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Reduced deforestation and economic growth

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Abstract

The clearing of forests for agricultural land and other marketable purposes is a well-trodden path of economic development. With these private benefits from deforestation come external costs: emissions from deforestation currently account for 12 per cent of global carbon emissions. A widespread intervention in reducing emissions from deforestation will affect the paths of agricultural expansion and economic growth of lower income nations. To investigate these processes, this paper presents a general, dynamic, stochastic model of deforestation and economic growth. The model is shown to generate unique deforestation and investment paths and a model without reduced deforestation policy is shown to have a stationary distribution of income and landholdings. There are three main findings. First, in the short run national output growth falls with compensation for reduced deforestation. Second, deforestation rates are reduced through compensating either reduced deforestation directly or the stock of forests; however, compensating the stock of forests is likely to be prohibitively expensive. Finally, by offering a fixed compensation rate, as opposed to a compensation rate tied to a stochastic carbon price, further reductions in deforestation can be achieved.

Keywords
Reduced deforestation; economic growth; climate policy; stochastic stability

JEL Classification

Q38, Q56, Q62.

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Reduced deforestation and economic growth

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February 3, 2014

Abstract

The clearing of forests for agricultural land and other marketable purposes is a well-trodden path of economic development. With these private benefits from deforestation come external costs: emissions from deforestation currently account for 12 per cent of global carbon emissions. A widespread intervention in reducing emissions from deforestation will affect the paths of agricultural expansion and economic growth of lower income nations. To investigate these processes, this paper presents a general, dynamic, stochastic model of deforestation and economic growth. The model is shown to generate unique deforestation and investment paths and a model without reduced deforestation policy is shown to have a stationary distribution of income and landholdings. There are three main findings. First, in the short run national output growth falls with compensation for reduced deforestation. Second, deforestation rates are reduced through compensating either reduced deforestation directly or the stock of forests; however, compensating the stock of forests is likely to be prohibitively expensive. Finally, by offering a fixed compensation rate, as opposed to a compensation rate tied to a stochastic carbon price, further reductions in deforestation can be achieved.

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1 Introduction

> *We made our oath beneath a mighty ironbark it were 8 ft. across as old as history its bark so black and rough it were like the armour of a foreign king. Might as well said Jem, then spat upon his hands and laid his axe into the brutal bark the flesh were sour and red...* (Carey, 2000, p. 104)

The story goes that with their father in gaol, a 15 year old Ned Kelly and his 9 year old brother Jem were left to develop their family's property at 11 Mile Creek in the Colony of Victoria, soon to become a State in federated Australia. Their strategy to generate income and avoid 'slaving for their aunts' involved felling trees to provide farming land. Ned and Jem's story is not unique, as the clearing of forested land for production is a well-trodden path of economic development. Deforestation facilitated development was also the experience in middle-ages Europe and Japan, pre-European Easter Island, and in post-European North America (Diamond, 2005). Presently, high rates of deforestation are found in lower income countries in the tropical belt (Chomitz et al., 2007).

In addition to agricultural benefits, deforestation has external costs. These costs are global: tropical deforestation accounts for approximately 12 per cent of total global emissions (van der Werf et al., 2009). Because reducing these emissions would impose opportunity costs of foregone income, tropical nations have little incentive to reduce deforestation emissions unilaterally. An initiative now known as REDD+[1] attempts to provide an incentive for tropical nations to incorporate the external costs of carbon emissions through compensating reduced deforestation (Coalition for Rainforest Nations, 2007).

Compensation may offset the cost of foregone income, but a REDD+ mechanism may still affect the broader economy. Reducing deforestation will slow the expansion of agricultural land, reducing growth in an important sector for low income countries (The World Bank, 2007). On the other hand, resources that would have been used in agriculture may migrate to other sectors and offset national output losses. Further, compensation received for reducing deforestation may be invested, raising future capital stocks and output. In this paper these effects are investigated through the development of a model that incorporates land expansion, capital accumulation and reduced deforestation policy.

[1] Reducing Emissions from Deforestation and forest Degradation. The '+' refers to activities that promote non carbon related benefits, amongst others. See Olander et al. (2012) for more information about changing scope of REDD over time.

Existing models cannot be relied upon to investigate reduced deforestation policy and the short to medium run effects of policy on the broader economy. First, many growth models implicitly assume agricultural land is perfectly substitutable with other capital stocks (Stern, 2011). This is not surprising when we consider that early growth models focused on developed nations and that most of these nations largely ceased agricultural expansion before Kuznets developed the stylised facts that lead to the development of modern growth models (Acemoglu, 2009). Second, where explicitly included the amount of land used in production is typically held fixed (Adamopoulos, 2008; Dekle and Vandenbroucke, 2012), clearly unsuitable for a process of expanding productive landholdings. Third, the existence of costs to defining property rights over the forest margin (Chomitz et al., 2007; Mendelsohn, 1994) rules out Hotelling-style extraction models (Dasgupta and Heal, 1974). Finally, the modeling of agricultural land in computable general equilibrium models is limited to static allocations or exogenous dynamic processes. As such, they are used to investigate alternative policies. For instance, a subsidy on land use (Warr and Yusuf, 2011), a global carbon tax (Golub et al., 2009), and the effect of macroeconomic policies on land use (Persson and Munasinghe, 1995; Cattaneo, 2001).

An exception to the above limitations is a recent paper investigating deforestation in an optimal control model (Ollivier, 2012). The model presented here builds upon the work of Ollivier through developing general conditions that guarantee unique, endogenous paths of both deforestation and investment as well as including uncertainty. There are two reasons for including uncertainty. First, uncertainty allows the study of compensation under stochastic global carbon prices. Second, as is well established in the broader literature on savings and investment the presence of uncertainty can alter behaviour (Hartman, 1972; Kimball, 1990; Caballero, 1991), and others have shown that productivity shocks change optimal policy (Heutel, 2012). The framework also lends itself to numerical experiments, which are conducted to investigate policy design principles. To investigate these principles the model is calibrated to match the recent experience in Indonesia.

The main findings are as follows. National output growth initially declines under compensation to reduce deforestation, but national income rises due to the inclusion of compensation payments. Compensation for forest stocks reduces deforestation, but is likely too costly to be a feasible option for reducing deforestation. Finally, offering a fixed compensation rate rather than a variable compensation rate further reduces deforestation.

National output declines in the short run for three reasons. First, landholdings are directly reduced by the policy. Second, as compensation raises future incomes the agent receiving compensation partly substitutes savings with compensation. Finally, under the parameterisation used lower landholdings also lower the marginal productivity of capital, further lowering the incentive to invest.

In lowering compensation for each unit of forest removed the compensation rate for forest stocks creates a similar marginal cost to the compensation rate for reduced deforestation. Total compensation will differ; however, since the total area of forests is typically larger than the area of reduced deforestation.

Compensation for forest stocks has been proposed as a way to include, through transferring wealth, countries with historically low deforestation rates (Woods Hold Research Center, 2008). The results of this paper cast doubt on the feasibility of such compensation as a means of reducing deforestation. Where there is a limited pool of funds available for REDD+, as seems likely (Eliasch, 2008) then increasing the area rewarded lowers the price per unit of reduced deforestation and hence the marginal cost of deforestation. An alternative means of including countries with good historical environmental management is suggested: setting a baseline for reduced deforestation higher than what the agent would deforest in the absence of policy. This policy option rewards historically good environmental management through a transfer of wealth: a higher compensation rate means the agent could deforest as much as the agent would have in the absence of a policy and still receive compensation. Further, total compensation is typically lower with inflated baselines than under forest stock compensation, permitting a higher payment per unit of reduced deforestation.

Finally, reducing uncertainty in compensation payments can reduce further deforestation. With convex marginal utility the possibility of a low compensation rate affects behaviour greater than the possibility of a high compensation rate. Thus the expected value to the agent of future uncertain compensation is less than the value of certain compensation.

2 Model

In this section, a model of economic growth with endogenous deforestation and avoided deforestation policy is developed.

An economic *agent* enjoys consuming a single good. The agent has two assets: *income* $y \in (0, \infty)$ and *productive land* $\ell \in [0, L]$, $L \in \mathbb{R}_{++}$. L is the total amount of land in the economy, with remaining area, $L - \ell$, forested.[2] The *state space* is $S := (0, \infty) \times [0, L]$, with typical element (y, ℓ).

Through its two actions the agent accumulates income and productive land over time. Production generates next period's income and deforestation generates next period's landholdings. The production technology g employs land and capital as inputs. Invested income determines next period's capital. Denote *investment* by k, which is non-negative and cannot exceed income, so that the feasible investment set is $[0, y]$. Capital is depreciated at the rate $\delta \in [0, 1]$ per period.

This period's *consumption* levels are equal to income net of investment, $c := y - k$. The agent's preference over consumption levels is represented by $\mathbb{R}_+ \ni c \mapsto u(c) \in \mathbb{R}$.

Assumption 1. *u is bounded, strictly increasing, strictly concave, differentiable, has $u(0) = 0$, satisfies $\lim_{c \downarrow 0} u_C = +\infty$.*[3]

Land is accumulated through *deforestation*, d. Next period's productive landholdings are equal to current landholdings plus deforestation, $\ell' = \ell + d$.[4] Deforestation is costly as the process involves clearing forests and preparing land for production. Deforestation effort comes at an increasing convex cost per unit of deforestation, with the effort cost being $[0, L] \ni d \mapsto h(d) \in \mathbb{R}_+$.

Assumption 2. *h is bounded, increasing, strictly convex and differentiable on $[0, L]$*

The sum of consumption utility and deforestation effort defines the agent's per period *reward function* $S \times [0, y] \times [0, L] \ni (y, \ell, k, \ell') \mapsto r(y, \ell, k, \ell') \in \mathbb{R}$.

$$r(y, \ell, k, \ell') := u(y - k) - h(\ell' - \ell) \tag{1}$$

Investment and next period's land generate next period's output using technology $S \ni (k, \ell') \mapsto g(k, \ell') \in \mathbb{R}_+$, which follows assumption 3. Production is augmented multiplicatively by a *productivity shock* $\chi \sim \mu_\chi$ where μ_χ is a distribution on $\mathbb{R}_{++}$.

Assumption 3. *g is increasing and concave in both arguments, continuously differentiable and satisfies $g(0, \ell') = g(k, 0) = 0$.*

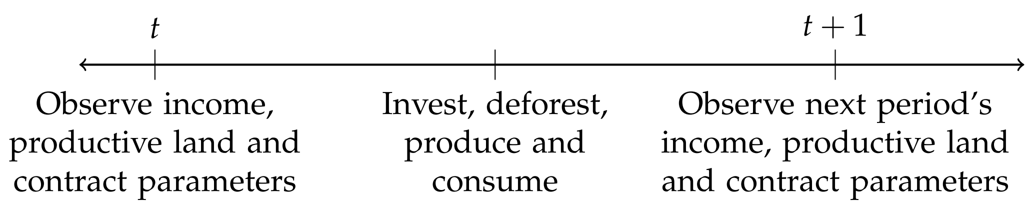
[2]Throughout this paper, 'land' or 'landholdings' will refer to land used in production. Forested land will be explicitly stated as such.

