Cost-Effective Payments for Reducing Emissions from Deforestation Under Uncertainty

Stefanie Engel[a] * Charles Palmer[b] † Luca Taschini[b] ‡
Simon Urech[a] §

[a] *ETH Zurich*

[b] *London School of Economics*

Abstract

The objective of this paper is to analyse the implications of landowners' option values in land allocation and derive policy recommendations for payments for Reducing Emissions from Deforestation and Forest Degradation (REDD+). We consider the cost-effectiveness of alternative designs of REDD+ payment schemes on the permanence of emission reductions. It is shown that the common practice of making either fixed payments per hectare or linking payments to carbon markets is not a cost-effective approach. A given level of permanence can be achieved at considerably lower cost to the REDD service buyer if REDD payments are linked to an agricultural commodity index that correlates with landowners' opportunity costs.

Keywords: Deforestation; Land use; Payments; Real option; Uncertainty.

JEL Classifications: Q23; Q28; Q15.

*Address: Environmental Policy and Economics PEPE, ETH Zurich, Switzerland. E-mail: `stefanie.engel@env.ethz.ch`

†Department of Geography and Environment, London School of Economics and Political Science, UK. E-mail: `c.palmer1@lse.ac.uk`

‡Address: The Grantham Research Institute on Climate Change and the Environment, the London School of Economics and Political Science, UK. E-mail: `l.taschini1@lse.ac.uk`

§Address: Environmental Policy and Economics PEPE, ETH Zurich, Switzerland. E-mail: `surech@ethz.ch`

DRAFT IN PROGRESS

1 Introduction

Over the last couple of decades there has been an increase in the application of stochastic control models in the forest management literature with an emphasis on incentives that drive land-use change under uncertainty. Of particular interest are those that focus on the switch from forest to agriculture and vice versa (e.g. Bulte et al. (2002); Schatzki (2003) ; Isik and Yang (2004); Wiemers and Behan (2004); Behan et al. (2006)). This research is relevant for the study of incentives and policies for Reducing Emissions from Deforestation and Degradation (hereafter REDD+), which may be included in a post-2012 global climate regime (UNFCCC, 2010).[1] Potential policy options which could be implemented to operationalise REDD+ span the range of (mostly well-established) interventions in forest and land use, although payments for environmental services (PES) are often emphasised (Angelsen, 2010; Palmer, 2011). Previous studies in the forest management literature that focus on incentives to switch between alternative land uses have important policy implications for payment design in REDD+ policy. Yet they do not consider the effects of different payment schemes on managing uncertainties nor do they focus explicitly on REDD+.

This paper investigates alternative REDD+ payment programs that a policy regulator (or more broadly, any REDD+ service buyer) may implement in order to dissuade a landowner from converting the land to alternative use. Since carbon sequestered in the terrestrial biosphere is not permanently removed from the atmosphere, it is at constant risk of being returned through deforestation, whether intentional or not. Reductions in emissions from REDD thus will not represent a permanent change in the cumulative flux of carbon dioxide to the atmosphere.[2] There are several types of risks that jeopardize so-called 'permanence' in forest carbon sinks.[3] In this paper, we focus on demand-side risk. This is the risk that an increase in the alternative use profits raises landowner's opportunity costs of keeping land under the original use above the REDD+ payment set in the program. In this case, it might become profitable for landowners to convert land use and permanence would not be warranted. Understanding how these risks affect landowner's decisions can provide valuable insights for the design of payment programs and how to ensure permanence. With

[1]'REDD+' encompasses policies and activities to prevent or slow deforestation and degradation, and increase forest carbon stocks. The latter denote the '+' in REDD+ and include activities such as agroforestry and forest restoration.

[2]While this also applies to industrial emissions sources, we adopt the viewpoint of Watson et al. (2000) that reductions in fossil fuel emissions can be regarded as leading to more permanent reductions in cumulative flows to the atmosphere in contrast to reductions in deforestation.

[3]Dutschke and Wong (2003) discusses the practicality and potential difficulties of addressing permanence in the presence of different types and levels of risks. Note that the term 'permanence' has a looser definition in this paper than that commonly used in the REDD+ literature. Under a national approach to reducing greenhouse gas emissions, for example, the concern is less about permanence of specific forest areas but instead whether a particular country continues to maintain changes in emissions below some reference level Dutschke and Angelsen (2008).

recent booms in commodities' prices - including in agriculture - there is an increasing need to design payments schemes that can adapt to impending population increases and rising food- and energy-related demands for land. While we believe our results are of general relevance for PES design, we focus our analysis on forest carbon and REDD+ payments. Stakeholders with billions of dollars invested in REDD+ fear that reductions in loss of forest carbon stocks may be credited now or rewarded across time, but that these stocks may later disappear due to opportunistic land conversion.[4]

We first develop and implement a general optimal switching model where a risk–neutral land owner can decide to convert her land use between two general alternatives, forest and agriculture. The REDD+ payment program constitutes one of the two alternatives. As is common in this literature, we assume conversion is instantaneous (e.g., see Guthrie and Kumareswaran (2009)). Conversion costs are sunk and future returns are uncertain. The objective of the landowner is to maximize his future expected returns. Although the model allows for a general investigation of continuous-time optimal switching strategies, we concentrate on maintaining forest permanence under uncertainty in the return to agriculture and REDD+ payments. In particular, the land owner is deciding between the continued use in forest conservation with REDD+ payments or the conversion to agriculture. Building on standard concepts of financial risk management, we propose a probabilistic permanence criterion. For a given unit of land, probability and time horizon, we identify sufficient conditions for the parameters of the payment program that guarantee the land to remain in forest over the given time horizon with a probability not lower than this level.

