**On the economics of tropical deforestation: carbon credit markets and national policies**

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**Abstract**

This paper contributes to the economics of deforestation by presenting a formal, infinite horizon dynamic model describing the use of tropical forest resources. As an alternative to clearing the forest, a landowner has the option to sell it to an international carbon crediting program. The model is used to investigate corrective incentive programs needed to ensure a socially optimal level of forest resources. Optimal conditions for a land income tax and carbon compensation rate are derived. The model highlights the fact that carbon compensations would raise the value of standing tropical forests. This paper also demonstrated that an effective carbon compensation policy in fact exists for national governments to enforce socially optimal levels of forest clearing. The optimality at the national level of carbon compensation policies crucially depends on land income taxation. Therefore, an international carbon compensation scheme should take into account policies existing at the national level that affect forest clearing.

**Keywords:**

Tropical forests; forest clearing; socially optimal stock; optimal policies; carbon compensation; land income tax.

## 1. Introduction

Globally, about 13 million hectares of forests are lost every year (FAO 2010), which accounts for up to 17 percent of total annual greenhouse gas (GHG) emissions in the world (van der Werf et al. 2009). The Stern Review (2007) has identified the avoidance of deforestation to reduce emissions as a potential key element of cost-effective climate policy for the future. Avoiding deforestation in developing countries may significantly cut emissions at a low cost over a short period of time (see, e.g., Greig-Gann 2008, Kindermann et al. 2008). The Cancun Climate Agreement 2010 included Reducing Emissions from Deforestation and Degradation in developing countries -plus (REDD+) as a component of a post-Kyoto climate regime. [1]

The core idea of REDD is that the global community rewards those who take action to reduce deforestation and forest degradation. Therefore, REDD can ideally serve as a multi-level (international, national and local) payment for environmental services (PES). At the international level, service buyers will pay service providers (i.e. governments or sub-national entities in developing countries) to provide an environmental service, such as reduced emissions from deforestation and degradation. At the national level, national governments or other intermediaries will be the service buyers who will pay the service providers (land owners), for example, to reduce emissions by conserving tropical forests (Angelsen and Wertz-Kanounnikoff 2008, p.12). In this development, interesting and important research questions are modeling the economics of tropical deforestation under a REDD-type carbon compensation scheme across an infinite time frame and investigating the optimal carbon compensation policy for national governments taking into account existing policies such as taxation.

A rich literature base has used dynamic models to investigate tropical deforestation from a range of perspectives.[2] Walker and Smith (1993) and Mateo (1997) used optimal stopping and optimal control models, respectively, to analyze the tropical-forest clearing policy of a private agent, such as a concessionaire and rancher. Using a dynamic

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[1] The Cancun Climate Agreement was reached during the UN Climate Conference 2010 held in Cancun, Mexico in December 2010. REDD was endorsed by the United Nations Framework Convention on Climate Change (UNFCCC) at its Bali conference in December 2007 as a means of combating global warming and climate change. In this article, we use the terms REDD and REDD-plus interchangeably.

[2] Barbier and Burgess (1997), Hardie and Parks (1997), Parks et al. (1998), Alix-Garcia (2007), Amacher et al. (2009, p. 166-173), and Angelsen (2010) used static models to study tropical deforestation under competitive land-use options. See Kaimowitz and Angelsen (1998), Angelsen and Kaimowitz (1999), Angelsen (1999), and Amacher et al. (2009, p. 163-165) for comprehensive reviews on analytical and other models of tropical deforestation.

modeling approach, Bulte and van Soest (1996) showed that encroachment by shifting cultivators may save virgin tropical forests from being cleared by concession loggers. Furthermore, analyses using dynamic models demonstrated that tropical deforestation decreases with securer property rights (Mendelsohn 1994, Amacher et al. 2009) and an increase in non-timber benefits from forests (Amacher et al. 2009), but increases with greater corruption and dependency of local people on forests (Barbier et al. 2005) as well as rising agricultural prices and profits from marketing timber (Hartwick et al. 2001). Angelsen (1994) also used a dynamic model to show that policies affecting the factors that govern the advancement of the agricultural frontier in forests, such as agricultural price, minimum wage and technological level can influence the intensity of tropical deforestation. As the above discussion suggests, the models used in these studies failed to incorporate carbon sequestration [3] and thus did not study tropical deforestation under carbon compensation or derive policy rules, e.g. for REDD mechanism.

This paper contributes to the formal analytical modeling of the deforestation problem by incorporating into it a carbon crediting option for the owner of tropical forestland. We use an infinite time horizon dynamic optimization model to explain the economics of tropical deforestation under a REDD-type scheme of compensating the owners of tropical forests for providing carbon services from their forests. The carbon crediting option in this scheme is reversible in the sense that a landowner can redeem the credited forestland to his use by purchasing it from the carbon credit program.

Tropical forests are important sources not only of timber, but also of non-timber and non-marketed services such as carbon sequestration, biodiversity and watershed conservation, wilderness, erosion control, and other soil protection benefits. Society values both timber and non-timber services from privately controlled forests. However, if the private sector is not paid for these non-timber services, the private optimal forest stock will remain smaller than the socially optimal one. In other words, when the amenity services of forests are a public good which the private sector does not fully value, divergence occurs between the social and private optima (van Kooten et al. 1995, Caparrós and Jacquemont 2003, Tassone et al. 2004). Tahvonen (1995) and Romero and Daz-Balteiro (1998) presented alternative approaches to calculate the rate of carbon subsidy/tax needed to remove this divergence. Englin and Klan (1990) and Koskela and Ollikainen (1997, 2003) examined the optimal design of Pigouvian

[3] Sohngen and Mendelsohn (2003) used an optimal control model to study deforestation under carbon sequestration without strictly focusing on tropical forests, but rather on all types of forests in the world.

taxes to correct the negative externalities that private harvesting imposes on society and thus to equate the private optima with the social optima. These studies modeled forests as a renewable resource and focused on managed forests with clearly defined ownership, rather than explicitly focusing on tropical forests or using tropical deforestation or treating forests as non-renewable resource. There is abundant literature discussing the extraction of non-renewable resources which dates back to the seminal work by Hotelling (1931). Brown and Wong (1993) modelled forests of Russia and Mæstad (2000) modelled tropical forests as non-renewable resource and discussed optimal timber extraction. These two studies, however, did not consider any carbon policy or taxes.

Policy measures such as taxing timber harvest income can induce less harvesting, which could contribute to increasing forest and carbon stocks (Wibe and Gong 2010). However, in a recent review study, Karsenty (2010) argued that taxes alone are insufficient to ensure sustainable tropical forest management; rather, they should serve as a component of a consistent set of actions and public policies for the best effect. To the best of our knowledge, no theoretical or empirical study has shown how taxes can be combined with other public policy tools such as carbon compensation to prevent tropical deforestation.