[3]Subscripts throughout the paper refer to derivatives.

[4]Apostrophes refer to the subsequent period, with double apostrophes referring to two periods hence.

Deforestation adversely affects an exogenous *foreign-agent*. Aware the (domestic) agent has no incentive to incorporate the foreign-agent's preferences and reduce deforestation the foreign-agent offers a compensation contract for reduced deforestation to the agent. This structure reflects the nature of REDD+ policy: reduced deforestation is being undertaken in tropical nations, and typically funded by foreign nations. Compensation for today's reduced deforestation is received by the agent as part of next period's income. The timing of the agent's actions is presented in figure 1.

Figure 1: Timing of the model



The compensation contract is composed of two components: compensation for reductions in deforestation rates and compensation for levels of forest stocks held.

Definition 1. *For any level of deforestation d, and forested landholdings held after deforestation $L - \ell - d$, a* compensation contract for reduced deforestation *consists of a tuple $(\rho, \lambda, \phi, \mu_\rho, \mu_\phi)$, where*

- *$\rho \cdot (\lambda - d)$ is the compensation for reduced deforestation:*
  - *μ_ρ is a distribution on $\mathbb{R}_+$*
  - *$\rho \sim \mu_\rho$ is the reduced deforestation compensation rate; and*
  - *$\lambda \in \mathbb{R}_+$ is a reference level.*
- *$\phi \cdot (L - \ell - d)$ is the compensation for forests stocks:*
  - *μ_ϕ is a distribution on $\mathbb{R}_+$*
  - *$\phi \sim \mu_\phi$ is the forest stock compensation rate.*
- *$\rho \cdot (\lambda - d) + \phi \cdot (L - \ell - d)$ is the total compensation payment.*

The two components of the compensation contract are composed of a price and a quantity. The reduced deforestation compensation rate $\rho \in \mathbb{R}_+$ is the price paid per unit of deforestation reduced over the one period life of the policy. Credited emissions reductions can potentially be sold on carbon markets (Eliasch, 2008; Angelsen et al., 2009), so ρ represents the carbon per unit area. Since there will be uncertainty over future carbon prices, uncertainty in the realised compensation rate is permitted by assuming that ρ is generated by a distribution μ_ρ on $\mathbb{R}_+$.

To generate a quantity of reduced deforestation, realised deforestation is compared to a reference level, $\lambda \in \mathbb{R}_+$. The reference level, otherwise known as a baseline or target, mimics what the deforestation level would have been in the absence of compensation. In practice, this counterfactual is difficult to forecast. With a numerical model, this counterfactual can be precisely established; however, this is not done for two reasons. First, while existence of the agent's optimal deforestation level can be ensured where the reference level is set to the counterfactual, uniqueness of the optimal deforestation level cannot.[5] As the focus in this paper is the level of deforestation over the short to medium term, uniqueness of the model generated deforestation level is a crucial property. Second, practical implementation of a REDD+ mechanism will involve choosing some reference level (Griscom et al., 2009; Corbera et al., 2010). The consequences of altering reference levels in practice can be investigated through allowing reference levels to vary in numerical experiments. Since REDD+ is intended to make nations no worse off, throughout this paper the reference level will be assumed to be greater than deforestation in the absence of a policy.

The second component of the policy is compensation for forest stocks. Total compensation for forest stocks is again composed of a price and quantity. The price is the forest stock compensation rate $\phi \in \mathbb{R}_+$, the payment per unit of forest remaining. The forest stock compensation rate, ϕ is a random variable with distribution μ_ϕ on $\mathbb{R}_+$. The quantity is the area of forest stocks held after deforestation $L - \ell - d$. Total compensation is added to next period's output and un-depreciated capital to form next period's income.

Next period's state is generated by the vector valued *transition function* $\mathbb{R}_{++} \times \mathbb{R}_+^2 \times [0, y] \times [0, L]^2 \ni (\chi, \rho, \phi, \ell, k, \ell') \mapsto H(\chi, \rho, \phi, \ell, k, \ell') \in S$ for any $(y, \ell) \in S$.

$$H(\chi, \rho, \phi, \ell, k, \ell') := \begin{pmatrix} \chi \cdot g(k, \ell') + k \cdot (1 - \delta) + \rho \cdot (\lambda + \ell - \ell') + \phi \cdot (L - \ell') \\ \ell' \end{pmatrix} \quad (2)$$

Assume the agent follows a time stationary *policy-function* $S \ni (y, \ell) \mapsto \pi(y, \ell) \in$

[5]Specifically, concavity of the optimal policy-function is required and cannot be ensured. The term 'optimal policy-function' is defined in definition 4.

$[0, y] \times [0, L]$ mapping income and landholdings into investment and next period's landholdings. The policy-function is restricted to be *feasible*, in that any pair of choices for any state (y, ℓ) is contained in $[0, y] \times [0, L]$. Define Π as the *set of feasible policy-functions*.

To simplify the notation, let $\mathbb{R}_{++} \times \mathbb{R}^2_+ =: Z \ni \zeta := (\mu_\chi, \mu_\rho, \mu_\phi)$ be a distribution consisting of the three independent distributions. Further, let z be the triple $z := (\chi, \rho, \phi)$. The *law of motion* is:

$$\begin{aligned}(y_{t+1}, \ell_{t+1}) = H(z_{t+1}, \ell_t, \pi^K(y_t, \ell_t), \pi^L(y_t, \ell_t))\\ (z_t)_{t\geq 1} \overset{\text{i.i.d.}}{\sim} \zeta\\ (y_0, \ell_0) \in S \text{ given}\\ t \in \mathbb{N}_0\end{aligned} \tag{3}$$

Assembling these pieces and given initial state (y, ℓ) and discount rate $\beta \in (0, 1)$, the agent's optimisation problem is to construct a policy-function to maximise the expected, discounted value of following this policy-function.

Definition 2. *The agent's* optimisation problem *is:*

$$\begin{aligned}\max_{\pi\in\Pi} v_\pi(y, \ell), \text{ where}\\ v_\pi(y, \ell) := \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t r(y_t, \ell_t, \pi^K(y_t, \ell_t), \pi^L(y_t, \ell_t))\right]\end{aligned}$$

subject to*:* (3)

where the expectations operator is over ζ. The maximum value of the optimisation problem is the deforestation-growth value function in definition 3.

Definition 3. *The* deforestation-growth value function *is* $v^*(y, \ell) := \sup\{v_\pi(y, \ell) : \pi \in \Pi\}$*, where* v_π *is defined in definition 2.*

The deforestation-growth value function will be obtained by following the optimal policy-function in definition 4.

Definition 4. *A policy-function* $\pi^* \in \Pi$ *is called* optimal *if* $v_{\pi^*} = v^*$ *for each* $(y, \ell) \in S$*.*

The deforestation-growth value function can be shown to follow a Bellman equation.

Proposition 1. *The deforestation-growth value function v^* is increasing and strictly concave on S. The deforestation-growth value function v^* is differentiable on the interior of S. It is the unique function in the set of increasing, strictly concave, bounded functions on S that satisfies:*

$$v^*(y,\ell) = \max_{(k,\ell')\in[0,y]\times[0,L]} \left\{ r(y,\ell,k,\ell') + \beta \int v^*\left(H(z,\ell,k,\ell')\right) \zeta(dz) \right\} \qquad ((y,\ell)\in S) \quad (4)$$

An optimal policy-function π^* exists. π^* is unique, continuous and nondecreasing on S.

Proof. See appendix A.1. □

In the model without a compensation contract for reduced deforestation, both investment and next period's landholdings can be shown to be increasing on the state space.

Proposition 2. *In the model without a compensation contract for reduced deforestation, both investment and next period's landholdings are non-decreasing on the state space. That is, for any (y,ℓ) and $(\hat{y},\hat{\ell})$ with $y \leq \hat{y}$ and $\ell \leq \hat{\ell}$, $\pi^{K*}(y,\ell) \leq \pi^{K*}(\hat{y},\hat{\ell})$ and $\pi^{L*}(y,\ell) \leq \pi^{L*}(\hat{y},\hat{\ell})$.*

Proof. See appendix A.2 □

Under additional restrictions the optimal income and land process as generated by the law of motion (3) has at least one stationary distribution. Let $\mathcal{P}(S)$ be the set of distributions on S and $\mathcal{B}(S)$ denote the Borel sets on S.

Definition 5. *A distribution $\psi \in \mathcal{P}(S)$ is called* stationary *if:*

$$\int \mathbb{1}_B \left[H(\chi, \pi^{K*}(y,\ell), \pi^{L*}(y,\ell)) \mu_\chi(d\chi) \right] \psi^*(y,\ell) = \psi^*(B) \qquad B \in \mathcal{B}(S) \qquad (5)$$

Modify the state space to $\underline{S} := \mathbb{R}_+ \times [\underline{L}, L]$ for $\underline{L} > 0$. This modification ensures sufficient incentive to invest at low landholdings and low income levels. The following assumption will be required:

Assumption 4. *In addition to assumption 3, for all $\ell \in [\underline{L}, L]$, g satisfies:*

- $\int [\chi g(k,\ell) + (1-\delta)k] \; \mu_\chi(d\chi) \leq ak + b$ *for $a \in (0,1)$ and $b < \infty$*
- $\lim_{k\downarrow 0} \int \frac{1}{\beta(\chi g_k(k,\ell) + (1-\delta))} \mu_\chi(d\chi) < 1.$

The first component of assumption 4 is a weak diminishing returns argument, and the second component ensures sufficient incentive to invest at low income and landholdings.