This performance criterion is operationalized by considering a REDD+ payment program that accommodates both a constant per–hectare payment and a per–hectare indexed payment component. In particular, such a component could be any observable price–index whose returns process are dependent or independent from the returns of the alternative land use. Moreover, we introduce a leverage effect multiplying this variable lag by a given weighting coefficient. In practice, two indices appear relevant in the REDD+ context. In the voluntary carbon markets, payments for carbon offsets are often linked in some way to carbon market prices, an approach that may be extended to REDD+ in the event of integration into carbon offset markets (see Gregersen et al. (2010)). An alternative approach that has been proposed in the literature, but to our knowledge has yet to be applied in actual payments schemes, is to index payments to an agricultural commodity index that correlates with landowners' opportunity costs (Benítez et al. (2006) Dutschke and Angelsen (2008)). The innovation of our framework is to incorporate indexed and hence, variable payments alongside the kinds of payments that are commonly observed in PES schemes around the world, i.e fixed ones (Engel et al., 2008).

Beginning with the Stern Review (2006), the decision problem of land conversion between forestry and an alternative use in the REDD literature has generally been tackled employing standard discount cash flows techniques (e.g. Nepstad et al. (2007); Boerner

[4]Along with possible REDD+ contract breach by landowners (see MacKenzie at al., 2010). While credit buffers, risk pools and insurance allow for some mitigation of risk, these provide only limited incentives to ensuring permanence at the landowner level.

and Wunder (2008) ; Butler et al. (2009)). However, such a decision problem involves sunk costs and uncertain profits. Studying the land conversion problem from forestry to agriculture, Schatzki (2003) shows that it is optimal for land owners to delay switching when conversion costs are sunk and returns from alternative land uses are uncertain. This is a standard result in real options theory and accounts for the idea that land use can be considered as a real asset with an attached perpetual option to convert it to another land use at any time.[5] Depending on the levels of the uncertainty that characterizes the problem, these option values to delay are potentially large and failure to explicitly model them may considerably affect payments design. Incorporating this option value in the payments for forest conservation may lower payment values. This implies that current estimates of the cost of REDD+ may be overestimated, an important point that is further investigated in this paper.

Choosing a desired probability level and a time horizon, we numerically evaluate the minimum REDD+ payment that satisfies the permanence criterion of conserving forest over time. In a stylized model, presented in Section 2, the landowner collects either uncertain REDD+ payments or uncertain agriculture profits. We find that the higher the uncertainty about the returns of the index–based component of the REDD payment, the higher the likelihood of land conversion. This result is in line with real options theory. For a given weighting coefficient, the fixed transfer needs to be enlarged to meet the permanence criterion. On the other hand, the higher the uncertainty about the agriculture returns, the lower the likelihood of land conversion. The constant transfer that meets the permanence criterion can be lowered as well. However, it is also important to understand the dependency structure between the two alternative land uses. The more correlated the returns of the index component of the REDD+ payment and the agriculture returns, the lower the cost of the policy. Identifying the most cost-effective combination of fixed and variable transfers is, however, only possible when the volatility of the price index is lower than that for the landowner's opportunity cost. In this case, cost-effectiveness can be achieved with a payment scheme with more weight given to the variable component.

The model is applied to real case scenarios in Section 3. In particular, we evaluate the minimum REDD+ payment that achieves a given permanence criterion while minimizing the program's transfer costs. We do this by calibrating the model to two observable price indices: the soy bean index of Parana State, Brazil, and the European Union's Emissions Trading System permit price. The costs of three scenarios are compared: (i) a fixed payment per hectare (no indexed payment), (ii) a payment that is linked to the soy index, and (iii) a payment that is linked to the carbon market price. We find that where the landowner's opportunity cost is highly correlated with the soy bean index then the most cost-effective policy is to implement a variable payment linked to this index rather than to carbon prices. This policy is also more cost-effective than using fixed payments alone. These results, along with their policy implications and limitations, are discussed in Section 4.

[5]We refer to McDonald and Siegel (1986) and Pindyck (1988) for an introductory discussion about options theory applied to real investments. A more comprehensive description of the real options theory can be found in Dixit and Pindyck (1994), Dixit (1989), and Pindyck (1991).

2 The Model

In this paper we value a representative single-hectare of land that can generate profits from one of two alternative uses: forest or agriculture. Whenever the land-use is switched, conversion costs are incurred. Costs for switching from forest to agriculture, (CC_{FA}) and, vice versa, from agriculture to forest, (CC_{AF}) are sunk. Once the switch from forest to agriculture has occurred payments preclude a switch back from agriculture to forest again. A switch, however, from agriculture to forest could be applied, for example, to assess payments for afforestation or reforestation as in the Clean Development Mechanism (CDM) of the Kyoto Protocol. Profits to the landowner from forest are generated by a REDD+ incentive payment program while profits from agriculture are generated by crop sales. Future expected returns both from forest (hereafter F) and agriculture (hereafter A) are uncertain. Moreover, conversion from forest to agriculture yields a one-time timber profit. This profit is a special case in our model. It can occur, for example, if deforestation takes the form of slash and burn. For simplicity, we assume a single grade of timber. When the forest is t years old, the volume of timber (per hectare) equals $V(t)$, for some deterministic function V.

2.1 Avoided deforestation payment program

We consider a payment program that accommodates both (i) a constant per-hectare payment (c) and (ii) a per-hectare indexed payment component (I) weighted by some coefficient (α). The second component I, corresponds to some observable price index the return process of which may be dependent or independent with respect to agricultural returns. Therefore, forest returns correspond to the sum of these two components, i.e. $F = c + \alpha \cdot I$. Our aim is to identify a pair (c, α) that makes profitable the carbon dioxide sequestration service of forest for a given time horizon. We then quantify the cost of different payment programs given the probability of keeping land in forest. We assume the index returns process I evolves according to the following stochastic process:

$$dI = \mu_I I dt + \sigma_I I dW_I, \tag{1}$$

where μ_I is the constant drift term, σ_I is a positive constant, and W_I is assumed to be normally distributed with mean 0 and variance 1. Similarly, we assume the agricultural return process A evolves according to a second stochastic process:

$$dA = \mu_A A dt + \sigma_A A dW_A, \tag{2}$$

where μ_A is the constant drift term, and σ_A is again a positive constant. Because the two return processes may be correlated, we introduce a second process W_a that is assumed to be normally distributed with mean 0 and variance 1, and such that $W_A = \rho_{IA} \cdot W_I + \sqrt{1 - \rho_{IA}^2} \cdot W_a$, and ρ_{IA} represents the unconditional correlation.