In this paper, we apply a deforestation model to investigate the optimal rates of land income tax and carbon compensation that ensure a socially optimal tropical forest stock. We also study how the carbon compensation policy of a national government should be determined in the presence of land income taxation. To derive socially optimal policy rules, we model deforestation for both the social planner and private sector. We base our description of the private sector on utility-maximizing individuals, communities, or firms, and then refer to them as 'private forestland owners' or 'private landowners'.[4]

This paper offers a number of policy-related contributions to the literature on tropical deforestation. First, it is shown that the land income tax rate required to enforce a socially optimal size of a tropical forest stock in private ownership should equal the proportional difference between the social and private amenity valuations of tropical forests. Second, the existence of an optimal land income taxation policy may require the government to pass the same amount of carbon compensation that it receives from the international

[4] According to RRI and ITTO (2009), globally about 31 percent of tropical forests fall under the direct ownership of indigenous and local communities, private individuals, and firms, and another 4 percent of tropical forests fall under formal public ownership are designated for the use of local communities and indigenous groups. This substantial ownership of tropical forests by the private sector makes it a very important player in policy discussions aiming to avoid tropical deforestation.

community on to private forestland owners to ensure a socially optimal tropical forest stock. However, under a pre-existing sub-optimal land income taxation policy, it may be optimal for the government to either over-transfer or under-transfer any such carbon compensation depending on the level of forest amenity valuation of private landowners. In the complete absence of a taxation policy, the government may require to over-transfer such carbon compensation to private landowners.

The remainder of the paper is structured as follows. In Section 2, we first present the carbon uptake model of the private landowner and social planner, and derive optimal conditions for the consumption, forest clearing, and carbon crediting of standing tropical forests. Section 3 presents the optimal policy rules in terms of the land income tax and carbon compensation through which national governments can enforce a socially optimal limit on the size of privately-held tropical forests. Finally, Section 4 presents the discussion and conclusions.

## 2. Decision model

### *2.1 Land area dynamics*

Assume that at the beginning of period $t \in \{t_0, t_0+1, t_0+2, ..........\infty\}$, the agent, who could be either a private forestland owner or social planner, owns $(x_t + y_t)$ hectares (ha) of tropical forest with a timber stock of $q$ $m^3 ha^{-1}$.[5] Of this forest, an area of $x_t$ ha is not carbon credited and free-to-clear, and an area of $y_t$ ha is carbon credited at the beginning of period $t$. The agent first clears a share $a_t$ ($0 \leq a_t \leq 1$) of his forest and then places a share $b_t$ ($0 \leq b_t \leq 1$) of the remaining standing forest into a carbon crediting scheme and receives a carbon payment from the government. We assume that tropical forests are managed as a non-renewable resource,[6] so the land area dynamics for the uncredited standing and carbon credited-forests can therefore be given as:

$$x_{t+1} = (x_t + y_t)(1 - a_t)(1 - b_t) \quad \forall t \tag{1.1}$$

$$y_{t+1} = (x_t + y_t)(1 - a_t)b_t \quad \forall t \tag{1.2}$$

[5] We assume that the biomass per ha is constant over time. Although Lewis et al. (2009) and Phillips et al. (2009) have recently challenged this conventional wisdom, accounting for the biomass growth in old-growth tropical forests would offer no deeper insight for our analysis.

[6] The non-renewability assumption of tropical forests is supported by the fact that tropical deforestation is more often a one-way phenomenon; once forest is cleared, the land goes to other uses, such as agriculture, and never reverts to forestry.

Thus, the total forest area develops as $(x_{t+1} + y_{t+1}) = (x_t + y_t)(1 - a_t)$. This implies that the credited area is directly related to the remaining area: $y_{t+1} = (x_{t+1} + y_{t+1})b_t$. In a given period, if the cleared area exceeds the free-to-clear area ($x_t$), then the agent must buy back enough carbon-credited land to enable the clearing. In other words, if the agent has less forest in the carbon crediting scheme in a given period than in the previous period (i.e. $y_t < y_{t-1}$), he must buy back forest area of $(y_t - y_{t-1})$ha from the scheme and incur a cost. The opposite holds true if the area change of credited forest is the opposite.

*2.2 Optimization problem*

We present a general formulation for the optimization problem which encompasses both the social optimum and the private optimum. The agent faces an inter-temporal utility maximization problem; he maximizes his utility over an infinite time horizon by choosing the optimal rates of forest clearing and carbon crediting of standing forest in each period. Utility is derived from both the monetary value of consumption ($c_t$) and the amenity services originating from the standing forest stock ($Q_t$). Both the consumption $u(.)$ and amenity $A(.)$ utilities are concave and increasing functions of their respective arguments (i.e. $u'$, $A' > 0$ and $u''$, $A''< 0$). The utility function $u(.)$ satisfies the Inada conditions,[7] and is additively separable between consumption and amenities utilities as well as among time periods. The consumption of the agent is limited by a budget constraint in which the present value of consumption expenditures cannot exceed his forestland value, $LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau)$, (explained in the next section) and external asset $w_{t_0}$ in period $t_0$. The real price of consumption is chosen as a numéraire. The amenity utility is assumed to have a smaller weight on the private preferences than on the social preferences, i.e. the private utility function is $A_p(Q_t) = \chi A(Q_t)$, where $\chi \in (0,1)$ and $A(Q_t)$ is the social amenity utility function. Thus for the social planner, $\chi = 1$, while the private amenity utility is a fraction of the social one. This can be justified by the fact that the social planner includes in his decision amenity benefits accruing to a wider group of people than does the private landowner; for example, deforestation within a community area may adversely impact the farming conditions of a neighboring community, an externality typically ignored by private landowners. Thus social externalities from a standing

[7] This implies that $u'(c) = \infty$ when $\lim c \to 0$. For the amenity utility, we assume $A'(Q) < M$ when $\lim Q \to 0$, where $M$ is a large but finite number. This implies that the amenity consumption is inessential.

forest are valued higher than private ones. Future utilities are considered expected utilities formed in the current period, $t_0$, and $E_{t_0}$ is the expectation operator. The forestland value depends on current and expected future harvest and crediting decisions, i.e., $\boldsymbol{a}_{t_0} = \{a_{t_0}, a_{t_0+1}, \ldots\}$ and $\boldsymbol{b}_{t_0} = \{b_{t_0}, b_{t_0+1}, \ldots\}$.

