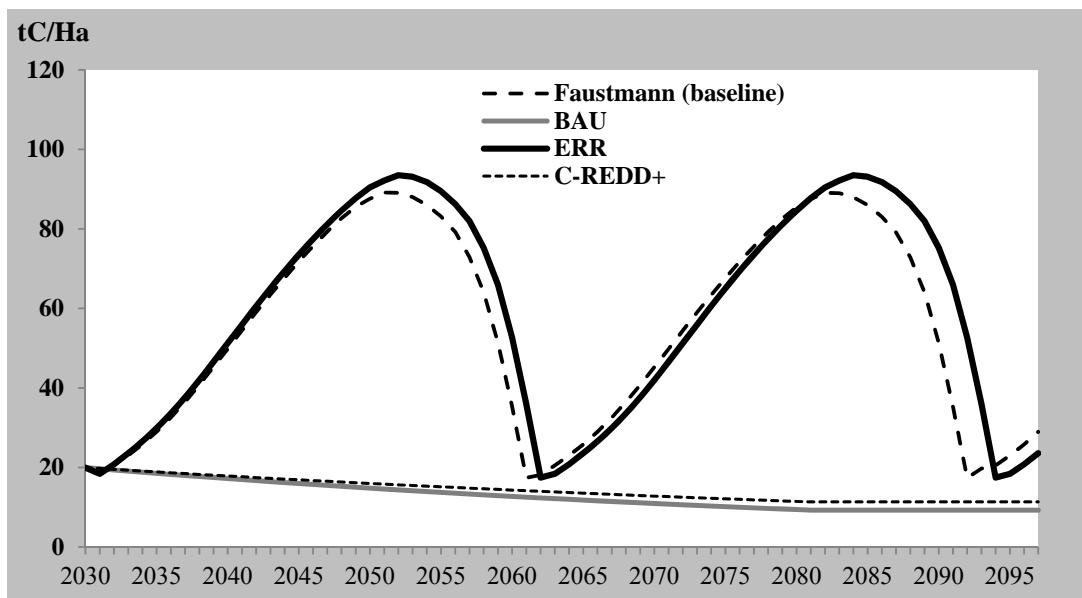


Figure 5. Emissions of forest landscapes at various levels of degradations: Efficient forestry practices are congruent with negative emissions permits.



Note: Authors' calculation converting green volume of mahogany in  $m^3$  to tC. Net emissions take into account a pickling rate  $\beta = 0.30$ .

Figure 6. Stock of carbon (below and above ground)



Averages in tC/Ha

BAU	Conventional REDD+	Faustmann (baseline)	ERR
12.86	14.33	55.07	58.62

Note: Authors' calculation converting green volume ( $m^3$ ) of mahogany to tC. Averages of carbon stock are for 64 years.