We consider different payment schedules for keeping land in forest in every period $t \in [0, T]$. In particular, a policy regulator can choose from three different payment structures: (i) a fixed constant payment c; (ii) a payment $P(t, c_{CI}, I_{CI}, \alpha_{CI})$ indexed to a commodity index (i.e. to some return value of the alternative land use); (iii) a payment $P(t, c_{EI}, I_{EI}, \alpha_{EI})$ indexed to an emissions index, i.e. the price of marketable permits traded on some market for permits. All these payments are specified per hectare of land. All cash-flow streams are valued by discounting their expected values at the constant, continuously compounded, risk-free interest rate r. Note that we model the returns directly instead of modelling the price and yield uncertainties separately. This simplifies our analysis considerably and allows us to utilize existing numerical techniques to solve the optimal land–conversion problem. In Section 3, we derive the return processes from underlying and observable price indices, yield processes, conversion costs, and payment programs.

2.2 Landowner's decision

Over each increment of time dt, a landowner receives Fdt if the land is in forest or Adt if the land is in agriculture. Assume first a starting point of land in forest. At each point in time, the landowner decides either to switch land use or not. The first action corresponds to conversion from forest to agriculture. This decision generates instantaneous profits net of conversion costs, and may also generate a one-time timber profit. Conversely, the landowner can delay the decision to harvest the forest and continue to receive payments. Thus, the value of a single hectare of forest is

$$f(F, A, t) = \max\{\pi^F, \pi^A - CC_{FA}\}. \tag{3}$$

The first term on the right-hand side describes the returns if the land is kept in forest. The landowner receives a payment of Fdt and the discounted future expected returns from the land. Therefore, π^F represents the landowner's return in the absence of forest conversion during the interval of length dt. In particular,

$$\pi^F = Fdt + e^{-rdt}\mathbb{E}[f(F + dF, A + dA, t + dt)], \tag{4}$$

where $\mathbb{E}$ is the expectation operator. The second term of Equation (3) is the return when the land is converted from forest to agriculture. The landowner incurs sunk conversion costs equal to CC_{FA}.[6]

For generality we account also for the possibility of converting from agriculture to forest. When the initial land use is agriculture, the landowner faces a similar decision-making problem. She can either produce the agricultural commodity before converting the land

[6] A one-off timber profit may be accounted for by letting the second term become $(\tau(t)-h)\cdot V(t)-CC_{FA}$. Here, h represents harvest costs per unit of timber, $V(t)$ is the volume of timber extracted from the t-years old forest, and $\tau(t)$ is the timber price at time t for some deterministic function τ. In Section 3 we account for the possibility of a one-off timber profit. For model tractability, however, we model the sum of the conversion costs, CC_{FA}, and the profit from the one-off timber harvest, $(\tau(t)-h)\cdot V(t)$, as a single variable labeled total conversion costs, TCC_{FA}.

to forest, or delay this decision and continue with agricultural production. Therefore, the value of a single hectare of agriculture is

$$g(F, A, t) = \max\{\pi^A, \pi^F - CC_{AF}\}. \tag{5}$$

Similar to the previous situation, the first term on the right-hand side describes the returns if the land is kept in agriculture. The landowner receives a profit Adt from agriculture and the discounted future expected returns of land:

$$\pi^A = Adt + e^{-rdt}E[g(F + dF, A + dA, t + dt)]. \tag{6}$$

If the landowner decides to switch from agriculture to forest she faces conversion costs equal to CC_{AF}.

For π^F and using Ito's Lemma, we obtain

$$\begin{aligned} \pi^F &= f(F, A, t) \\ &+ \Big(\frac{\partial f}{\partial t} + \frac{1}{2}\sigma_F^2 F^2 \frac{\partial^2 f}{\partial F^2} + \mu_F F \frac{\partial f}{\partial F} + \frac{1}{2}\sigma_A^2 A^2 \frac{\partial^2 f}{\partial A^2} + \mu_A A \frac{\partial f}{\partial A} - \rho_{FA}\sigma_F\sigma_A \frac{\partial f}{\partial F \partial A} - rf\Big)dt \\ &+ Fdt \end{aligned} \tag{7}$$

Similarly, for π^A we obtain

$$\begin{aligned} \pi^A &= g(F, A, t) \\ &+ \Big(\frac{\partial g}{\partial t} + \frac{1}{2}\sigma_A^2 A^2 \frac{\partial^2 g}{\partial A^2} + \mu_A A \frac{\partial g}{\partial A} + \frac{1}{2}\sigma_F^2 F^2 \frac{\partial^2 g}{\partial F^2} + \mu_F F \frac{\partial g}{\partial F} - \rho_{FA}\sigma_F\sigma_A \frac{\partial g}{\partial F \partial A} - rg\Big)dt \\ &+ Adt \end{aligned} \tag{8}$$