We insert in the model two policy parameters: $\tau$ and $S$ - forestland income tax and lump sum subsidy, respectively. These parameters are set to zero (and are thus absent) in the social planner's problem, but are included in the private landowner's problem.[8] The land income tax can be defined as a proportional tax on the landowner's total land income that originates from forest clearing and the carbon crediting of the standing forest. Now the agent's expected utility maximization problem formed in the beginning of period $t_0$ can be expressed as:

$$\underset{\{a_t, b_t, c_t\}_{t=t_0}^{\infty}}{Max} U_t = \left[ E_{t_0} \sum_{t=t_0}^{\infty} \beta^{t-t_0} \left[ u(c_t) + \chi A(Q_t) \right] \right] \tag{2.1}$$

subject to

$$\sum_{t=t_0}^{\infty} \delta^{t-t_0} c_t \leq w_{t_0} + LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c; \tau) + S \tag{2.2}$$

$$Q_t = (x_t + y_t)(1 - a_t)q \quad \forall t \tag{2.3}$$

where $\beta = (1+\rho)^{-1}$ and $\delta = (1+r)^{-1}$ and $\rho$ and $r$ are the time discount and market interest rates, respectively, both of which are strictly positive. The forestland value is formalized next.

*2.3 Land value in a carbon credit system*

We model the economics of tropical deforestation under carbon compensation, a feature that allows the model to study a REDD-type regime with implied international, national, and local levels. We assume a regime in which the international community is concerned only about carbon, while the national government (i.e. the social planner) and private landowners take the carbon crediting system as given. The national government observes a wider set of benefits from the growing stock (such as habitat) than do private landowners. Through carbon and taxation policies, the national government induces

[8] The subsidy, $S$, can be treated as compensation that holds the landowner to his initial budget constraint, i.e. the subsidy compensates the landowner for lost income. Moreover, in our model, the primary aim of this tax, which is equivalent to the land value tax, is to correct externalities caused by private clearing of tropical forests. The tax is therefore, absent from the social planner's problem.

landowners to behave along the social optimum with regard to carbon, habitat, and other public goods.

Forest clearing provides the agent revenues from timber as well as from selling or renting the cleared land for other uses (recall discussion in Footnote 6). Furthermore, he is entitled to receive a carbon compensation payment for the uncleared standing forest. This payment is linked to the market price of carbon, and its rate is initially determined by an international climate regime (ICR) and given to both the government and private landowners.[9] The carbon payments add to the land value since these payments are received for the uncut standing forests. The credit system is assumed to be reversible in the sense that the agent can redeem the credited land. In fact, if the cleared area in a period exceeds the free-to-clear area in that period, then the agent must buy back enough carbon credited land to be able to clear the full desired area. Carbon crediting therefore yields revenues or costs depending on the changes in the credited area.

Let, $p_t^{tim}$ be the timber price per $m^3$, $p_t^l$ the price per ha of cleared forestland, $k_t$ the forest-clearing (e.g. from slash and burn) cost per ha, and $p_t^c$ the unit market price of carbon on the international carbon market during period $t$. Let us assume that only the first period timber, cleared land, and carbon prices, and forest clearing cost are known, but those in all future periods are uncertain and follow a trend-stationary process. The forest clearing cost, $k_t$, follows a convex path over time. Therefore, all future prices, revenues and costs can be considered expectations. Furthermore, $\theta$ denotes the carbon content of wood in tons per $m^3$, and $\eta$ ($0 \leq \eta \leq 1$) is the carbon compensation rate that an ICR gives to the government, which then passes it on to the private landowner. The carbon compensation rate is therefore the same in both the social planner's and the private landowner's problems, and $\eta p_t^c$ can be considered the effective carbon price to both agents.[10] The land value to the private landowner in the current period $t_0$ is the present value of expected income flows derived from the forest, and can be expressed as (see also Appendix 1(i)):

$$LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c; \tau) = (x_{t_0} + y_{t_0}) lv_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c; \tau) \quad (3.1)$$

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[9] Thus, we assume the existence of an internationally established market for tradable carbon credits.

[10] For example, this share can be set as $\eta$ = (1-*pickling factor*). The term 'pickling factor' used by, for example, van Kooten et al. (1995), represents the portion of the total forest biomass to be used after the harvest for purposes of carbon storage (e.g. construction). Thus, the idea is that benefits for foregone deforestation are discounted by the amount of cut timber that ends up as carbon storage. Another reason for incomplete compensation could be that part of the carbon emissions from forest clearing could be partially offset for subsequent land use.

In (3.1), *lv* is the forestland value per ha, which depends on $x_{t_0}$ and $y_{t_0}$ through the income per ha in initial period $t_0$, as shown in (3.2 and 3.3). Now *lv* can be expressed as:

$$lv_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) = \hat{\pi}^{t_0}_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) + E_{t_0} \sum_{t=t_0+1}^{\infty} \delta^{t-t_0} \hat{\pi}^{t_0}_t (\boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) \quad (3.2)$$

On the RHS of (3.2), the first term yields income per ha in the current period and the second term gives the sum of incomes in all future periods, which can be expressed as:

$$\hat{\pi}^{t_0}_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) = (1-\tau)\left\{a_{t_0} R^h_{t_0} + \left[(1-a_{t_0})b_{t_0} - y_{t_0}(x_{t_0} + y_{t_0})^{-1}\right] R^c_{t_0}\right\} \quad (3.3)$$

$$\hat{\pi}^{t_0}_t(\boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) = (1-\tau)\left\{a_t R^h_t + \left[(1-a_t)b_t - b_{t-1}\right] R^c_t\right\} \prod_{s=t_0}^{t-1} (1-a_s) \quad (3.4)$$

where, $R^h_t = p^{tim}_t q - k_t + p^l_t \quad \forall t$, (3.5)

and $R^c_t = \theta q \eta p^c_t \quad \forall t$ (3.6)

Setting $\tau = 0$ in (3.1-3.4) yields the land value for the social planner. Equation (3.3) gives the value generated for forestland per ha in period $t_0$, and (3.4) gives the expected value per ha generated in each of the future periods as perceived in period $t_0$. In (3.3) and (3.4), the first terms inside the brackets give the revenue net of clearing costs from clearing a share of a hectare of forest in a given period. The clearing revenue in any given period, *t* – as described by (3.5) – comes from selling timber and cleared land for other uses in that period. The second terms inside the brackets in (3.3) and (3.4) yield the value of the standing forest in the carbon assignment net of the carbon pay-off, where $R^c_t$ – as defined by (3.6) – is the carbon return (cost) for storing carbon by not clearing (releasing carbon by clearing) one ha of forest.