Proposition 3. *On a state space* $\underline{S} := (0,\infty) \times [\underline{L}, L]$*, there exists at least one nontrivial stationary distribution* $\psi^* \in \mathcal{P}(\underline{S})$*.*

Proof. See appendix A.3 □

2.1 First order conditions

The agent chooses investment levels and next period's levels of productive landholdings according to the following conditions:

$$
\begin{aligned}
u_C(y-k) &\geq \beta \int v_Y^*(\chi g(k,\ell') + k\cdot(1-\delta) + \rho\cdot(\lambda+\ell-\ell') + \phi\cdot(L-\ell'),\ell') \\
&\qquad \times (\chi g_K(k,\ell') + 1 - \delta)\zeta(dz) \\
h_L(\ell'-\ell) &\geq \beta \int v_Y^*(\chi g(k,\ell') + k\cdot(1-\delta) + \rho\cdot(\lambda+\ell-\ell') + \phi\cdot(L-\ell'),\ell') \\
&\qquad \times (\chi g_L(k,\ell') - \rho - \lambda) + v_L^*\,\zeta(dz) \\
v_Y^*(y,\ell) &= u_C(y-k) \\
v_L^*(y,\ell) &= h_L(\ell'-\ell) \\
&\qquad + \beta \int v_Y^*(\chi g(k,\ell') + k\cdot(1-\delta) + \rho\cdot(\lambda+\ell-\ell') + \phi\cdot(L-\ell'),\ell')\rho\,\zeta(dz)
\end{aligned}
$$

These form the intertemporal conditions which hold with equality on the interior of S. These conditions imply consumption is increasing in income levels.

Proposition 4. *Optimal consumption* $c(y) := y - \pi^{K*}(y,\ell)$*, is increasing in income levels. That is,* $y \leq y'$ *implies* $c(y) \leq c(y')$

Proof. See appendix A.4 □

As a benchmark, assume no compensation payments are made.[6] Along the interior of the state space the first order conditions are:

$$u_C(y-k) = \beta \int u_C\left(\chi g(k,\ell') + k\cdot(1-\delta) - k'\right)\left(\chi g_K(k,\ell') + 1 - \delta\right)\mu_\chi(d\chi) \tag{7a}$$

$$h_L(\ell'-\ell) = \beta \int u_C\left(\chi g(k,\ell') + k\cdot(1-\delta) - k'\right)\chi g_L(k,\ell') + h_L(\ell''-\ell')\,\mu_\chi(d\chi) \tag{7b}$$

[6]For example by letting the distributions on compensation rates satisfy $\mathbb{P}\{\rho = 0\} = \mathbb{P}\{\phi = 0\} = 1$.

The agent's capital investment decision (7a) equates the marginal cost of investment in terms of foregone current consumption to the expected, discounted marginal benefit. The marginal benefit stems from the additional consumption an additional unit of invested capital generates.

Landholdings influence investment through the production technology g. Higher landholdings increase output and decrease the marginal utility of consumption (see assumption 3 and proposition 4). The net effect of landholdings on investment depends on how landholdings change the marginal productivity of capital. Where higher landholdings decrease the marginal productivity of capital, then higher landholdings unambiguously decrease investment. Where higher landholdings increase the marginal productivity of capital the effect is ambiguous.

The optimal land decision (7b) balances this period's marginal deforestation effort cost with next period's discounted, expected marginal benefit. Next period's marginal benefit is the sum of the benefit of an additional unit of land and the reduction in next period's deforestation effort cost. Next period's marginal effort cost is reduced because the more the agent clears today, the less the agent needs to clear tomorrow to hold any level of landholdings two periods from now.

2.1.1 Inter-temporal conditions: compensation for reduced deforestation

The effect of a compensation contract for reduced deforestation on optimal decisions is now investigated. Along the interior of the state space the first order conditions are:

$$\begin{aligned} u_C(y-k) \geq \beta \int & u_C\left(\chi g(k,\ell') + k\cdot(1-\delta) + \rho\cdot(\lambda+\ell-\ell') + \phi\cdot(L-\ell') - k'\right) \\ & \times \left(\chi g_K(k,\ell') + 1 - \delta\right)\,\zeta(dz) \end{aligned} \tag{8a}$$

$$\begin{aligned} h_L(\ell'-\ell) \geq \beta \int & u_C\left(\chi g(k,\ell') + k\cdot(1-\delta) + \rho\cdot(\lambda+\ell-\ell') + \phi\cdot(L-\ell') - k'\right) \\ & \times \left(\chi g_L(k,\ell') - \rho - \phi\right) + h_L(\ell''-\ell') + \beta \int \Big[u_C\big(\chi' g(k',\ell'') \\ & + k'\cdot(1-\delta) + \rho'\cdot(\lambda+\ell'-\ell'') + \phi'\cdot(L-\ell'') - k''\big)\rho'\,\zeta(dz')\Big]\,\zeta(dz) \end{aligned} \tag{8b}$$

The policy affects the investment decision (8a) in two ways. First, by design compensation (weakly) increases future income. As consumption is increasing in income (see proposition 4), compensation lowers the marginal utility of future consumption and the incentive to invest. Intuitively the agent's need to withhold income to save is reduced because reducing deforestation and maintaining forest stocks is a form of saving. Second, the reduction in landholdings changes the marginal productivity of capital. Where the marginal productivity of capital is strictly increasing in landholdings, compensation unambiguously reduces the short term incentive to accumulate capital relative to a world without compensation. This result is stated as a proposition, with the superscript R denoting states and actions under Reduced deforestation policy.

Proposition 5. *Let the payments for reduced deforestation fully compensate income losses, so that* $y' < y^{R'}$. *Where the marginal productivity of capital is increasing in landholdings the introduction of compensation for reduced deforestation will reduce investment in the first period. That is,* $0 \leq g_{KL}$ *implies* $k^R \leq k$.

Proof. See appendix A.5. □

Compensation for either reduced deforestation or forest stock lowers the marginal benefit of an additional unit of deforestation (8b). Where increasing the compensation rate increases next period's income the effect of increasing either compensation rate will be moderated by a declining marginal utility of consumption by proposition 4. The reference level also influences behaviour through next period's income. Again by proposition 4, increasing the reference level lowers the marginal utility of consumption.

Compensation for reduced deforestation has an additional effect of increasing the marginal benefits of clearing land, $\beta^2 \int \int u'_C \rho' \; \zeta(dz') \; \zeta(dz)$. To see how this counterintuitive effect arises, note that set of next period's landholdings that receives compensation (including zero compensation) for reduced deforestation is the interval from no land to the sum of the reference level and next period's landholdings, $[0, \lambda + \ell']$. Increasing next period's landholdings increases the upper bound of this set in the following period. Deforestation today raises allowable landholdings two periods from now that still receives compensation for reduced deforestation.

3 A numerical investigation of deforestation and economic growth in Indonesia

The effects of policy parameters are investegated numerically through fitted value iteration.[7] The model is calibrated to match the recent experience in Indonesia. Indonesia is a relevant country for two reasons. First, Indonesia is the second largest source of emissions from land-use, land-use change and forestry (FAOSTAT, 2013). Second, Indonesia is already receiving compensation for reducing deforestation (Solheim and Natalegawa, 2010; Tollefson, 2009; Brockhaus et al., 2012; Sloan et al., 2012).

3.1 Calibration

Assumption 5 shows the functional forms and assumption 6 shows the benchmark parameter values used in this analysis. The production function's parameters are chosen to match Indonesian data over 2006–2010, and the deforestation effort cost function and utility functions are calibrated so that the model matches recent deforestation and income accumulation rates.

Assumption 5.

$$u(c) = 1 - e^{-\theta c}$$

$$g(k, \ell) = Ak^{\alpha}\ell^{\eta}$$

$$h(d) = Bd^{\psi}$$

Assumption 6.

θ	β	μ_χ	A	α
0.85	*0.962*	$\mathbb{P}(\chi = 1.0) = 1$	*2.35*	*0.503*

η	δ	B	ψ	L
0.02	*0.11*	*0.04*	*2.0*	*5.4*

The units of output and income are in 100 trillions of year 2000 Indonesian Rupiahs (IDR_{2000}). Land is in 100,000 square kilometres, which is slightly larger than a fifth of

[7]Based on (Stachurski, 2008, Algorithm 1), on a grid of size 50 x 50 with a tolerance of 1e^{-5}. This method ensures the approximation converges to the global solution v^*. The routine is implemented using the open source `NumPy`, `SciPy` and `matplotlib` libraries in the `python` language. The procedure relies on a numerical minimiser developed in Byrd et al. (1995). Scripts available upon request.

the Indonesian island of Sumatra. Since land is homogenous in this model the value of land is assumed to be proportional to land area. At an average of 1251.8 tonnes of CO_2 equivalent (tCO_2e) per hectare arising from deforestation in Indonesia (Busch et al., 2012) and using July 1, 2001 exchange rates (XE, 2013), $\rho \approx 8000$ $IDR_{2000}/tCO_2e \approx 0.9$ USD_{2000}/tCO_2e.

The data on capital stocks, GDP and population is taken from van der Eng (2010). Residential capital is excluded from the final amount. The data does not include the value of land or forests, nor does the data contain information on livestock or crop values. Agricultural land use data comes from the World Bank's development indicators (The World Bank, 2013). This data does not include the area under forestry production. The maximum amount of land L is set to the sum of agricultural and forested areas. The initial per capita forested area is 3.97, and with per capita initial landholdings equalling 1.43, L = 5.4 (FAOSTAT, 2013).[8] The output elasticity of land η, is set to 0.02 and the output elasticity of capital α is set to 0.503 (Warr and Yusuf, 2011, table 3). A is calibrated to 2.35. The capital depreciation rate is set to $\delta = 0.11$ (van der Eng, 2009, figure 5). The discount rate is $\beta = 1/1 + r$, where r is the real interest rate and is r is set to 0.04, as the mean of recent years' observations (The World Bank, 2013). θ is calibrated to 0.85, ensuring the model generated income paths match data.

To the author's knowledge, there does not exist any estimates that could be used as parameter values for the deforestation cost function. The cost function is calibrated so the path of deforestation generated by the model replicates the recent path of deforestation, with $\psi = 2.0$ and $B = 0.04$.

A deterministic version of the model (see assumption 7) is used for the bulk of the numerical analysis. As a benchmark the policy rewards reduced deforestation and not forest stocks. To simplify, notation regarding distributions will be dropped.

Assumption 7.

μ_ρ	λ	μ_ϕ
$\mathbb{P}\{\rho = 0.5\} = 1$	*0.042*	$\mathbb{P}\{\phi = 0.0\} = 1$

[8]The data for forested areas is the land under natural or planted stands of trees of at least 5 meters in situ and excludes tree stands in agricultural production systems. For example, in fruit plantations and agroforestry systems

3.2 The counterfactual rate of deforestation

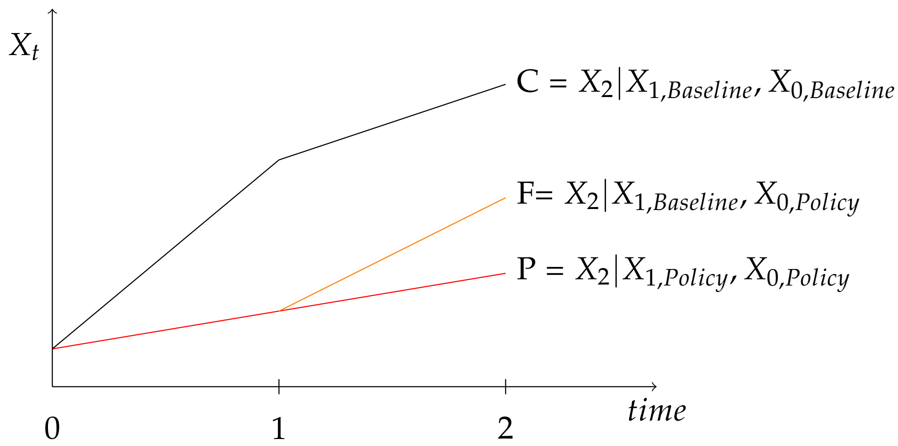
The effectiveness of policy can be assessed through comparing policy outcomes with the outcomes that would have arisen in the absence of a policy (Holland, 1986). In this model, this definition yields multiple measures of effectiveness. Multiple measures arise because this period's reduced deforestation policy affects next period's state. Since optimal actions are state dependent the effectiveness of next period's policy depends on policy this period. This path dependency of policy needs to be accounted for in assessing the effectiveness of policy over time.