We know from Equation (3) that $f(F, A, t)$ must be at least as large as π^F and $\pi^A - CC_{FA}$. That is, $f(F, A, t)$ must satisfy

$$0 \geq \frac{\partial f}{\partial t} + \frac{1}{2}\sigma_F^2 F \frac{\partial^2 f}{\partial F^2} + \mu_F F \frac{\partial f}{\partial F} + \frac{1}{2}\sigma_A^2 A \frac{\partial^2 f}{\partial A^2} + \mu_A A \frac{\partial f}{\partial A} - \rho_{FA}\sigma_F\sigma_A \frac{\partial f}{\partial F \partial A} - rf + F \tag{9}$$

$$f(F, A, t) \geq \pi^A - CC_{FA} \tag{10}$$

We also know from Equation (5) that $g(F, A, t)$ must be at least as large as π^A and $\pi^F - CC_{AF}$. Therefore, $g(F, A, t)$ must satisfy

$$0 \geq \frac{\partial g}{\partial t} + \frac{1}{2}\sigma_A^2 A \frac{\partial^2 g}{\partial A^2} + \mu_A A \frac{\partial g}{\partial A} + \frac{1}{2}\sigma_F^2 F \frac{\partial^2 g}{\partial F^2} + \mu_F F \frac{\partial g}{\partial F} - \rho_{FA}\sigma_F\sigma_A \frac{\partial g}{\partial F \partial A} - rg + A \tag{11}$$

$$g(F, A, t) \geq \pi^F - CC_{AF} \tag{12}$$

At least one of the two conditions for $f(\cdot)$ and $g(\cdot)$ must hold with equality. For example, for land in forest, if Equation (9) is an equality, then the landowner should keep her land in forest. Conversely, if Equation (10) is an equality, the landowner should switch to agriculture. For land in agriculture, if Equation (11) is an equality, then the landowner should keep her land in agriculture. Conversely, if Equation (12) is an equality, the landowner should switch to forest. In all other cases, the landowner is indifferent between converting and not converting. Therefore, it is optimal to wait. Because the two value functions $f(F, A, t)$ and $g(F, A, t)$ are interdependent, there are no analytical solutions to the system of the Equations (9), (10), (11) and (12). Therefore, we solve the optimal switching problem numerically using the collocation method.[7]

2.3 Probabilistic permanence criterion

Although the model accounts for bi-directional conversion, recall that our aim is to investigate the incentives that might ensure the landowner continues keeping the land in forest thus postponing the conversion to agriculture. Therefore, in what follows we mainly concentrate on the switch from forest to agriculture.[8]

Once the underlying, observable index market I is chosen, a specific criteria is required to identify the (c, α) pair that ensures land is kept in forest. Building on standard concepts of financial risk management, we propose a probabilistic permanence criterion. For a given hectare of forestland, a pre-set probability (p) and a chosen time horizon (T), the pair (c, α) is derived to ensure that the land remains in forest over the given time horizon with a probability not lower than the specified level. As we discuss later, this *minimum payment*, i.e. any pair (c, α) that ensures land stays in forest with probability p, is not necessarily unique.

To compute the minimum payment we first evaluate the optimal conversion boundaries given the parameters of the forest F and the agriculture returns A, respectively; the conversion costs CC_{FA} and CC_{AF}; the correlation factor between the two alternative land uses, forest and agriculture, $\rho_{I,A}$; and the discount factor r. Such conversion boundaries are represented in Figure 1. The dashed line (C_{FA}) corresponds to the switching boundary for the conversion from forest to agriculture; the solid line (C_{AF}) corresponds the switching boundary for the conversion from agriculture to forest. Since avoided deforestation is the relevant question here we simulate S sample paths of the forest returns F for T years according to the parameters previously specified. Every s months each sample path

[7] This approach approximates the unknown value functions $f(F, A, t)$ and $g(F, A, t)$ using linear combination of n known basis functions. We refer to Miranda and Fackler (2002) and Dangl and Wirl (2004) for a comprehensive explanation. Often, the finite difference method is used to solve numerically the value functions in the framework of stochastic dynamic optimization. However, the collocation method result has proven to be a fast and more robust alternative.

[8] For generality we account also for the possibility of converting from agriculture to forest, as may be the case, for example, when considering payments for afforestation under the CDM. As noted, some π^F under REDD+ is not possible once the forest has been converted to agriculture.

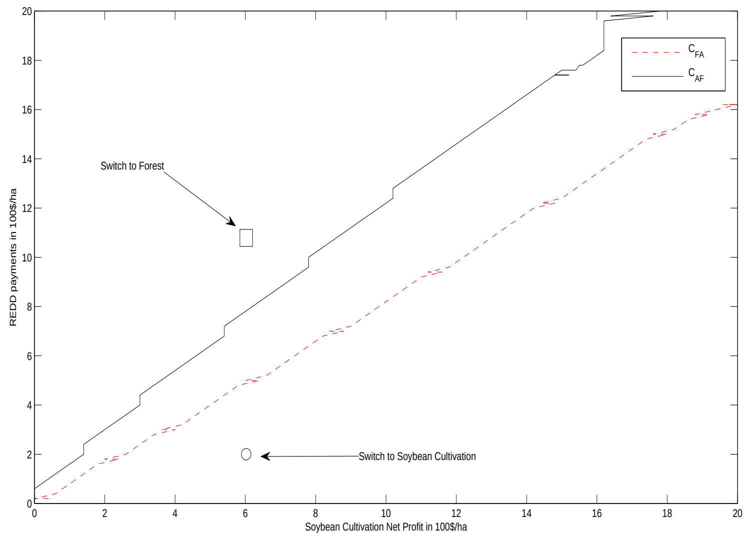


Figure 1: Switching and waiting regions. The dashed line represents the switching boundary for the conversion from forest to agriculture, C_{FA}. The solid line represents the switching boundary for the conversion from agriculture to forest, C_{AF}. Bullets represent a simulated forest return; squares represent a simulated agriculture return.

of the F returns is compared with the corresponding conversion boundary. Thus, every s months we determine whether the land is kept in its current use, forest, or converted to its alternative use, agriculture. In general, supposing the land is in forest from day one, when a simulated forest return (bullet in Figure 1) turns out to be below the conversion boundary from forest to agriculture, the landowner switches. Conversely (square in Figure 1), she keeps the land in forest. Supposing the land is in agriculture, when a simulated agriculture return turns out to be above the conversion boundary from agriculture to forest, the landowner switches. Conversely, she keeps the land in agriculture. The area between the two switching boundaries is the waiting region.