### *2.4 Optimal rules*

#### *2.4.1 Consumption*

The optimization problems for the private landowner and the social planner differ only by parameterization. In this specification, as stated earlier, the problem of the social planner has, $\chi = 1$, $\tau = 0$, and $S = 0$ whereas the private landowner has $\chi \in (0,1)$, $\tau \in (0,1)$, and $S > 0$. The optimality conditions are therefore similar. The Lagrangian of the optimization problem given by (2.1 – 2.3) is:

$$L(\boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}; \tau) = E_{t_0} \sum_{t=t_0}^{\infty} \beta^{t-t_0} \left[u(c_t) + \chi A(Q_t)\right] + \lambda \left( w_{t_0} + LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) + S - \sum_{t=t_0}^{\infty} \delta^{t-t_0} c_t \right)$$

(4)

The solution to the problem is found by solving the Karush-Kuhn-Tucker conditions necessary for the optimum. The optimal consumption rule in period $t$ ($t \geq t_0$) has an interior solution due to the Inada conditions and can be expressed as:

$$\frac{\partial L(\boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}; \tau)}{\partial c_t} = E_{t_0}\left(\frac{\beta}{\delta}\right)^{t-t_0} u'(c_t) = \lambda \quad \forall t \qquad (5.1)$$

Since consumption in current period $t_0$ is already realized, the first order condition for consumption in this period can be given as:

$$u'(c_{t_0}) = \lambda \qquad (5.2)$$

Above, $u'(c_t)$ denotes the marginal utility of consumption in period $t$. The conditions (5.1) and (5.2) state that at the optimum, the marginal utility of consumption equals the shadow price of consumption. Now, using (5.1) and (5.2), the consumption rule can more generally be expressed as:

$$u'(c_{t_0}) = E_{t_0}\left(\frac{\beta}{\delta}\right)^{t-t_0} u'(c_t) \qquad (5.3)$$

Differentiating the Lagrangian function (4) w.r.t. the shadow price of consumption ($\lambda$) yields:

$$w_{t_0} + LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) + S - \sum_{t=t_0}^{\infty} \delta^{t-t_0} c_t = 0 \qquad (5.4)$$

Equation (5.4) implies that the agent is neither over-consuming nor wasting any resources. The time dimension of the solution regarding consumption (5.1) and the shadow price of consumption (5.4) presented above, as well as that of forest clearing (6.1) and carbon crediting (7.1) to be presented below is understood as follows. The actions for current period $t = t_0$ take place as the optimality conditions state. For future periods $t > t_0$, the conditions for optimality present the expected decisions based on information at $t = t_0$. These expected actions induce expected values for the monetary wealth and land value. The decision problem is solved in every period as the new realizations for the random variables are observed.

### *2.4.2 Forest clearing*

The optimal private forest clearing rule for any period $t$ ($t \geq t_0$) can be given as:

$$\frac{\partial L(\boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}; \tau)}{\partial a_t} = E_{t_0} \sum_{s=t}^{\infty} \beta^{s-t_0} \chi A'(Q_s) \frac{\partial Q_s}{\partial a_t} + \lambda(x_{t_0} + y_{t_0}) \frac{\partial lv_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau)}{\partial a_t} \overset{<}{\underset{>}{=}} 0 \qquad (6.1)$$

Now explicitly expressing the differential terms in the middle part of (6.1) and doing some rearrangement, (6.1) can be rewritten as (see also Appendix 1(ii)):

$$E_{t_0}\delta^{t-t_0}R_t^h \overset{<}{\underset{>}{=}} E_{t_0}\delta^{t-t_0}\left[b_t R_t^c + (1-\tau)^{-1}\delta lv_{t+1}(\boldsymbol{a}_{t_0+1},\boldsymbol{b}_{t_0}, p_{t_0+1}^c;\tau)\right]$$
$$+(1-\tau)^{-1}E_{t_0}\left\{\beta^{t-t_0}\lambda^{-1}\left(\chi A'(Q_t)+\sum_{u=t+1}^{\infty}\beta^{u-t}\chi A'(Q_u)\prod_{v=t+1}^{u-1}(1-a_v)\right)q\right\} \tag{6.2}$$

The forest clearing rule (6.2) is non-linear in clearing share $a_t$ through $A'(.)$. It can be noted from (6.2) that the forestland value per ha in period $t+1$ depends on the current period ($t$)'s carbon crediting decision, not on the current period's clearing decision. The left hand side (LHS) of (6.2) represents the marginal benefits of forest clearing, while the RHS represents the marginal costs of it. If (6.2) holds as an inequality, the optimal forest clearing takes a corner solution, and an interior solution occurs in case of equality in (6.2). In the corner case, the agent clears his entire forest (i.e. $a_{t_0}=1$) if the marginal benefit of clearing exceeds the marginal cost [11], and if the marginal cost exceeds the marginal revenue, the agent leaves his entire forest standing, (i.e. $a_{t_0}=0$). A natural interpretation of the interior case, (i.e. $0<a_{t_0}<1$) is that forests are cleared to the point where the marginal benefits of forest clearing equal its marginal costs.

The marginal benefit of forest clearing (the LHS of (6.2)) is the revenue from clearing one ha of forest, i.e. revenues from selling timber and land for alternative uses (recall (3.5)). The first term of the two terms that constitute the marginal monetary cost of forest clearing (the RHS of (6.2)) yields the lost carbon return in period $t$, $b_t R_t^c$, and the return from forest clearing and carbon crediting in all future periods beyond $t$, which can also be described as the change in expected land value or the present value of a unit hectare of forest in period $t+1$. The second term yields the discounted sum of the relative marginal utilities of forest amenity in all periods, which indicates that the optimal forest clearing rate in period $t$, i.e. $a_t$ depends on consumption (through $\lambda$, recall (6.1)) and thus on the wealth of the agents through the term $\frac{1}{1-\tau}E_{t_0}\left\{\beta^{t-t_0}\frac{1}{\lambda}\left(\chi A'(Q_t)+\sum_{u=t+1}^{\infty}\beta^{u-t}\chi A'(Q_u)\prod_{v=t+1}^{u-1}(1-a_v)\right)q\right\}$. In this term, $A'(.)$ is the marginal amenity value of the forest resources per ha. Because of the concavity of $A(.)$, the marginal amenity value is a decreasing function of the size of the forest resources removed by

[11] This can happen because Inada condition is not assumed for the amenity utility function (see also Footnote 8).

forest clearing, but because *u(.)* also concave, it is an increasing function of the external wealth of the agents.[12] Therefore, the wealthier is the agent, the lower is the preference for deforestation.