The structure suggests a need to distinguish between two types of outcomes to measure the effectiveness of reduced deforestation policy; outcomes after one period need to be distinguished from outcomes after multiple periods. Where a policy is implemented for one period, some measure of the outcome under policy and the counterfactual outcome yields the effectiveness of the policy. Term this the *one period* counterfactual. In the next period, let the path with a compensation contract for reduced deforestation undertake another contract. The one period counterfactual is also required to assess the effectiveness of the policy in this second period. Another relevant question is how well reduced deforestation has performed over its lifetime. After two periods the counterfactual whereby no reduced policy was implemented in either period is required to assess the effectiveness of the policy implemented in both periods. Term this the *trajectory* counterfactual.

The idea is illustrated in figure 2. Here, X_t is the outcome variable of interest at time t. For instance, a change in agricultural land. Outcome C is the counterfactual trajectory, where there is no policy in either period. Outcome P is where a policy has been implemented for two periods. Outcome F is the path where the policy is undertaken only in the first period. There are two relevant counterfactuals when assessing outcomes at $t = 2$. First the one period effect is some measure of the distance between F and P. In addition the trajectory effect is some measure of the distance between P and C.

These different counterfactuals reflect different objectives in reduced deforestation policy. One objective is to reduce deforestation over the life of an agreement. For example, this short run objective is required to implement baselines and reward emissions reductions. The one period counterfactual corresponds to this short run objective. Another objective is the stock of forests in the longer run, which in part determines the total amount of emissions released. The trajectory counterfactual corresponds to this long run objective.

Figure 2: The two types of counterfactuals present in intertemporal policy.



Statistics for the two types of effectiveness measures are constructed as follows. Given an initial condition $(y_0, \ell_0) \in S$ and optimal policy π^*, (3) generates sequences of income and landholdings both with and without policy. Distinguish sequences with a policy by the superscript R.

$$\Delta^i(n, \ell_0, y_0, (\rho, \lambda, \phi, \mu_\rho, \mu_\phi)) = 100 \cdot \frac{i_n - i_n^R}{i_n - i_0} \qquad \text{subject to (3)} \tag{10}$$

for $i \in \{\ell, y\}$. This measure is trajectory reduced deforestation (output) at time n. The one period reduced deforestation (output) is (10) with $n = 1$. The steady state reduced deforestation is a special case of (10) as $n \to \infty$.

To measure how compensation changes over time, compensation payments as a proportion of counterfactual output is used.

$$\Xi(n, \ell_0, y_0, (\rho, \lambda, \phi, \mu_\rho, \mu_\phi)) = 100 \cdot \frac{\rho(\lambda + \ell_{n-1}^R - \ell_n^R) + \phi(L - \ell_n^R)}{y_n} \qquad \text{subject to (3)} \tag{11}$$

3.3 Results

The section will present results on the effects of varying reduced deforestation policy parameters. The initial state is equal to 2010 values, (y_0, ℓ_0) = (24.608, 1.427).

3.3.1 Varying the reduced deforestation compensation rate, ρ

The compensation rates investigated are $\rho \in \{0.3, 0.5, 0.7\}$. Table 1 shows compensation for reduced deforestation works as desired: a compensation rate of $\rho = 0.3$ reduces deforestation by approximately 24 per cent in the first period. Increasing the compensation rate from 0.3 to 0.7 reduces deforestation by a further 34 per cent. After ten years, reduced deforestation with $\rho = 0.3$ is approximately 20 per cent. A higher compensation rate decreases deforestation at any point in time, but the effect of increasing the compensation rate diminishes over time.

Table 1: The effect of varying the compensation rate ρ on landholdings and output. The figures in cells are reductions in deforestation (output) as defined in (10): $\Delta^i(n, 24.608, 1.427, (\rho, 0.042, 0.0))$ for $i \in \{\ell, y\}$. All other parameters follow assumption 6.

		n			
	ρ	1	3	5	10
Land	0.3	23.9	22.2	21.3	20.2
	0.5	42.1	38.3	36.3	33.8
	0.7	68.3	53.7	51.7	48.2
Output	0.3	0.9	0.8	0.5	0.3
	0.5	1.6	0.8	0.3	0.3
	0.7	2.5	1.0	0.6	0.4

Output immediately declines due to the policy, as implied by proposition 5. For the investigated compensation rates, output reductions after one period range between 0.9 and 2.5 per cent. After ten years, output reductions across the compensation rates investigated are within 0.1 per cent of each other. This convergence to counterfactual trajectory output implies annual output growth is greater than the counterfactual after the first period. The process driven by reinvesting received compensation as manufactured capital.

Table 2 shows how total compensation paid as a proportion of trajectory counterfactual output changes with compensation rates. Compensation rates can be expected to increase total compensation paid by both increasing the per unit payment and inducing more deforestation. In the first period, compensation is approximately 7 per cent of national output with $\rho = 0.3$. A compensation rate $\rho = 0.7$ results in total compensation payments of around 22 per cent of total output.

To put these numbers in context, the Norway-Indonesia moratorium provided USD 1 billion for forest reduction efforts (Solheim and Natalegawa, 2010; Sloan et al., 2012). For comparison, assume this is solely for the initial two-year moratorium on new licenses for forest lands.[9] Under this scenario, total compensation is equivalent to 0.08 per cent of national output.

Table 2: The effect of varying the compensation rate ρ on total compensation paid as a proportion of trajectory counterfactual output. The figures in cells are the compensation as a percentage of counterfactual output as defined in (11): $\Xi(n, 24.608, 1.427, (\rho, 0.042, 0.0))$. All other parameters follow assumption 6.

	n			
ρ	1	3	5	10
0.3	6.9	7.3	7.6	8.0
0.5	13.8	13.6	13.8	13.8
0.7	22.1	21.1	21.2	20.4

3.3.2 Varying the reference level, λ

The reference levels investigated are $\lambda \in \{0.042, 0.046, 0.05\}$, all of which exceed deforestation levels along any benchmark path. The changes in deforestation and output for various reference rates are presented in table 3.

Table 3: The effect of varying the reference level λ on landholdings and output. The figures in cells are reductions in deforestation (output) as defined in (10): $\Delta^i(n, 24.608, 1.427, (0.5, \lambda, 0.0))$ for $i \in \{\ell, y\}$. All other parameters follow assumption 6.

		n			
	λ	1	3	5	10
Land	0.042	42.1	38.3	36.3	35.8
	0.046	42.3	38.5	36.7	34.5
	0.050	42.7	39.0	37.1	34.9
Output	0.042	1.6	0.8	0.3	0.3
	0.046	1.7	0.9	0.6	0.4
	0.050	2.0	0.8	0.4	0.4

Increasing the reference level reduces both deforestation and output. An increase in the reference level from $\lambda = 0.042$ to $\lambda = 0.050$ reduces deforestation by 0.6 per cent. Over time the effect of increasing the reference level on output diminishes. This effect arises because compensation is reinvested as capital. Table 4 shows compensation increasing from 14 to 18 per cent of benchmark output.

[9] To be clear, this is not the case.

Table 4: The effect of varying the reference level λ on total compensation paid as a proportion of trajectory counterfactual output. The figures in cells are the compensation as a percentage of counterfactual output as defined in (11): $\Xi(n, 24.608, 1.427, (0.5, \lambda, 0.0))$. All other parameters follow assumption 6.

λ	1	3	5	10
0.042	13.8	13.6	13.8	13.8
0.046	15.9	15.6	15.8	15.6
0.050	18.1	17.7	17.7	17.5

3.3.3 Varying the forest stock compensation rate, ϕ

Without any precise information on the value of non-market assets within forests relative to the value of carbon the forest stock compensation rate is set as one-hundredth of the reduced deforestation rate. That is, $\phi \in \{0.003, 0.005, 0.007\}$. The values are admittedly ad hoc; however, the underlying story is robust to changes in the forest stock compensation rate.

Table 5: The effect of varying the forest stock compensation rate ϕ on landholdings and output. The figures in cells are proportional deforestation rates (and output) as defined in (10): $\Delta^i(n, 24.608, 1.427, (0.5, 0.042, \phi))$ for $i \in \{\ell, y\}$. All other parameters follow assumption 6.

		n			
	ϕ	1	3	5	10
	0.000	42.1	38.3	36.3	33.8
Land	0.003	44.4	40.7	38.8	36.4
	0.005	56.0	42.2	40.3	37.9
	0.007	57.5	43.6	41.8	39.4
	0.000	1.6	0.8	0.3	0.3
Output	0.003	2.6	1.0	0.6	0.2
	0.005	3.7	1.4	0.9	0.3
	0.007	4.5	1.7	1.0	0.5

Including compensation for forest stocks decreases deforestation (see table 5). In the absence of stock compensation, proportional deforestation is 42 per cent. At a forest stock compensation rate rate $\phi = 0.003$, deforestation reduced is 44 per cent. Increasing the compensation rate to $\phi = 0.007$ reduces the change in landholdings by a further 2.5 per cent.

This reduced deforestation from forest stock compensation comes at a large price. With a reduced deforestation compensation rate of 0.5 and a zero forest stock compensation rate, total compensation was equivalent to 14 per cent of benchmark output (see table 6). For slightly more than a further 2 per cent of reduced deforestation, total compensation payments rise by 12 per cent of benchmark output. This is because payments are made based on the size of forest stock, which is large relative to the area of reduced deforestation.

Table 6: The effect of varying the stock compensation rate ϕ on total compensation paid as a proportion of trajectory counterfactual output. The figures in cells are the compensation as a percentage of counterfactual output as defined in (11): $\Xi(n, 24.608, 1.427, (0.5, 0.042, \phi))$. All other parameters follow assumption 6.