Assuming the land is in forest, every s months we count the number of sample paths on which the land has not been converted. Dividing this value by the number of simulations S, we obtain the frequency of land in forest for each period. We label this frequency p. We impose that once the land use is switched it stays in agriculture for the rest of the T years.[9] By imposing this condition, the probability of remaining in forest, p, is monotonically non-increasing through time. Thus, considering the permanence criterion described above, what matters is the level of p at the final period T. It is worth noticing that p reads also as the probability of avoiding deforestation and, therefore, $(1-p)$ corresponds to the probability of deforestation. In what follows we search for the pairs (c, α) that guarantee the land to

[9]Given our interest is keeping land in forest, we purposely neglect those situations where, once in agriculture, it may be viable to switch back to forest at a later point.

remain in forest for T years with a probability p not lower than 90 percent.

2.4 Numerical model simulations

In this sub-section, we simulate the model numerically in order to explore the most cost-effective payment structures for ensuring that forest stays in forest with a probability of 90 percent (hereafter termed the permanence criterion). Thus, we elicit combinations of the size of the constant per-hectare component (c) of the payment scheme along with that of the variable, indexed component (α) for the cheapest overall payment from the perspective of the policy regulator. In particular, the objective of the policy regulator is to determine the pair (c, α) that satisfies the permanence criterion at lowest cost. Achieving policy cost-effectiveness while avoiding deforestation and hence, ensuring the environmental effectiveness of the programme first requires that we compare the two alternative returns to the landowner: agricultural profits on one hand and those coming from the regulator's payments. A number of policy insights follow, particularly with respect to indexing payments to the landowner's opportunity cost.

To understand the policy implications of indexing payments to agricultural returns, we initially assume that the parameters of the model are set at plausible values. The initial value of the agriculture commodity, for instance, is set equal to unconditional mean of the log return of returns from Brazilian soybean, the agriculture commodity that is used in Section 3 to illustrate an alternative land use. We also assume that the timber revenues partially offset the costs of conversion and harvesting, CC_{FA}. Therefore, total conversion costs, given as CC_{FA}, are assumed smaller than CC_{AF}. Model simulations are run over a hypothetical 30 year period.[10] All parameters are reported in Table 1.

Once the underlying observable index has been identified, the pair (c, α) is derived such that the corresponding payment scheme satisfies the permanence criterion. In the presence of a non–zero indexed component, the cost of the policy is uncertain and equal to $\mathbb{E}\left[\int_0^T F(t)dt\right]$. We numerically determine, therefore, the policy cost using the parameters in Table 1. Two different scenarios are considered for the dependency structure between the two alternative land uses: uncorrelated and positively correlated. When the returns of the two alternative land uses are independent and hence, uncorrelated, the identification of the cost-effective policy is quite straightforward. Figure 2(a) shows the average cost of the payment scheme for different combinations of (c, α) that satisfy the permanence criterion. When there is little or no correlation between the index and landowner's opportunity cost, it would be more cost-effective to increase the fixed payment and reduce as much as possible the variable payment. As discussed in the next section, this result would be relevant when considering aligning payments with the carbon market price since the correlation with the landowner's opportunity cost is likely to be close to zero.

When the returns of the two alternative land uses are positively correlated, it is not

[10] CDM guidelines propose that Land Use, Land Use Change and Forestry projects have a duration of between 20 and 60 years.

Parameter	Value
μ_I (drift of the index returns)	0
μ_A (drift of the agriculture returns)	0
σ_I (volatility of the index returns)	0.15
σ_A (volatility of the agriculture returns)	0.15
$\rho_{I,A}$	0.9
I_0 (initial value of the index returns)	3
A_0 (initial value of agriculture returns)	3
CC_{FA}	5
CC_{AF}	10
r (discount factor)	0.05
T years and s periods per year	30 and 2
S (number of simulations)	10,000
p	≥ 0.90

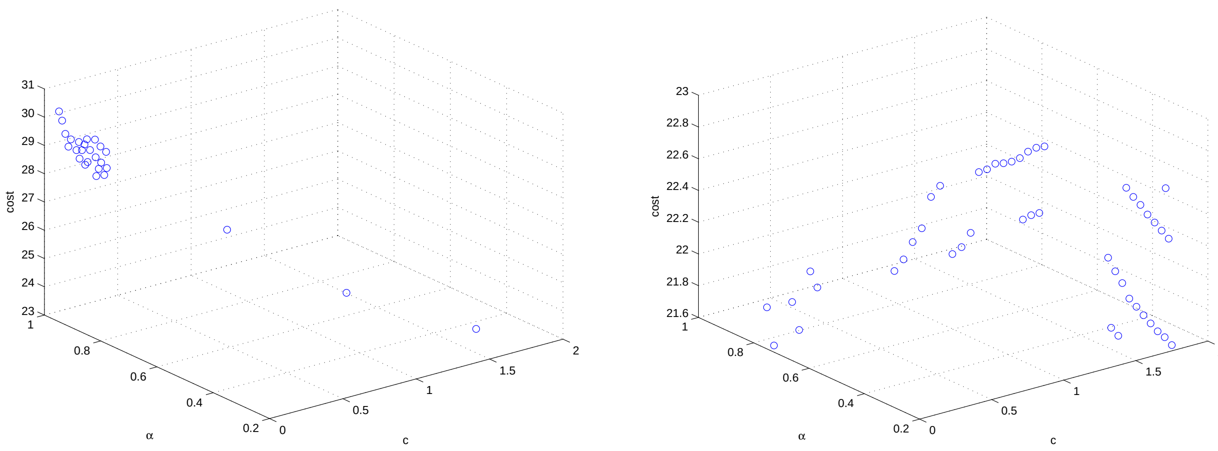
Table 1: Benchmark parameters employed for the model simulations.

possible to uniquely identify the cost-effective policy. Figure 2(b) shows the average cost of the payment scheme for different combinations of (c, α) that satisfy the permanence criterion. The cost of the policy is lower for combinations of c low (high) and α high (low), respectively. When the landowner's opportunity cost is positively correlated with a particular index, then ceteris paribus (comparable probability level), the higher the correlation the lower the cost of the policy. As shown in Table 2, a lower correlation value requires an higher constant component c or an higher variable, indexed component α.