Rule (6.2) also implies that the higher the current price of cleared forestland in alternative uses, $p_t^l$, the higher the return from forest clearing $R_t^h$ (recall 3.5) and thus the greater the marginal benefit of forest clearing. The cleared land price is a reflection of the return from alternative uses of deforested land, such as slash and burn agriculture, pasturing, shifting cultivation, or cash crops, and thus reflects the demand for cleared land. Therefore, the larger the return from alternative uses of land cleared of forest, the higher the forest clearing rate. The presence of carbon return on the marginal cost side of forest clearing indicates that the carbon market options add value to the standing forest land, and thus reduce the profitability and the probability of forest clearing.

The result of tropical forest clearing and cleared land price merits further discussion in light of Barbier and Burgess (1997), Hartwick et al. (2001) and Alix-Garcia (2007), who showed that the higher the rental value of alternative uses, the greater the supply of converted forest land to those uses, as an increase in the land supplied to those uses can only be achieved by bidding away from forests at increasingly higher prices. Total deforestation depends on the value of deforested land, which is essentially determined by the value of timber on that forestland and the price of cleared land in alternative uses (Hartwick et al. 2001, Alix-Garcia 2007). Forest clearing decreases as the price or rental value of the land in forest use increases (e.g. Barbier and Burgess 1997). The price or rental value of forest land use is directly linked to the opportunity costs of foregone timber production and environmental benefits from sustainable forestry. From (7.2) it is evident that the optimal clearing also depends on the carbon crediting of standing forest, $b_t$.

### *2.4.3 Carbon crediting*

The rule for the optimal carbon crediting share of the uncleared land, covering two corner-solution cases, in period $t$ ($t \geq t_0$) is:

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[12] To preserve an unchanged value for $\frac{1}{1-\tau} E_{t_0}\left\{\beta^{t-t_0}\frac{1}{\lambda}\left(\chi A'(Q_t)+\sum_{u=t+1}^{\infty}\beta^{u-t}\chi A'(Q_u)\prod_{v=t+1}^{u-1}(1-a_v)\right)q\right\}$, a recudction in $\lambda$, and thus $u'(.)$ must be matched by a reduction in $A'(.)$.

$$\frac{\partial L(\boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}; \tau)}{\partial b_t} = \lambda \frac{\partial}{\partial b_t} LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) \underset{>}{\overset{<}{}} 0 \qquad (7.1)$$

Expressing the differential term in the middle part of (7.1) explicitly, using (3.6) and rearranging, we can rewrite (7.1) as (see also Appendix 1):

$$E_{t_0} R^c_t > (<) E_{t_0} \delta R^c_{t+1} \Rightarrow E_{t_0} p^c_t > (<) E_{t_0} \delta p^c_{t+1} \Rightarrow b_t = 1 (b_t = 0) \qquad (7.2)$$

Condition (7.2) yields a corner solution for the carbon crediting: in each period the agent sells the remaining uncredited standing forest entirely to the carbon assignment if the marginal benefit of the carbon crediting (LHS) exceeds the marginal cost of it (RHS); otherwise, he sells nothing (see 3.6). As (7.2) suggests, in each period, the marginal benefit is the carbon price in that period, while the marginal cost is the discounted expected carbon price in the following period.

According to (7.2), the carbon crediting can be described as a pawn shop. The agent takes the forest into a pawn shop and receives money in exchange for it. If he wants to harvest the trees, he must buy the forest back from the pawn shop with that period's price. This procedure is worthwhile if the current carbon credit price is higher than the present value of the future price of carbon credits. Therefore, with a constant carbon price it is always profitable to keep the non-harvested forest in the carbon crediting scheme, i.e. $b$ = 1 always holds true.

## 3. Optimal policies

### *3.1 Optimal land income taxation*

We will next derive an expression for an optimal income tax rate, i.e., we will determine a tax rate that will make the private landowner change his behavior in such a way as to lead to the socially optimal size of the forest resources from national perspective. We study a case, where the international community requires the carbon compensation parameter, $\eta$, to be the same for both the landowner and the national government (social planner), i.e., the regime requires that the national government passes the full (no less, no more) compensation on to local agents. As shown below in this section, a constant income tax level therefore exists that would bring private behavior consistent with what is socially (on the national level) optimal.

As previously stated in Section 2.4.1, setting parameter values $\chi = 1$, $\tau = 0$, and $S = 0$ in (5.1), (6.1) and (7.1) yields the solution to the social planner's problem which thus gives the social optimum. The optimal actions are denoted by $(\boldsymbol{a}_{t_0}{}^*, \boldsymbol{b}_{t_0}{}^*, c_{t_0}{}^*)$ which yield expected optimal land value $LV_{t_0}^{\ *}$ as perceived in period $t_0$. The optimal policy forces the private landowner to behave in socially optimal manner even though the perceived utility from his standing stock is different. This can be performed using a Pigouvian tax $\tau$ with a lump-sum subsidy $S$ which fully compensates for the lost income. Our aim is to make equations (5.1), (6.1), and (7.1) match for both the social planner and the private landowner.

Equations (5.1) and (7.1) are behaviorally equivalent for both the private landowner and the social planner. Thus, the policy parameters must alter the budget constraint and the first order condition for forest clearing (6.1). Since similar cutting and crediting behavior yields an equal pre-tax land value, $LV_{t_0}^{\ *}$, the budget constraint is maintained by compensating the tax payment through a subsidy. Thus, it holds that $S^* = \tau^* LV_{t_0}^{\ *}$. Therefore, what remains to be found is the optimal tax rate, $\tau^*$ with behaviorally equivalent first order conditions for both the landowner and the social planner:

$$\begin{aligned}&E_{t_0}\sum_{s=t}^{\infty}\beta^{s-t_0}A'(Q_s)\frac{\partial Q_s}{\partial a_t}+\lambda\frac{\partial LV_{t_0}(x_{t_0},y_{t_0},\boldsymbol{a}_{t_0},\boldsymbol{b}_{t_0},p_{t_0}^c,0)}{\partial a_t}\\&=\left[E_{t_0}\sum_{s=t}^{\infty}\beta^{s-t_0}\chi A'(Q_s)\frac{\partial Q_s}{\partial a_t}+\lambda\frac{\partial LV_{t_0}(x_{t_0},y_{t_0},\boldsymbol{a}_{t_0},\boldsymbol{b}_{t_0},p_{t_0}^c;\tau^*)}{\partial a_t}\right]\gamma\end{aligned}\qquad(8)$$