ϕ	1	3	5	10
0.000	13.8	13.6	13.8	13.8
0.003	26.0	25.2	24.9	23.9
0.005	34.1	32.9	32.2	30.6
0.007	42.3	40.6	39.6	37.3

3.3.4 Stochastic productivity levels and compensation rates

Uncertainty in compensation rates will arise if the long term aim of linking REDD+ with global carbon markets is realised (Eliasch, 2008; Angelsen et al., 2009). In this world the foreign-agent has an additional option in contract design: offering a fixed compensation rate, or a variable compensation rate tied to uncertain carbon prices.

There are two channels through which the optimal policy-function with variable compensation could differ from the optimal policy-function with fixed compensation. First, the expected values of productivity shocks and variable compensation rates could differ from the deterministic values. This possibility is removed by setting the expected values in this section equal to the deterministic values in assumption 7. A second channel operates through an asymmetric value of the shocks to the agent. This occurs where future benefits of deforestation are non-linear, as in the Euler equation (8).

The parameterisation is kept simple, as the qualitative result is of interest. Let random variables of productivity levels and compensation rates equal $\chi = \hat{\chi} \cdot x$ and $\rho = \hat{\rho} \cdot r$. The distributions of x and r follow assumption 8. The values for $\hat{\chi}$ and $\hat{\rho}$ follow the values used in the investigation of the deterministic system, as found in assumption 7. All other parameters follow assumptions 6 and 7.

To investigate the effect of removing uncertainty from compensation, empirical cumulative distribution functions are presented. The empirical cumulative distribution function, taken from 10,000 observations of the stochastic law of motion (3) after five

Table 7: Distribution parameters

Assumption 8.

μ_x	μ_r	μ_ϕ	σ_x	σ_r
$\ln\mathcal{N}\big(-\sigma_x^2/2, \sigma_x\big)$	$\ln\mathcal{N}\big(-\sigma_r^2/2, \sigma_r\big)$	$\mathbb{P}\{\phi = 0.0\} = 1$	*0.1*	*0.1*

years. For any value of landholdings ℓ, the distribution function $F_n(\ell)$ tells the proportion of observations that had landholdings less than ℓ.

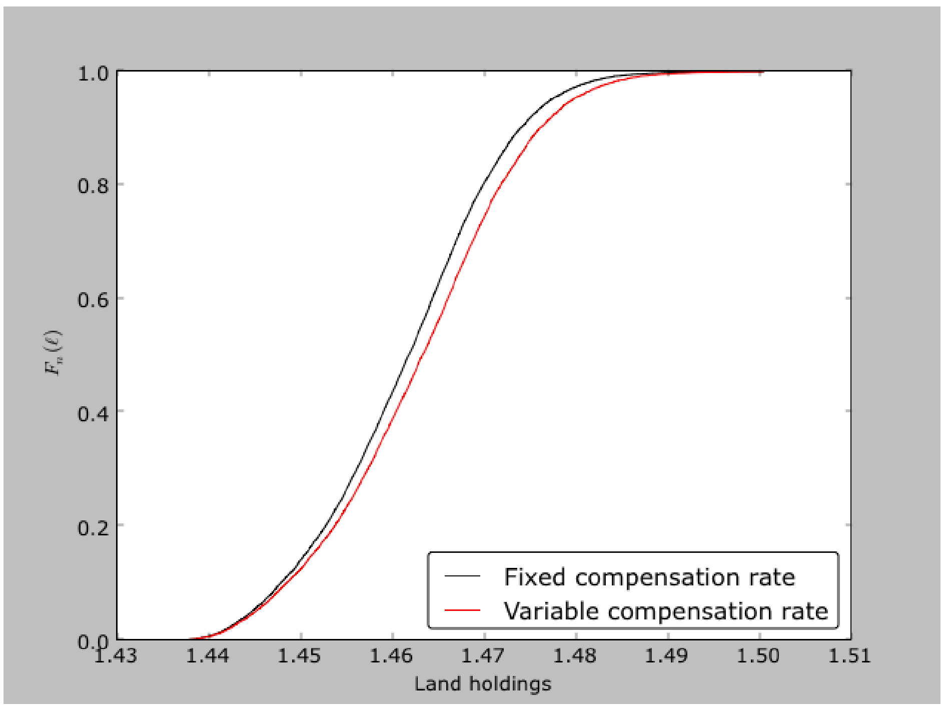


Figure 3: The empirical cumulative distribution functions of landholdings after five years with compensation for reduced deforestation. Compensation levels are either deterministic (fixed) or stochastic (variable). Parameters are as in assumptions 6 and 8, with deterministic compensation rates having μ_ρ satisfy $\mathbb{P}\{\rho = 0.3\} = 1$. The empirical cumulative distribution functions are calculated using 10,000 observations from the stochastic recursive sequence (3).

The estimated distribution functions for landholdings are presented in figure 3. The figure shows landholdings under the fixed compensation rates are more likely to be lower than landholdings under variable compensation rates. That is, more deforestation is reduced with a fixed compensation rate. Greater reductions in deforestation occur because under variable compensation and convex marginal utility, lower compensation rates influence behaviour by more than higher compensation rates. This is a manifestation of a more general phenomenon known as prudence (Kimball, 1990).

4 Conclusion

I develop a general model for investigating the interaction between deforestation, reduced deforestation policy and economic growth. The model permits many different assumptions about functional form, whilst still guaranteeing a unique path of deforestation. Conditions are established under which the model exhibits monotonocity of optimal actions and stationary distributions of state variables. A numerical investigation using Indonesian data generates additional insights into design principles of reduced deforestation policy.

There are three main results. First, where capital and land are complimentary in production, policy causes output to decline in the first period of the policy. Second, compensation for forest stocks also reduces deforestation, but is unlikely to be feasible due to high total compensation payments. Finally, that fixed compensation rates reduce more deforestation than variable compensation rates.

Where land and capital are complimentary in production, policy causes a decline in output growth for three reasons. First because lowering landholdings directly lowers output. Second, compensation for reduced deforestation increases future income. As consumption is increasing in income (see proposition 4), increasing compensation lowers the marginal benefit of an additional unit of invested capital. Finally, the marginal productivity of capital declines where capital and landholdings are complementary in production.

The reduced deforestation compensation rate drives most of the reduced deforestation. Altering the reference level for deforestation rates reduces deforestation; however, the magnitude is small. Compensation of forest stocks also creates a small incentive not to deforest. This reduction is costly, an additional 2 per cent reduction in deforestation increases total compensation paid by 12 per cent of benchmark national production. This increase arises because forest stocks are large relative to the area of deforestation reduced.

Stock compensation rates have been suggested as a way to include countries with historically low deforestation rates, and high forest stock holdings (Cattaneo, 2008, 2009). Since these countries by definition have large areas of forest, compensation for forest stocks will be more costly. With a limited pool of funds, as is likely with a REDD+ mechanism (Eliasch, 2008), increasing the quantity of forest rewarded lowers the payment per unit land rewarded. This lowers both the transfer of funds to each nation and the incentive to avoid deforestation.

The results in the paper suggests a lower cost alternative to include countries with low deforestation rates. By increasing the reference level, countries with historically low deforestation rates can still receive a transfer for historically good performance. As total quantities rewarded are lower under this proposal, a higher payment per unit deforestation avoided can be offered with a limited pool of funds. This higher payment creates a higher incentive to reduce deforestation.

Including uncertainty into production and compensation rates offers an additional option for the policy-maker, who could offer a contract with either fixed compensation rates, or with variable compensation rates tied to a global carbon price. I find that the estimated probability of having lower landholdings is greater under fixed compensation rates than under variable compensation rates. This occurs because the agent has convex marginal utility. Under this condition the agent places more weight on low compensation rates than higher compensation rates. This final result shows that removing uncertainty in compensation rates can further reduce deforestation.

The framework in this paper provides a base for future research along two lines. First, the model could be extended to include seemingly relevant factors like labour markets and rural-urban migration (Merry et al., 2008). Second, the base framework with an endogenously growing agricultural and capital sector could provide insights into structural change (Moro, 2012), or 'unified growth theory' (Galor, 2011), where the research agenda is to build a growth model capable of explaining the transition from pre to post industrial revolution growth.

A Reduced deforestation and economic growth

In this section, proofs of the propositions presented in the body of the chapter on growth are presented. Lemmas required to complete the proofs of these propositions follow in section B.

A.1 Proof of proposition 1

Proof. To begin, recall the *state space* $S := (0, \infty) \times [0, L]$. It will be useful to define the two dimensions of the state as $S^Y := (0, \infty)$ and $S^L := [0, L]$. Define the *action space* as $X := S$, with (k, ℓ') a typical element of X. Let $S \ni (y, \ell) \mapsto Y(y, \ell) = [0, y] \times S^L \subset X$ be the *feasible action correspondence* mapping the state into feasible actions.

Recall the *reward function* (1). By assumptions 1 and 2 the reward function is strictly concave, continuously differentiable and bounded on the *set of feasible state-action pairs*, $\text{gr}Y := \{(y, \ell, k, \ell') \in S \times X : (k, \ell') \in Y(y, \ell)\}$; increasing on S for all $(k, \ell') \in Y(y, \ell)$.

With assumption 3 the *transition function* (2) is differentiable, continuous and concave on $\text{gr}Y$ for all $z \in Z$, and strictly increasing on S for all $(k, \ell') \in Y(y, \ell)$, $z \in Z$.

The feasible correspondence Y yields values in a closed and bounded subset of $\mathbb{R}^2$ and thus is compact valued by the Heine-Borel theorem (Stachurski, 2009, Theorem 3.2.19). To show that the feasible correspondence is continuous, note that if $p(y, \ell) = (0, 0)$ and $q(y, \ell) = (y, L)$, then p and q are both continuous functions. Since $Y = \{(k, \ell') \in X : p(y, \ell) \leq (k, \ell') \leq q(y, \ell)\}$, Y is a continuous correspondence by lemma 2 in appendix B. Finally the state space and the set of feasible state-action pairs are a convex sets.

Now, let $\mathcal{C}icbS$ be the set of concave, increasing, continuous and bounded functions on S and endow this space with the sup-norm d_∞.