$\rho_{I,A} = 0.5$		$\rho_{I,A} = 0.9$	
c	α	c	α
0.945	0.52	0.846	0.52
0.715	0.60	0.62	0.60
0.31	0.75	0.09	0.75

Table 2: Pairs (c, α) for different level of correlation. The remaining parameters are the one specified in Table 1.

Consistent with conventional findings in the real option literature, we observe that an increase in the uncertainty level of the alternative returns lower the likelihood of land conversion. Table 3 reports the costs for the benchmark and alternative scenarios. In this last the volatility of the index is lower and the volatility of the landowner's opportunity cost is higher than the benchmark scenario. In this case we can say that the cost-effective policy would be one with a higher variable payment at the expense of a lower fixed payment.



(a) (b)

Figure 2: Average cost of the payment scheme for different combinations of (c, α) that satisfy the permanence criterion $p \geq 0.9$ when the returns of the two alternative land uses are uncorrelated (left) or are positively correlated with $\rho_{I,A} = 0.9$. (right). Costs on the z-axis are in 100 \$ per ha.

Benchmark		Alternative	
c	α	c	α
0.846	0.52	0.9	0.52
0.62	0.60	0.65	0.60
0.09	0.75	0.15	0.75

Table 3: Pairs (c, α) considering different scenarios of the volatility levels. In both scenarios $\rho_{I,A} = 0.9$; $\sigma_I = 0.15$ and $\sigma_A = 0.15$ in the benchmark case; $\sigma_I = 0.1$ and $\sigma_A = 0.2$ in the other scenario. The remaining parameters are the one specified in Table 1.

All previous results hold (with reverse sign) when the two alternative land uses are negatively correlated. Testing a policy where the variable component is indexed to an underlying that is negative correlated, however, has no economic meaning.

3 Model Simulations

This section applies the model presented in Section 2 to real-world data. We first calibrate the model to these data and search for the optimal minimum payment that satisfies a given probability level p. In particular, we apply two different observable price indices and construct the returns process I. The results are then discussed at the end of the section.

3.1 Calibration of Model Parameters

The parameters of the first index, i.e. those of the agriculture index returns process of Equation (1), are calibrated based on the time series of the Dow Jones UBS Soybean Index from March 31, 2006 to 2011. These are estimated via maximum likelihood and are reported in Table 4.

	Log returns
μ (ha)	0
σ^2 (ha)	0.018

Table 4: Estimated parameters for the agricultural index (Dow Jones USB Soybean Index).

The second index is based on the carbon dioxide (hereafter CO_2) emission permits price. While not applied to the CDM, linking payments to the secondary market price of permits was originally considered in previous meetings of the United Nations Framework Convention on Climate Change (see Mehta and Capoor (2003); Streck (2005)). Linking payments to compliance carbon markets is hence a possibility. In the voluntary markets, on the other hand, carbon prices and the amount of carbon sequestered are used to calculate payment levels, e.g. see Palmer and Silber (2010).

We consider the amount of CO_2 that would be emitted in case of deforestation on a single hectare of forest land multiplied by the permit price. This index is quantified as:

$$I = CO_2^{Ha} \cdot PC \cdot PERM - CM \tag{13}$$

where CO_2^{Ha} is the amount (in tons) of carbon dioxide per hectare, PC is the price of carbon credits and CM are management and transaction costs. $PERM$ is a factor that accounts for the fact that land-based carbon sequestration may not be permanent, thereby making emission reduction credits from REDD+ less valuable than emission permits generated under the emission trading scheme. Kim et al. (2008) report that so-called 'permanence discounts' in the range of 50 percent are not uncommon. This means that an impermanent sequestration offset may only receive payments amounting to 50 percent of the market carbon price.[11] Since α has a corresponding function in our model we set the

[11]Note that this figure is based on soil-carbon sequestration and afforestation only and is sensitive to a

value of the $PERM$ parameter to 100 percent and, as before, set the permanence criterion, p, at 90 percent. The values of CO_2^{Ha} and CM are reported in Table 7, while those for PC are in table 5.

We base the parameters of PC on the price of the emission permits traded in the European Union Emission Trading Scheme (ETS), since it represent the most liquid emissions market. We consider quoted futures with maturity 2010 from March 31, 2006 to June 2010. Prices are converted into US$.

The parameters of the returns process of Equation 1 are calibrated using the time series of the CO_2 permits index constructed using Equation 13.

	Log returns
μ	0
σ^2	0.029

Table 5: Estimated GBM parameters for the log returns of the European Union Allowance (EUA) carbon price.

For the amount of carbon per ha (the parameter CO_2^{Ha}), we rely on the values and methodology cited in Busch et al. (2009). The default value in Busch et al. (2009) of US$ 4.20 per hectare per year (2008 figures) is used for management and transaction costs. These parameters are reported in Table 7.

Land conversion costs include profits (from timber harvesting) and costs (i.e. timber extraction costs, taxes, farm land costs and clearing and farm establishment costs). For the profit from timber harvesting, we assume that average timber rent in Brazil is US$ 261 per hectare (Busch et al., 2009).[12] See table 7 for the conversion costs used.

The agricultural return process of Equation (2) is the net profit of soybean per hectare. We use the CEPEA/ESALQ index for soybean produced in Parana state, a major soybean producing region in Brazil (see figure 3). The prices are quoted in US$ per 60 kg bag. We assume an average yield of 3,000 kg of soybean per hectare[13], and normalize the price series by dividing all prices by 100. We subtract average production costs of US$ 400 per hectare of land utilising data from Dohlman et al. (2001).