In (8) $t \geq t_0$ , and parameter $\gamma > 0$ allows for scaling of the first order conditions. Note that equal behavior with equal budget constraints yield equal Lagrange multipliers for the two optimization problems. By assuming a constant land income tax rate, we can express the land value with a dynamic land income tax rate given by (3.1):[13]

$$LV_{t_0}(x_{t_0},y_{t_0},\boldsymbol{a}_{t_0},\boldsymbol{b}_{t_0},p_{t_0}^c;\tau)=(1-\tau)(x_{t_0}+y_{t_0})lv_{t_0}(x_{t_0},y_{t_0},\boldsymbol{a}_{t_0},\boldsymbol{b}_{t_0},p_{t_0}^c,0)\qquad(9)$$

Now in (8), applying (9) and making the land value terms equal by choosing $\gamma = (1-\tau^*)^{-1}$ :

$$\begin{aligned}&E_{t_0}\sum_{s=t}^{\infty}\beta^{s-t_0}A'(Q_s)\frac{\partial Q_s}{\partial a_t}+\lambda(x_{t_0}+y_{t_0})\frac{\partial lv_{t_0}(x_{t_0},y_{t_0},\boldsymbol{a}_{t_0},\boldsymbol{b}_{t_0},p_{t_0}^c,0)}{\partial a_t}\\&=(1-\tau^*)^{-1}E_{t_0}\sum_{s=t}^{\infty}\beta^{s-t_0}\chi A'(Q_s)\frac{\partial Q_s}{\partial a_t}+\lambda(x_{t_0}+y_{t_0})\frac{\partial lv_{t_0}(x_{t_0},y_{t_0},\boldsymbol{a}_{t_0},\boldsymbol{b}_{t_0},p_{t_0}^c,0)}{\partial a_t}\end{aligned}\qquad(10)$$

which leads directly to the following optimal tax rate (see also Appendix 2):

[13] Equation (9) implies that the explicit expression of land value with a constant land income tax rate is the same as that with a dynamic land income tax rate. Therefore, these two land values yield identical first-order conditions, and thus policy rules.

$$\tau^* = 1 - \frac{E_{t_0} \sum_{s=t}^{\infty} \beta^{s-t_0} \chi A'(Q_s) \frac{\partial Q_s}{\partial a_t}}{E_{t_0} \sum_{s=t}^{\infty} \beta^{s-t_0} A'(Q_s) \frac{\partial Q_s}{\partial a_t}} \tag{11}$$

Given the specification for the utility function we observe

$$\tau^* = 1 - \chi \tag{12}$$

The derived result can be stated in the form of the following proposition:

*Proposition 1: When the national government passes the same amount of carbon compensation that it received from international community, on to private landowners, a constant land income tax rate exists which leads to a socially optimal size of privately held tropical forests. This tax rate equals the proportional difference between the social and private amenity valuations of the forests at a socially optimal level of forest resources.*

The straightforward intuition behind the above proposition is that an optimal land income tax corrects the discrepancy between the social and private benefits of the amenity services of the forest resources. From (12) we can see that the optimal tax will always be positive and less than one since $\chi \in (0,1)$ for the private landowner. A tax decreases the monetary benefits of clearing and thus makes the preservation of the amenity services more competitive to the private landowner. In this sense, the land income tax behaves like a Pigouvian tax in that its efficiency relies on the private landowners do receiving some amenity utilities from the forest resources. If this were not the case, the land income tax would not affect the landowners' behavior.[14] It should also be noted that the proportionality between the private and social amenity utilities ensures the existence of a constant tax rate. Besides the income taxation, the government can use a carbon compensation parameter to alter the harvesting patterns of the private forestland owners. This option is explored below.

### *3.2 Optimal carbon compensation*

In Section 3.1, the carbon compensation rate, $\eta$, was assumed to be given by an ICR, and thus the parameter took the same value in the problems of the national government (i.e. the social planner) and the private landowner. This implies no flexibility at the national government level in determining the carbon compensation rate to pass on to the private landowner. In this section we study a case where the international regime gives national

[14] It can be noted from (12) that if the private and social preferences for forest amenities were the same (i.e. $\chi = 1$), no tax would be needed to enforce a socially optimal stock in privately held forests.

governments the flexibility of determining the carbon compensation rate to be used at the national level. Instead, what is considered given in the analysis of this section is the tax rate. Therefore, we next study the question of what is the optimal carbon compensation rate for the national government given a pre-existing income taxation rate.

One could argue that in an ICR relying on a carbon credit market, the carbon credit buyers, who would to a large extent comprise industrialized wealthy countries or entities therein, would want to see the sellers, the national governments of less developed countries, to pass the full amount of carbon compensation (and perhaps more) on to the private forestland owners who are the service providers in these countries. From the fairness point of view of an ICR this would seem just. However, when accounting for the pre-existing land income taxation, the socially optimal rate of carbon compensation for the government of a tropical forest owning country to pass on to private landowners may differ from the rate the government itself receives from an ICR. The optimal carbon compensation policy can be defined as the ratio $\varphi = \eta^* / \eta$ where $\eta^*$ is the optimal share of the carbon compensation which the national government passes on to the landowners and $\eta$ is the carbon compensation share used by the ICR. The optimal carbon compensation policy can therefore be given as (see Appendix 3 for derivation):

$$\varphi = 1 + \frac{E_{t_0} \sum_{s=t}^{\infty} \beta^{s-t_0} \left[ A'(Q_s) - (1-\tau)^{-1} \chi A'(Q_s) \right] \frac{\partial Q_s}{\partial a_t}}{\lambda \left( x_{t_0} + y_{t_0} \right) \frac{\partial lv_{t_0}^c (x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c, 0)}{\partial a_t}} \qquad (13)$$

where

$$\frac{\partial lv_{t_0}^c (x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c, 0)}{\partial a_t} = \delta^{t-t_0} E_{t_0} \left[ -b_t R_t^c - \delta lv_{t+1}^c (\boldsymbol{a}_{t+1}, \boldsymbol{b}_t, p_{t+1}^c) \right] \prod_{s=t_0}^{t-1} (1 - a_s)$$

According to (13), in period *t*, whether $\varphi = 1$ (i.e. $\eta^* = \eta$), $\varphi > 1$ (i.e. $\eta^* > \eta$), or $\varphi < 1$ (i.e. $\eta^* < \eta$) depends on the ratio term on the RHS. As per assumption, $\frac{\partial lv_{t_0}^c (x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c, 0)}{\partial a_t} < 0$, the denominator is negative. Because also $\frac{\partial Q_s}{\partial a_t} < 0$ and the sign of the ratio term depends on sign of $\left[ A'(Q_s) - (1-\tau)^{-1} \chi A'(Q_s) \right]$. When the land income tax is optimally set (recall eq. (12)), the numerator and thus the whole ratio term in (14) disappears, and the carbon policy parameter gets a value of 1. This implies that, in the presence of an optimal land income taxation policy, it would be optimal for the government to pass the full carbon compensation received from the ICR on to landowner.