Definition 6. *For $w \in \mathcal{C}icbS$, define the* Bellman operator $T : \mathcal{C}icbS \to \mathcal{C}icbS$ *as:*

$$Tw(y, \ell) = \max_{(k, \ell') \in Y(y, \ell)} \left\{ r(y, \ell, k, \ell') + \beta \int w\big(H(z, k', \ell, \ell')\big)\zeta(dz) \right\} \qquad ((y, \ell) \in S) \tag{12}$$

Definition 7. *Given $w : \mathcal{C}icbS \to \mathbb{R}$, a policy-function $\pi \in \Pi$ is w-*greedy *if:*

$$\pi(y, \ell) \in \underset{(k, \ell') \in Y(y, \ell)}{\arg\max} \left\{ r(y, \ell, k, \ell') + \beta \int w\big(H(z, \ell, k', \ell')\big)\zeta(dz) \right\} \qquad ((y, \ell) \in S)$$

By Stachurski (2009, Theorem 12.1.12), v^* is the unique fixed point of T, that $v^* \in \mathcal{C}icbS$ and that it is the unique function in $\mathcal{C}icbS$ that satisfies equation 4. Further, there exists a v^*-greedy policy-function π^*. By Stachurski (2009, Lemma 10.1.21), a v^*-greedy policy-function is optimal as defined in 4.

That v^* is strictly concave can be ensured (Stachurski, 2009, Exercise 12.1.13). Since there exists an optimal policy-function, and that v^* is strictly concave, there is at most one optimal policy-function (Sundaram, 1996, Theorem 7.14). An application of Berge's theorem (Stachurski, 2009, Theorem B.1.3) of the maximum ensures the continuity of the policy-function $\pi^* := \arg\max_{(k,\ell')\in Y(y,\ell)} v^*$ on S.

□

A.1.1 Proof of differentiability

The proof in this section is based on Stachurski (2009, Propositions 12.1.17, 12.1.18). The value function is defined on two dimensions: income and land. The proofs in this section will prove differentiability in the income, then the land dimension.

Income For $w \in \mathcal{C}icbS$, define J_Y as

$$J_Y(y,k) := u(y-k) - h(\ell' - \ell) + \beta \int w[\chi g(k,\ell') + \rho \cdot (\lambda + \ell - \ell') + \phi \cdot (L - \ell') + k \cdot (1-\delta), \ell']\zeta(dz)$$

Where $y > 0$ and $k < y$ by lemma 1, for any $(\ell', \ell) \in S^L \times S^L$. Replacing W in Stachurski (2009, Proposition 12.1.18) with J_Y and following through with the rest of the proof of Proposition 12.1.18 yields:

$$(Tw)_Y(y,\ell) = u_C(y - \pi^K(y,\ell))$$

Land It will be shown that the value function is differentiable on the interior of the land dimension, $\text{int}(S^L)$. Obtaining differentiability in the land dimension uses the same idea as above, but is slightly different.

Let

$$J_L(\ell,\ell') := u(y-k) - h(\ell' - \ell) + V(\ell,\ell')$$

Where $\ell \in \text{int}(S^L)$, for any $(y,k) \in \text{gr}Y$ and

$$V(\ell,\ell') := \beta \int w[y',\ell']\mu_\chi(d\chi)$$

where $y' = \chi g(\pi^K(y,\ell), \pi^L(y,\ell)) + \rho \cdot (\lambda + \ell - \pi^L(y,\ell)) + \phi \cdot (L - \pi^L(y,\ell)) + \pi^K(y,\ell) \cdot (1-\delta)$

Since $\ell \int \text{int}(S^L)$, there exists an open neighbourhood G of zero with:

$$J_L(\ell+a,\pi^L(y,\ell)) \le Tw(y,\ell+a) = J_L(\ell+a,\pi^L(y,\ell+a)) \qquad \forall a \in G$$

And so,

$$\begin{aligned} Tw(y,\ell+a) - Tw(y,\ell) \ge & J_L(\ell+a,\pi^L(y,\ell)) - J_L(\ell,\pi^L(y,\ell)) \\ = & -h(\pi^L(y,\ell)-\ell-a) + V(\ell+a,\pi^L(y,\ell)) \\ & + h(\pi^L(y,\ell)-\ell) - V(\ell,\pi^L(y,\ell)) \end{aligned}$$

Replace a with a sequence $(a_n) \subset G$, $a_n > 0$ and $a_n \downarrow 0$:

$$\begin{aligned} \frac{Tw(y,\ell+a_n) - Tw(y,\ell)}{a_n} \le & \\ & -\frac{h(\pi^L(y,\ell)-\ell-a_n) - h(\pi^L(y,\ell)-\ell)}{a_n} \\ & + \frac{V(\ell+a_n,\pi^L(y,\ell)) - V(\ell,\pi^L(y,\ell))}{a_n} \qquad \forall n \in \mathbb{N} \end{aligned}$$

Since Tw inherits the concavity of w the right derivative in the land dimension DTw_{L+} exists. Further, V is differentiable in its first dimension by the above result showing the existence of v_Y^*. As $a_n \downarrow 0$ and since limits are preserved under inequalities (Bartle and Sherbert, 2011, Theorem 3.2.5), $DTw_{L+}(y,\ell) \ge -h_L(\pi^L(y,\ell)-\ell) + V_L(\ell,\pi^L(y,\ell))$.

Reversing the procedure by letting $(a_n) \subset G$, $a_n < 0$ and $a_n \uparrow 0$:

$$\begin{aligned} \frac{Tw(y,\ell+a_n) - Tw(y,\ell)}{a_n} \ge & \\ & -\frac{h(\pi^L(y,\ell)-\ell-a_n) - h(\pi^L(y,\ell)-\ell)}{a_n} \\ & + \frac{V(\ell+a_n,\pi^L(y,\ell)) - V(\ell,\pi^L(y,\ell))}{a_n} \qquad \forall n \in \mathbb{N} \end{aligned}$$

We know that the left derivative in the land dimension, DTw_{L-} exists by the concavity of Tw, and that v_Y^* exists. Taking $n \to \infty$ yields $DTw_{L-} \le -h_L(\pi^L(y,\ell)-\ell) + V_L(\ell,\pi^L(y,\ell))$.

That is, $DTw_{L-} \le -h_L(\pi^L(y,\ell)-\ell) + V_L(\ell,\pi^L(y,\ell)) \le DTw_{L+}$; however, by concavity in Tw, $DTw_{L+} \le DTw_{L-}$. Since both the left and right derivatives are equal the following holds on the int(S^L)

$$Tw_\ell(y,\ell) = -h_L + \beta \int u_c \rho \; \mu_\chi(d\chi)$$

Since v^* is the unique fixed point of T in $\mathcal{C}icbS$, $v^* = w^* = Tw^*$ and v^* is differentiable on the interior of S.

A.2 Proof of proposition 2

Proof. Where there is no compensation contract the transition function (2), $H(\chi, \rho, \phi), \ell, \pi^K(y,\ell), \pi^L(y,\ell))$ can be rewritten as $H(\chi, \pi^K(y,\ell), \pi^L(y,\ell))$.

Let (k, ℓ') be the optimal actions at $(y,\ell) \in S$ as defined in definition 4. Likewise, let $(\hat{k}, \hat{\ell}')$ be the optimal actions corresponding to $(\hat{y}, \hat{\ell}) \in S$. Where $\hat{y} > y$ and $\hat{\ell} > \ell$, then $\hat{k} > k$ and $\hat{\ell} > \ell$.

From the definition of the deforestation-growth value function:

$$\begin{aligned}
v^*(y,\ell) &= \max_{(k,\ell') \in \text{gr}Y(y,\ell)} \left\{ r(y,\ell,k,\ell') + \beta \int v^*\big(H(\chi,k,\ell')\big) \; \mu_\chi(d\chi) \right\} \\
&\geq r(y,\ell,\hat{k},\hat{\ell}') + \beta \int v^*\big(H(\chi,\hat{k},\hat{\ell}')\big) \; \mu_\chi(d\chi) \\
v^*(\hat{y},\hat{\ell}) &= \max_{(\hat{k},\hat{\ell}') \in \text{gr}Y(\hat{y},\hat{\ell})} \left\{ r(\hat{y},\hat{\ell},\hat{k},\hat{\ell}') + \beta \int v^*\big(H(\chi,\hat{k},\hat{\ell}')\big) \; \mu_\chi(d\chi) \right\} \\
&\geq r(\hat{y},\hat{\ell},k,\ell') + \beta \int v^*\big(H(\chi,k,\ell')\big) \; \mu_\chi(d\chi)
\end{aligned}$$

From these

$$u(\hat{y}-k) - u(\hat{y}-\hat{k}) + h(\hat{\ell}'-\hat{\ell}) - h(\ell'-\hat{\ell}) \leq u(y-k) - u(y-\hat{k}) + h(\hat{\ell}'-\ell) - h(\ell'-\ell) \tag{16}$$

For a contradiction, let $\hat{k} < k$ and $\hat{\ell}' < \ell'$. Beginning with consumption, note that $y - k - (y - \hat{k}) = \hat{k} - k = \hat{y} - k - (\hat{y} - \hat{k})$ and that $\hat{y} - \hat{k} > y - k$. Since u is strictly increasing and strictly concave, by Sundaram (1996, Theorem 12.22) or Stachurski (2009, Example 12.1.6) that $u(y-k) - u(y-\hat{k}) < u(\hat{y}-k) - u(\hat{y}-\hat{k})$. Noting that $\ell' - \ell > \ell' - \hat{\ell} > \hat{\ell}' - \ell > \hat{\ell}' - \hat{\ell}$, an analogous argument holds for increasing and strictly convex h that $-(h(\hat{\ell}'-\ell) - h(\ell'-\ell)) < -(h(\ell'-\hat{\ell}) - h(\hat{\ell}'-\hat{\ell}))$. These strict inequalities contradict (16).

□

A.3 Proof of proposition 3

Proof. To prove the existence of at least one nontrivial stationary distribution, a *norm-like*[10] function w on S as well as nonnegative constants $\alpha < 1$ and $\beta < \infty$ such that

$$\int w(y', \ell')\zeta(dz) \leq \alpha w(y, \ell) + \beta \tag{17}$$

are required (Stachurski, 2009, Proposition 12.1.32). The norm-like function will be constructed through summing two norm-like functions $w := w_1 + w_2$, letting $\alpha := \max\{\alpha_1, \alpha_2\}$ and $\beta := \beta_1 + \beta_2$ (Stachurski, 2009, Exercise 12.1.26).

Let $w_1(y, \ell) = |y|$. Note that by assumption 4, for each $\ell \in [\underline{L}, L]$, a threshold $\bar{k}$ such that for $k > \bar{k}$, $\int \chi g(k, \ell)\mu_\chi(d\chi) < (a + \delta - 1)k < \alpha_1 k$ for some $\alpha_1 \in (0, 1)$. Let $\beta_1 := g(\bar{k}, L)$, then

$$\int w_1(H(\chi, \pi^K(y, \ell), \pi^L(y, \ell))\mu_\chi(d\chi) \leq \alpha_1 k + \beta_1 \leq \alpha_1|y| + \beta_1 = \alpha_1 w_1(y, \ell) + \beta_1$$

This drift condition ensures that the income distribution does not escape to infinity.