Finally, Table 7 reports parameters related to the agricultural and permits indices, and the conversion costs used in the model. Note that simulations are run for five years only, equivalent to the period of the time series data utilised. The calibrated parameters of Equation (2) are reported in Table 6.

number of assumptions about the model parameters. Kim et al. (2008) calculate the permanence discount as a function of the future needs to replace offsets and the magnitude of any necessary maintenance costs.

[12]Other research suggests a wide range in estimates of timber returns. For example, Boerner and Wunder (2008) find total net returns from timber extraction in Mato Grosso to range from US$ 109 to 734 per ha.

[13]Estimativa do Custo de Producao de Soja, 2009. `http://www.cpao.embrapa.br/publicacoes/ficha.php?tipo=COT&num=155&ano=2009`

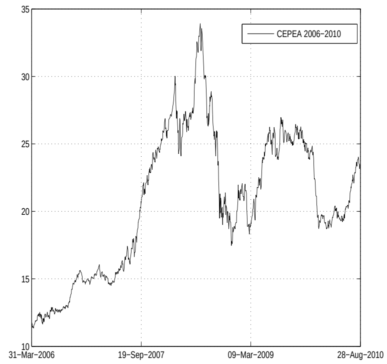


Figure 3: The CEPEA/ESALQ index, 2006-2010.

	Log returns
μ	0
σ^2	0.0192
$\rho_{a,\cdot}$	0.93

Table 6: Estimated parameters for the Cepea Brazilian soybean log returns, March 2006-August 2010. ρ is the constant correlation coefficient between prices of Brazilian soybean (CEPEA) and the Dow Jones index.

	Value
Avg. kg/ha harvest (soybean)	3000 kg (=50 bags of 60kg)
Cost of production per ha	400 $
CM (management costs per ha)	4.22 $
Above and below ground biomass carbon (tons C/ha)	106
Soil carbon (tons C/ha)	96.67
Total Carbon (tons C/ha)	116 (106 + 0.1*96.67)
Total CO_2 (tons CO_2/ha) (factor 3.67)	426
TCC_{FA} per ha	-200/500
CC_{AF} pe ha	1000
$I_{CI,0}$ (mean of log of Index payment (commodity index))	3
$I_{EI,0}$ (mean of log of Index payment ($C0_2$ emissions index))	4.25
A_0 (mean of log of agriculture profits)	3
r (discount factor)	0.05
S (number of Monte Carlo simulations)	10,000
T years and s periods per year	5 and 2
Number of days per year	250

Table 7: Parameters related to agriculture, REDD+ payments and conversion costs.

3.2 Discussion

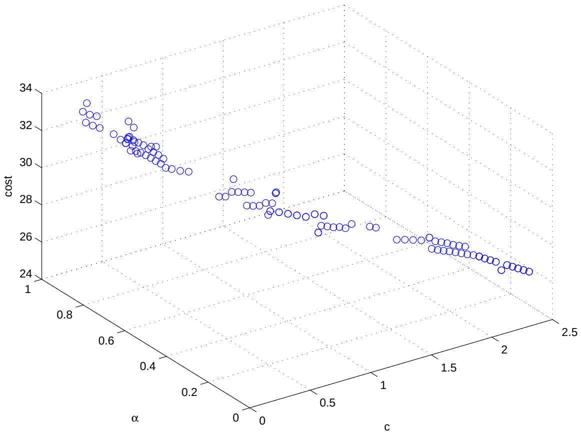
TO BE COMPLETED, FIGURES TO BE REDONE.

Using the calibration of model parameters, we determine the pair (c, α) under the constraint of minimal cost and a permanence criterion of at least 90 percent. Our aim is to compare the relative cost-effectiveness of three scenarios: fixed payments per hectare (scenario 1; $\alpha = 0$); a REDD+ payment that is indexed to the CEPEA/ESALQ index for soybean produced in Parana state (scenario 2; $\rho > 0$); and, a REDD+ payment that is indexed to the carbon market price in the European Union ETS (scenario 3; $\rho = 0$). The first scenario corresponds to the kind of payment scheme as commonly used in PES schemes around the world. The corner solution where $\alpha = 0$ approximates scenario 1. In all scenarios, we assume that REDD+ payments are being made to landowners in the Brazilian state of Parana.

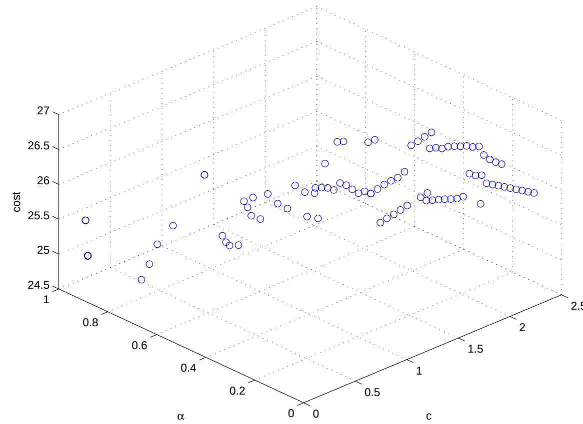
First, we examine cases under scenario 2 in which payments are indexed to soy prices. Thus, there is an assumed high, positive correlation (0.9) between the landowner's opportunity cost of forest conversion and movements in soy prices. Figure 4(b) shows the case where conversion costs are negative, which implies that deforestation yields profits from timber harvesting. Figure 2(b) shows the identical case, except that conversion costs are positive thus implying zero or low timber profits. Examination of figure 4(b) appears to indicate that it might be optimal to choose a relatively high level of α, i.e. strongly tying payments to the soy index. An α of around 0.8 lowers the total scheme cost to under US$ 2500 per ha. Yet, as discussed in Section 2, there is relatively little difference in cost when comparing a scheme with high α-low c and one with low α-high c. This difference is even smaller when excluding timber profits, as in Figure 2(b). But since total scheme costs are around US$ 2200 per ha, targeting REDD+ in areas of low timber profitability could be more cost-effective than targeting areas of high timber profitability.