If the tax is not optimally set, then whether $\varphi = \eta^* > \eta$ or $\varphi = \eta^* < \eta$ depends on value of $\chi$, i.e. weight assigned to private amenity valuations compared to social amenity valuation. The closer the value of $\chi$ to 1, the more likely it is that in $\left[A'(Q_s) - (1-\tau)^{-1}\chi A'(Q_s)\right]$ the second term will dominate the first term as $(1-\tau)^{-1} > 1$ (recall $\tau \in (0,1)$) and thus the more likely it is that the numerator will be negative and the policy term will receive a value of less than one ($\varphi < 1$). On the other hand, the closer the value of $\chi$ to 0, the more likely it is that the numerator will be positive and that the policy term will receive a value more than one ($\varphi > 1$). This implies that under a pre-existing sub-optimal land income taxation policy it may be optimal for the national government to either under-transfer or over-transfer the carbon compensation it received from the ICR to landowners depending on the weight the private landowners assign to forest amenities. On the other hand, when there is no tax at all, then the first term inside the square bracket in the numerator of the ratio term of (13) dominates the second term, and thus $\varphi > 1$. This implies that the government may need to over transfer the carbon compensation to landowners without a pre-existing taxation policy. We summarize the key results from this section in the following proposition.

*Proposition 2: Within the assumed international system of carbon credit markets, effective carbon compensation policies typically exist under which a national government can enforce a socially optimal level of forest clearing. In particular, given pre-existing sub-optimal taxation policies in a given country, it may be optimal for the government either to under- or over-transfer carbon compensations to landowners. If the tax policy is unavailable, then the government may need to over-transfer the carbon compensation to landowners.*

The international policy implication of the proposition is that the international community should observe existing national policies in carbon credit-receiving countries and allow national governments flexibility in terms of passing on carbon compensation payments at the national level.

## 5. Discussion and conclusions

This paper investigates optimal policies in terms of land income taxation and carbon compensation that enforce a socially optimal tropical forest stock using an infinite time horizon dynamic optimization model. The model explains the economics of tropical deforestation under a REDD-type carbon compensation scheme and points out that a carbon compensation scheme would increase the value of standing forests. One of the key results of the paper relates to the constancy of policy rules in a dynamic context, and the dependency of this constancy on the nature of social as opposed to private amenity valuations. It shows that the rate of land income tax needed to enforce a socially optimal size of tropical forest stock in the private sector should equal the proportional difference between the social and private amenity valuations of tropical forests at a socially optimal level of forest resources.

The results also show that the carbon compensation policies of the government of a tropical forest-owning country crucially depend on pre-existing land income taxation in that country. In the presence of an optimal land income taxation policy, the government may need to pass on to landowners the very carbon compensation that it receives from the international community to ensure a socially optimal tropical forest stock. However, a pre-existing sub-optimal land income taxation policy may make it optimal for the government to either over-transfer or under-transfer the carbon compensation depending on private landowner's forest amenity valuation of. When no tax policy exists at all, the government may require to over-transfer the carbon compensation to the landowner. These findings suggest that rather than imposing fixed compensation rates for reduced deforestation or un-cleared forest resources, it would be preferable for the international community to allow the national government to set the carbon compensation rate freely, i.e., the government still uses the existing international community rate, but is free to decide how much of it is then passed on to private landowners in the country. This stems from the joint effects of carbon compensation and the taxation systems. Therefore, we can recommend that an international carbon compensation scheme for tropical forest conservation take into account national policies already in place, such as taxation. Furthermore, a more general implication of the results of this paper is that the carbon compensation scheme studied could be one possible way to establish international compensatory policies between developed and less developed countries as hypothesized in the REDD initiative of the UNFCC.

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## Appendices

## Appendix A. Explanation of land value, and first order conditions for forest clearing and carbon crediting

### (*i*) *Explanation of land value*

Plugging in (3.2) in (3.1) yields:

$$LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau)$$

$$= \left(x_{t_0} + y_{t_0}\right)\left[\hat{\pi}^{t_0}_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) + E_{t_0}\sum_{t=t_0+1}^{\infty}\delta^{t-t_0}\hat{\pi}^{t_0}_t(\boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau)\right]$$

$$= \left(x_{t_0} + y_{t_0}\right)\left[\hat{\pi}^{t_0}_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) + \left(1 - a_{t_0}\right)E_{t_0}\delta\sum_{t=t_0+1}^{\infty}\delta^{t-t_0-1}\hat{\pi}^{t_0}_t(\boldsymbol{a}_{t_0+1}, \boldsymbol{b}_{t_0}, p^c_{t_0+1}; \tau)\right]$$

$$= \left(x_{t_0} + y_{t_0}\right)\left[\hat{\pi}^{t_0}_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) + \left(1 - a_{t_0}\right)E_{t_0}\delta lv_{t_0+1}(\boldsymbol{a}_{t_0+1}, \boldsymbol{b}_{t_0}, p^c_{t_0+1}; \tau)\right] \qquad (A.1)$$

### (*ii*) *Forest clearing*

The first differential term in the middle part of (6.1) in the text shows the effect of clear-cutting on current and future standing stocks of timber. The explicit expression for this term is derived below. In (2.3), we have

$$Q_t = \left(x_t + y_t\right)\left(1 - a_t\right)q \quad \text{when } t \geq t_0 \qquad (A.2)$$

We know that $\left(x_{t_0} + y_{t_0}\right)\prod_{s=t_0}^{t-1}\left(1 - a_s\right) = \left(x_t + y_t\right)$

Now, plugging in above equation in (A.2) yields:

$$Q_s = \left(x_{t_0} + y_{t_0}\right)q\left(1 - a_s\right)\prod_{u=t_0}^{s-1}\left(1 - a_u\right) \qquad (A.3)$$

Thus,

$$\frac{\partial Q_s}{\partial a_t} = -\left(x_{t_0} + y_{t_0}\right)q\prod_{u \in T^{t-1}_{t_0}}\left(1 - a_u\right)\prod_{v \in T^s_{t+1}}\left(1 - a_v\right) \text{ when } s \geq t_0 \text{ and } T^s_{t_0} = \{t_0, t_0 + 1, \ldots\ldots, s\} \qquad (A.4)$$