The second problem is to ensure that there is sufficient incentives to invest at low incomes.[11] For $\ell \in [\underline{L}, L]$, set $w_2(y, \ell) = (u'(y))^{1/2}$ and let $y' := \chi g(\pi^K(y, \ell)\pi^L(y, \ell)) + (1 - \delta)\pi^K(y, \ell)$

$$\begin{aligned}
\int w_2(H(z, \pi(y, \ell)))\zeta(dz) &= \int \left[u'(y')\right]^{1/2} \mu_\chi(d\chi) \\
&= \int \left[u'(y')\frac{\chi g_k + 1 - \delta}{\chi g_k + 1 - \delta}\right]^{1/2} \mu_\chi(d\chi) \\
&\leq \left[\int u'(y')(\chi g_k + 1 - \delta)\mu_\chi(d\chi)\right]^{1/2} \left[\frac{\beta^{-1}}{\int(\chi g_k + 1 - \delta)\mu_\chi(d\chi)}\right]^{1/2} \\
&= w_2(y) \left[\frac{\beta^{-1}}{\int \chi g_k + 1 - \delta\mu_\chi(d\chi)}\right]^{1/2}
\end{aligned}$$

Now, with assumption 4, there exists some $\hat{y} \in (0, \infty)$ such that for $y < \hat{y}$ and all $\ell \in [\underline{L}, L]$, one can find an $\alpha_2 < 1$ such that for $y < \hat{y}$, $\int w_2(\pi(y, \underline{L}))\mu_\chi(d\chi) \leq \alpha_2 w_2(y, \underline{L})$.

For $y \geq \hat{y}$

$$\int w_2(H(\chi, \pi^K(y, \ell), \pi^L(y, \ell)))\mu_\chi(d\chi) \leq \int w_2(H(\chi, \pi^K(\hat{y}, \ell), \pi^L(\hat{y}, \ell)))\mu_\chi(d\chi) =: \beta_2$$

[10] Let S be a Borel subset of $\mathbb{R}$. A function $w : S \to \mathbb{R}_+$ is norm-like if its sublevel sets are precompact Stachurski (2009, Definition 8.2.9). That is, if the sets $C_a := \{x \in S : w(x) \leq a\}$ are precompact in (S, d_2), where d_2 is the Euclidean distance.

[11] Note that this is where some positive $\underline{L}$ is required for a sufficient incentive to invest at low income levels with production functions satisfying $\lim_{\ell \downarrow 0} g_k = 0$.

thus

$$\int w_2(H(\chi, \pi^K(y,\ell), \pi^L(y,\ell)))\mu_\chi(d\chi) \leq \alpha_2 \int w_2(y,\ell) + \beta_2$$

And letting $\alpha = \max\{\alpha_1, \alpha_2\}$, $\beta = \beta_1 + \beta_2$ the drift condition $w = \alpha(w_1 + w_2) + \beta_1 + \beta_2$. This satisfies equation (17).

It now remains to be shown that $w = w_1 + w_2$ is norm-like. Note that $\lim_{y\to\infty} w_1(y,\ell) = \lim_{y\to 0} w_2(y,\ell) = \infty$ for any $\ell \in [\underline{L}, L]$. The sublevel sets $C_a := \{(y,\ell) \in S : w(y,\ell) \leq a\}$ are of the form $[\underline{u}_a, \bar{v}_a] \times [\underline{L}, L]$, where $\underline{u}_a := \min_{y\in(0,\infty)} w(y,\cdot) = a$ and $\bar{v}_a := \max_{y\in(0,\infty)} w(y,\cdot) = a$. We have ensured that $\underline{u}_a > 0$ and $\bar{v}_a < \infty$. These sets are precompact in $(0,\infty)$ for arbitrary $a \in \mathbb{R}_+$.

By Rudin (1976, Theorem 2.33) the land dimension of the sub-level set $C_L := [\underline{L}, L] \subset S^{\underline{L}}$ is compact relative to $S^{\underline{L}} = [\underline{L}, L]$, since as a closed and bounded subset it is compact relative to $\mathbb{R}$ and $[\underline{L}, L]$ is compact relative to $\mathbb{R}$. C_L is therefore precompact in $[\underline{L}, L]$. By lemma 3 the sets C_a are also precompact and hence, w is norm-like. □

A.4 Proof of proposition 4

Proof. From the envelope condition, $v^*_Y(y,\ell) = u_C(y-k)$. Since v^* is strictly concave by proposition 1, v^*_Y is strictly decreasing in income. For this, convex u_C and $v^*_Y = u_C$ to hold, $c(y)$ must be increasing in y □

A.5 Proof of proposition 5

Proof. Since the policy fully compensates for any income loss, $y' \leq y^{R'}$. By proposition 4, next period consumption will be higher with avoided deforestation policy, or $c(y) < c(y^R)$. Also, as the policy rewards reduced deforestation, next period's landholdings are always lower and $\ell^{R'} < \ell'$. Assume for a contradiction that $k < k^R$. Then $u_C(y-k) < u_C(y-k^R)$ for any $y \in (0,\infty)$. Since $0 \leq g_{KL}$:

$$g_K(k^R, \ell^{R'}) \leq g_K(k^R, \ell') \leq g_K(k, \ell')$$

then

$$\beta \int u_C(c(y^{R'}))g_K(k^R, \ell^{R'})\zeta(dz) \leq \beta \int u_C(c(y))g_K(k,\ell')\zeta(dz)$$

This leads to $u_C(y-k^R) \leq u_C(y-k)$, a contradiction. □

B Additional lemmas

Lemma 1. *Let π be a policy-function that satisfies* (12) *for some $w \in \mathcal{C}icbS$. It is always the case that $\pi^K(y,\ell) < y$ for $y > 0$, $(\ell', \ell) \in S^L \times S^L$.*

Proof. Let $j(k) := u(y-k) - h(\ell' - \ell) + W(k)$, where $W(k) := \beta \int w[\chi g(k,\ell') + \rho \cdot (\lambda + \ell - \ell') + \phi \cdot (L - \ell') + k \cdot (1-\delta), \ell']\zeta(dz)$. For any $\epsilon > 0$:

$$\frac{j(y) - j(y-\epsilon)}{\epsilon} = \frac{-u(\epsilon)}{\epsilon} + \frac{W(y) - W(y-\epsilon)}{\epsilon} \tag{18}$$

Now replace B.14 in Stachurski (2009, p.351) with (18) and follow through the rest of the proof. Conclude that consumption is always positive at positive income levels. □

Lemma 2. *Let $A \subset \mathbb{R}^k_+$, $B \subset \mathbb{R}^\ell_+$ let g and h be continuous functions from A to $\mathbb{R}^\ell_+$, and let $\phi : A \to B$ be defined by:*

$$\phi(x) = \{y \in \mathbb{R}^l_+ : g(x) \leq y \leq h(x)\} \qquad (x \in A)$$

If g and h are continuous functions, then the correspondence ϕ is also continuous

Proof. For continuity, a correspondence is required to be both upper and lower hemi-continuous. These will be proved in order.

Upper hemi-continuity: Pick any $a \in A$. Let $(a_n) \subset A$ be a sequence such that $a_n \to a$. (a_n) is therefore bounded. Let $(b_n) \subset B$, $b_n \in \phi(a_n)$, $\forall n \in \mathbb{N}$. There exists a subsequence (b_{n_j}) and a $b \in \phi(a)$, with $(b_{n_j}) \to b$, as $j \to \infty$.

Define $C := \{a\} \cup \{a_n\}_{n \in \mathbb{N}}$. C is closed, bounded and is in a subset of $(\mathbb{R}^k, d_2)$ and is therefore compact by the Heine-Borel theorem. Note that the image of a compact set under a continuous function is compact. Moreover, compact sets in $(\mathbb{R}^k, d_2)$ are closed and bounded, again by Heine-Borel theorem. Let $g := (g_1, ..., g_\ell)$, that is, let the continuous function g be comprised of ℓ continuous equations, one for each dimension in B. Note that $g_i : \mathbb{R}^k_+ \to \mathbb{R}_+$. Do the same for h. $\forall i \in \{1, ..., \ell\}$ define: $G_i := \inf_{x \in C} g_i(x)$ and $H_i := \sup_{x \in C} h_i(x)$, which exist by the Weierstrass theorem. Let $G := (G_1, ..., G_\ell)$ and $H := (H_1, ..., H_\ell)$. One can now bound b_n: $G \leq b_n \leq H$. By the Bolzano-Weierstrass theorem, there exists a $(b_{n_j}) \to b$. Since $g(a_{n_j}) \leq b_n \leq h(a_{n_j})$ for all $j \in \mathbb{N}$ and for all $i \in \{1, ..., \ell\}$. By taking limits, since g and h are continuous and limits preserve partial orders, $g(a) \leq b \leq h(a)$. Hence, $b \in \phi(a)$ as required. ϕ is upper hemi-continuous.

Lower hemi-continuity: This follows immediately from Stachurski (2009, Lemma B.1.1, Theorem 3.1.11).

Since ϕ is both upper and lower hemi-continuous, it is continuous.

□

Lemma 3. *The Cartesian product, $A \times B \subset E \times F$ of two single dimensional subspaces, $A \subset E, B \subset F$ is precompact if both A and B are both precompact.*

Proof. If A is precompact, for every sequence $(a_n) \subset A$, there is exists a subsequence $(a_{n(k)})$ such that $a_{n(k)} \to a \in E$. A similar statement can be made for a sequence $(b_n) \subset B$.

Let $(x_n) := (a_n, b_n) \subset A \times B$. This sequence is comprised of two sequences $(a_n) \subset A$ and $(b_n) \subset B$. Since both of these sequences have subsequences that converge to some $(a, b) \in E \times F$, this defines a subsequence $(z_{n(k)})$ that converges to $x := (a, b) \in E \times F$. Thus, any sequence in $A \times B$ has a subsequence that converges to a point in $E \times F$. That is, $A \times B$ is precompact. □

References

Acemoglu, D.: 2009, *Introduction to Modern Economic Growth*, Princeton University Press, Princeton, New Jersey.

Adamopoulos, T.: 2008, Land inequality and the transition to modern growth, *Review of Economic Dynamics* **11**(2), 257 – 282.
URL: *http://www.sciencedirect.com/science/article/pii/S1094202507000452*

Angelsen, A., Brown, S., Loisel, C., Peskett, L., Streck, C. and Zarin, D.: 2009, Reducing Emissions from Deforestation and Forest Degradation (REDD): An Options Assessment Report., *Technical report*, Meridian Institute.
URL: *http://www.redd-oar.org/links/REDD-OAR_en.pdf*

Bartle, R. G. and Sherbert, D. R.: 2011, *Introduction to real analysis*, Vol. 4, Wiley.