The second differential term in the middle part of (6.1) in the text shows the effect of clear-cutting on land value perceived in period $t_0$. The explicit expression of this (using (3.5)) is:

$$\frac{\partial}{\partial a_t} LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c; \tau) = \left(x_{t_0} + y_{t_0}\right) E_{t_0} \frac{\partial}{\partial a_t} lv_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c; \tau)$$

$$= E_{t_0}(1-\tau)\delta^{t-t_0}\left[R_t^h - b_t R_t^c - \sum_{u=t+1}^{\infty} \delta^{u-t}\left\{a_u R_u^h + \left((1-a_u)b_u - b_{u-1}\right)R_u^c\right\}\prod_{v=t+1}^{u-1}(1-a_v)\right]\left(x_{t_0} + y_{t_0}\right)\prod_{s=t_0}^{t-1}(1-a_s)$$

Now for the second term inside the square bracket in the RHS of the above equation, following the analogous steps applied in deriving the second term inside the square bracket on the RHS of (A1), we derive:

$$\frac{\partial}{\partial a_t} LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p_{t_0}^c; \tau)$$

$$= E_{t_0}(1-\tau)\delta^{t-t_0}\left[R_t^h - b_t R_t^c - (1-\tau)^{-1}\delta lv_{t_0+1}(\boldsymbol{a}_{t_0+1}, \boldsymbol{b}_{t_0}, p_{t_0+1}^c; \tau)\right]\left(x_{t_0} + y_{t_0}\right)\prod_{s=t_0}^{t-1}(1-a_s) \quad \text{(A.5)}$$

Now plugging in (A.4) and (A.5) in (6.1) and doing some rearrangement, we obtain (6.2) in the text.

***(iii)* Carbon crediting**

The differential term on the middle part of (7.1) in the text gives effect of carbon crediting on land value perceived in period $t_0$. The explicit expression of this (using (3.6)):

$$\frac{\partial}{\partial b_t} LV_{t_0}(x_{t_0}, y_{t_0}, a_{t_0}, b_{t_0}, p_{t_0}^c, \tau) = E_{t_0}(1-\tau)\left[R_t^c - \delta R_{t+1}^c\right]\left(x_{t_0} + y_{t_0}\right)\prod_{s=t_0}^{t}(1-a_s) \quad \text{(A.6)}$$

Plugging in (A.6) in (7.1) and doing some rearrangement we obtain (7.2) in the text.

**Appendix B. Optimal land income tax**

Plugging in (A.3) in (11) we obtain:

$$\tau^* = 1 - \frac{E_{t_0}\sum_{s=t}^{\infty}\beta^{s-t_0} A_P'(Q_s)\prod_{u\in T_{t_0}^{t-1}}(1-a_u)\prod_{v\in T_{t+1}^{s}}(1-a_v)}{E_{t_0}\sum_{s=t}^{\infty}\beta^{s-t_0} A'(Q_s)\prod_{u\in T_{t_0}^{t-1}}(1-a_u)\prod_{v\in T_{t+1}^{s}}(1-a_v)} \quad \text{(A.7)}$$

In (A.7) one can observe that the optimal tax rate depends on the path of $Q_t$. Apparently, this may give the impression that the tax rate determined at period $t_0$ may not optimal when considered at period $t_0$+1, i.e. time inconsistent. However, this problem vanishes with the assumption that $A_P'(Q_s) = \chi A'(Q_s)$, with $\chi \in (0,1)$.

**Appendix C. Optimal carbon compensation policy**

We can re-write the land value given by (3.1) separating income flows in terms of forest clearing and carbon crediting:

$$LV_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau, \varphi) \\ = \left(x_{t_0} + y_{t_0}\right) E_{t_0}\left[lv^h_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) + lv^c_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau, \varphi)\right] \quad \text{(A.8)}$$

where,

$$lv^h_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau) = (1-\tau)\left[a_{t_0} R^h_{t_0} + E_{t_0} a_t R^h_t \left(x_{t_0} + y_{t_0}\right) \prod_{s=t_0}^{t-1} (1 - a_i)\right] \quad \text{(A.9)}$$

$$lv^c_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}; \tau, \varphi) \\ = (1-\tau)\left\{\left[(1 - a_{t_0}) b_{t_0} - y_{t_0}\left(x_{t_0} + y_{t_0}\right)^{-1}\right] R^c_{t_0} + E_{t_0}\left[(1 - a_t) b_t - b_{t-1}\right] R^c_t \left(x_{t_0} + y_{t_0}\right) \prod_{s=t_0}^{t-1} (1 - a_s)\right\} \quad \text{(A.10)}$$

An optimal policy then implies that the social and private first-order conditions coincide, thus applying (9):

$$E_{t_0} \sum_{s=t}^{\infty} \beta^{s-t_0} A'(Q_s) \frac{\partial Q_s}{\partial a_t} + \lambda\left(x_{t_0} + y_{t_0}\right)\left[\frac{\partial lv^h_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}, 0)}{\partial a_t} + \lambda_t \frac{\partial lv^c_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}, 0)}{\partial a_t}\right] \\ = \left[\begin{array}{l} E_{t_0} \sum_{s=t}^{\infty} \beta^{s-t_0} \chi A'(Q_s) \frac{\partial Q_s}{\partial a_t} + (1-\tau)\lambda\left(x_{t_0} + y_{t_0}\right) \frac{\partial lv^h_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}, 0)}{\partial a_t} \\ + \lambda(1-\tau)\left(x_{t_0} + y_{t_0}\right) \frac{\partial lv^c_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}, 0)}{\partial a_t} \varphi \end{array}\right] \gamma$$

(A.11)

where parameter $\gamma > 0$ allows for scaling of the first order conditions. Now choosing $\gamma = (1-\tau)^{-1}$ and removing land value terms for forest clearing we get:

$$E_{t_0} \sum_{s=t}^{\infty} \beta^{s-t_0} A'(Q_s) \frac{\partial Q_s}{\partial a_t} + \lambda\left(x_{t_0} + y_{t_0}\right) \frac{\partial lv^c_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}, 0)}{\partial a_t} \\ = (1-\tau)^{-1} E_{t_0} \sum_{s=t}^{\infty} \beta^{s-t_0} \chi A'(Q_s) \frac{\partial Q_s}{\partial a_t} + \lambda\left(x_{t_0} + y_{t_0}\right) \frac{\partial lv^c_{t_0}(x_{t_0}, y_{t_0}, \boldsymbol{a}_{t_0}, \boldsymbol{b}_{t_0}, p^c_{t_0}, 0)}{\partial a_t} \varphi \quad \text{(A.12)}$$

Further rearrangement in (A.12) leads to (13).