Brockhaus, M., Obidzinski, K., Dermawan, A., Laumonier, Y. and Luttrell, C.: 2012, An overview of forest and land allocation policies in Indonesia: Is the current framework sufficient to meet the needs of REDD+?, *Forest Policy and Economics* **18**(0), 30 – 37.
URL: *http://www.sciencedirect.com/science/article/pii/S1389934111001596*

Busch, J., Lubowski, R. N., Godoy, F., Steininger, M., Yusuf, A. A., Austin, K., Hewson, J., Juhn, D., Farid, M. and Boltz, F.: 2012, Structuring economic incentives to reduce emissions from deforestation within Indonesia, *Proceedings of the National Academy of Sciences* .
URL: *http://www.pnas.org/content/early/2012/01/05/1109034109.abstract*

Byrd, R. H., Lu, P., Nocedal, J. and Zhu, C.: 1995, A limited memory algorithm for bound constrained optimization, *SIAM Journal on Scientific Computing* **16**(5), 1190–1208.
URL: *http://epubs.siam.org/doi/abs/10.1137/0916069*

Caballero, R. J.: 1991, On the sign of the investment-uncertainty relationship, *The American Economic Review* **81**(1), 279–288.
URL: *http://www.jstor.org/stable/2006800*

Carey, P.: 2000, *The true history of the Kelly gang*, University of Queensland Press, St Lucia.

Cattaneo, A.: 2001, Deforestation in the Brazilian Amazon: Comparing the Impacts of Macroeconomic Shocks, Land Tenure, and Technological Change, *Land Economics* **77**(2), pp. 219–240.
URL: *http://www.jstor.org/stable/3147091*

Cattaneo, A.: 2008, A stock-flow mechanism to reduce emissions from deforestation. Submission by Woods Hole Research Center and IPAM to the UNFCCC regarding Workshop on policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries.

Cattaneo, A.: 2009, A "Stock-Flow-with Targets" Mechanism for Distributing Incentive Payments to Reduce Emissions from Deforestation, *Technical report*, The Woods Hole Research Center.
URL: *http://www.whrc.org/policy/pdf/cop15/Stock-flow_with_targets_COP.pdf*

Chomitz, K., Buys, P., Luca, G. D., Thomas, T. and Wertz-Kanounnikoff, S.: 2007, At Loggerheads? Agricultural Expansion, Poverty Reduction and Environment in the Tropical Forests, *Technical report*, The World Bank.

Coalition for Rainforest Nations: 2007, Reducing emissions from deforestation in developing countries: approaches to stimulate action. Submission of views to the UNFCCC COP 11 by Bolivia, Central African Republic, Costa Rica, Democratic Republic of the Congo, Dominican Republic, Fiji, Ghana, Guatemala, Honduras, Kenya, Madagascar, Nicaragua, Panama, Papua New Guinea, Samoa, Solomon Islands, and Vanuatu, *Technical report*.
URL: *http://unfccc.int/resource/docs/2007/sbsta/eng/misc02.pdf*

Corbera, E., Estrada, M. and Brown, K.: 2010, Reducing greenhouse gas emissions from deforestation and forest degradation in developing countries: revisiting the assumptions, *Climatic Change* **100**, 355–388.
URL: *http://dx.doi.org/10.1007/s10584-009-9773-1*

Dasgupta, P. and Heal, G.: 1974, The Optimal Depletion of Exhaustible Resources, *The Review of Economic Studies* **41**, pp. 3–28.
URL: *http://www.jstor.org/stable/2296369*

Dekle, R. and Vandenbroucke, G.: 2012, A quantitative analysis of China's structural transformation, *Journal of Economic Dynamics and Control* **36**(1), 119 – 135.
URL: *http://www.sciencedirect.com/science/article/pii/S0165188911001631*

Diamond, J.: 2005, *Collapse: How Societies Choose to Fail or Succeed*, Viking Press.

Eliasch, J.: 2008, *Climate change : financing global forests : the Eliasch review*, Earthscan London ; Sterling, VA.

FAOSTAT: 2013, Food and Agriculture Organization of the United Nations Statistical Database, *Statistical Database* .
URL: *http://faostat.fao.org/*

Galor, O.: 2011, *Unified growth theory*, Princeton University Press.

Golub, A., Hertel, T., Lee, H.-L., Rose, S. and Sohngen, B.: 2009, The opportunity cost of land use and the global potential for greenhouse gas mitigation in agriculture and forestry, *Resource and Energy Economics* **31**(4), 299 – 319.
URL: *http://www.sciencedirect.com/science/article/pii/S0928765509000220*

Griscom, B., Shoch, D., Stanley, B., Cortez, R. and Virgilio, N.: 2009, Sensitivity of amounts and distribution of tropical forest carbon credits depending on baseline rules, *Environmental Science & Policy* **12**(7), 897 – 911.
URL: *http://www.sciencedirect.com/science/article/pii/S1462901109001002*

Hartman, R.: 1972, The effects of price and cost uncertainty on investment, *Journal of economic theory* **5**(2), 258–266.
URL: *http://www.sciencedirect.com/science/article/pii/0022053172901056*

Heutel, G.: 2012, How should environmental policy respond to business cycles? Optimal policy under persistent productivity shocks, *Review of Economic Dynamics* **15**(2), 244 – 264.
URL: *http://www.sciencedirect.com/science/article/pii/S1094202511000238*

Holland, P. W.: 1986, Statistics and Causal Inference, *Journal of the American Statistical Association* **81**(396), 945–960.
URL: *http://www.tandfonline.com/doi/abs/10.1080/01621459.1986.10478354*

Kimball, M. S.: 1990, Precautionary Saving in the Small and in the Large, *Econometrica* **58**(1), pp. 53–73.
URL: *http://www.jstor.org/stable/2938334*

Mendelsohn, R.: 1994, Property Rights and Tropical Deforestation, *Oxford Economic Papers* **46**, pp. 750–756.
URL: *http://www.jstor.org/stable/2663497*

Merry, F., Amacher, G. and Lima, E.: 2008, Land values in frontier settlements of the brazilian amazon, *World Development* **36**(11), 2390 – 2401.
URL: *http://www.sciencedirect.com/science/article/pii/S0305750X08001836*

Moro, A.: 2012, The structural transformation between manufacturing and services and the decline in the {US} {GDP} volatility, *Review of Economic Dynamics* **15**(3), 402 – 415.
URL: *http://www.sciencedirect.com/science/article/pii/S1094202511000421*

Olander, L. P., Galik, C. S. and Kissinger, G. A.: 2012, Operationalizing REDD+: scope of reduced emissions from deforestation and forest degradation, *Current Opinion in Environmental Sustainability* **4**(6), 661 – 669.
URL: *http://www.sciencedirect.com/science/article/pii/S1877343512000942*

Ollivier, H.: 2012, Growth, deforestation and the efficiency of the redd mechanism, *Journal of Environmental Economics and Management* .
URL: *http://www.sciencedirect.com/science/article/pii/S0095069612000721*

Persson, A. and Munasinghe, M.: 1995, Natural Resource Management and Economy wide Policies in Costa Rica: A Computable General Equilibrium (CGE) Modelling Approach, *The World Bank Economic Review* **9**(2), pp. 259–285.
URL: *http://www.jstor.org/stable/3989920*

Rudin, W.: 1976, *Principles of Mathematical Analysis (International Series in Pure & Applied Mathematics)*, McGraw-Hill Publishing Co.

Sloan, S., Edwards, D. P. and Laurance, W. F.: 2012, Does Indonesia's REDD+ moratorium on new concessions spare imminently threatened forests?, *Conservation Letters* **5**(3), 222–231.
URL: *http://dx.doi.org/10.1111/j.1755-263X.2012.00233.x*

Solheim, E. and Natalegawa, R.: 2010, Letter of intent between the Government of the Kingdom of Norway and the Government of the Republic of Indonesia on "cooperation on reducing greenhouse gas emissions from deforestation and forest degradation".
URL: *http://www.regjeringen.no/upload/SMK/Vedlegg/2010/Indonesia_avtale.pdf*

Stachurski, J.: 2008, Continuous State Dynamic Programming via Nonexpansive Approximation, *Computational Economics* **31**, 141–160. 10.1007/s10614-007-9111-5.
URL: *http://dx.doi.org/10.1007/s10614-007-9111-5*

Stachurski, J.: 2009, *Economic Dynamics: Theory and Computation*, The MIT Press, Cambridge, Massachusetts.

Stern, D. I.: 2011, The role of energy in economic growth, *Annals of the New York Academy of Sciences* **1219**(1), 26–51.
URL: *http://dx.doi.org/10.1111/j.1749-6632.2010.05921.x*

Sundaram, R. K.: 1996, *A first course in optimization theory*, Cambridge University Press, Cambridge, UK.

The World Bank: 2007, *World development report 2008: Agriculture for development*, World Bank.

The World Bank: 2013, World Development Indicators. Accessed: 03-Jan-2013.
URL: *http://data.worldbank.org/data-catalog/world-development-indicators*

Tollefson, J.: 2009, Paying to save the rainforests, *Nature* **460**(7258), 936.
URL: *http://www.nature.com/news/2009/090819/full/460936a.html*

van der Eng, P.: 2009, Capital formation and capital stock in Indonesia, 1950–2007, *Bulletin of Indonesian Economic Studies* **45**(3), 345–371.
URL: *http://www.tandfonline.com/doi/abs/10.1080/00074910903301662*

van der Eng, P.: 2010, The sources of long-term economic growth in Indonesia, 1880–2008, *Explorations in Economic History* **47**(3), 294 – 309.
URL: *http://www.sciencedirect.com/science/article/pii/S0014498309000540*

van der Werf, G. R., Morton, D. C., DeFries, R. S., Olivier, J. G., Kasibhatla, P. S., Jackson, R. B., Collatz, G. J. and Randerson, J.: 2009, CO_2 emissions from forest loss, *Nature Geoscience* **2**(11), 737–738.
URL: *http://www.nature.com/ngeo/journal/v2/n11/full/ngeo671.html*

Warr, P. and Yusuf, A. A.: 2011, Reducing Indonesia's deforestation-based greenhouse gas emissions, *Australian Journal of Agricultural and Resource Economics* **55**(3), 297–321.
URL: *http://dx.doi.org/10.1111/j.1467-8489.2011.00540.x*

Woods Hold Research Center: 2008, How to Distribute REDD Funds Across Countries? A Stock-Flow Mechanism, *Technical report*, Woods Hold Research Center.
URL: *www.whrc.org/policy/pdf/cop14/Stock_Flow_Mechanism.pdf*

XE: 2013, XE Currency Table: IDR - Indonesian Rupiah, http://www.xe.com/currencytables/?from=IDR&date=2000-07-01. Accessed: 2013-10-20.