Second, figures 5(a) and 5(b) represent typical cases of scenario 3 in which payments are indexed to the carbon market. The only difference between the two figures is again the level of conversion costs. Figure 5(a) shows that costs are considerably higher for scenario 3. Thus payments are lower in 4(a) in contrast to those in 5(a). Regardless of whether considering conversion costs or not, the most cost-effective payment scheme is one with a relatively high level of c. Figures 5(a) and 5(b) indicate that scheme costs in scenario 3 decline as α decreases. This implies that a fixed payment (scenario 1) is preferable to one indexed to the carbon market price. If payments are strongly indexed to carbon prices (high α), scheme costs go up to nearly US$ 3800 per ha. In light of indexing REDD+ contracts to the carbon market price this result has important policy implications. Our results indicate that scheme costs could be reduced drastically (by more than US$ 1300 per ha) while maintaining the same level of permanence if payments are instead linked to an agricultural commodity price index. Also note that fixed payments (scenario 1) are less cost-effective than those linked to the soy index.

In order to demonstrate robustness of results, we investigate an intermediate case where the correlation parameter is set to zero (as in scenario 3) but the variance of payments is



(a)



(b)

Figure 4: Average cost of the payment scheme for different combinations of (c, α) that satisfy the permanence criterion $p \geq 0.9$ when the conversion cost C_{FA} is -2. The returns of the two alternative land uses are uncorrelated (left) or are positively correlated with $\rho_{I,A} = 0.9$. (right). Costs on the z-axis are in 100 \$ per ha.

still equal to that of soy profits (as in scenario 2). The difference between the cases is again due to the level of conversion costs. Irrespective of whether or not timber profits are included, a scheme that emphasised fixed payments would be the more cost-effective policy option. Overall, for all scenarios, a higher conversion cost C_{FA} leads to lower total scheme costs. Both the values for α and $c$are lower. Further results indicate that increasing the volatility also has an effect. A more volatile soy price will lead to significantly lower scheme costs. The higher volatility increases the opportunity costs to change land use and consequently increases the frequency level in forest.

4 Conclusions

This paper investigates the implications of landowners' option values in land-use decision making with a focus on switching between forest and agriculture. Irreversible sunk costs along with uncertainties over the returns from future land use are modelled in order to provide insights into the design of payments schemes for Reducing Emissions from Deforestation and Degradation (REDD+). In particular, scheme design is motivated by concerns regarding how policy might secure forest carbon sinks over time while remaining cost-effective. Since 'perfect permanence' is clearly impossible to attain given the range of uncertainties involved in forest policy, the aim is to minimise the risk of deforestation as a result of landowners' changing opportunity costs via the application of a probabilistic approach to payment design.

In applying real options theory, we develop a model in which a variable payment based

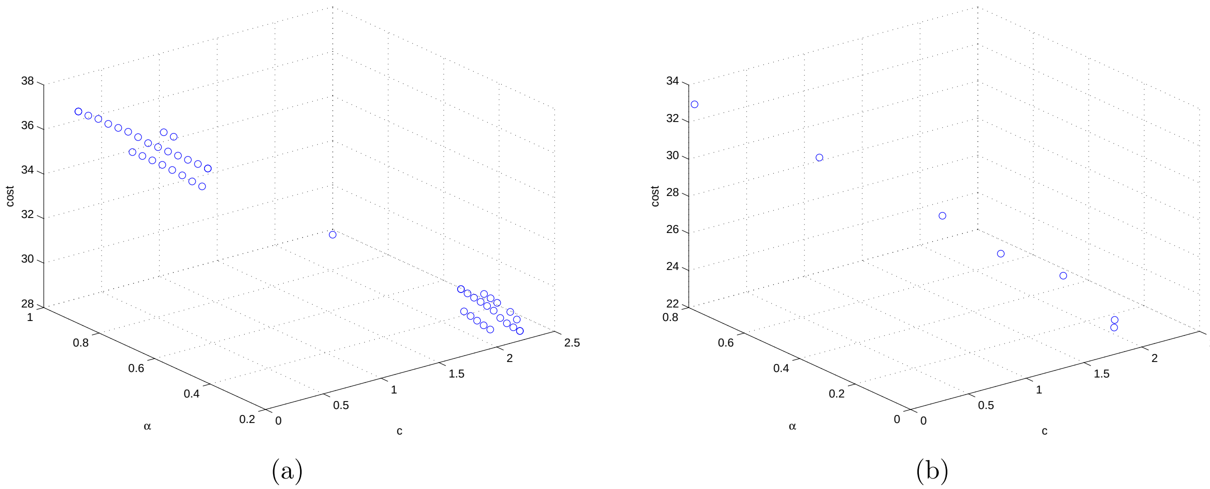


Figure 5: Average cost of the payment scheme for different combinations of (c, α) that satisfy the permanence criterion $p \geq 0.9$ when the conversion cost C_{FA} is -2 (left) or is 5 (right). These two figures represent scenario 3 in which payments are indexed to the carbon market. Thus the returns are uncorrelated. Costs on the z-axis are in 100 \$ per ha.

on an observable price index is introduced alongside a constant, fixed payment. The latter are the usual vehicle for many PES schemes in operation around the world (scenario 1). Variable payments based on an agricultural commodity index (scenario 2) are an innovation that has been proposed in the literature but has not been implemented in actual carbon payments nor has it been thoroughly explored in previous research. Variable payments based on carbon prices (scenario 3) are often observed in the voluntary carbon market and could feature if REDD+ is integrated into a carbon offset market. In all our simulations we set the probabilistic or permanence criterion at 90 percent.

Consistent with the real option literature, we find that increasing uncertainties increase land conversion thresholds in Section 2. This has the following implications. First, the presence of higher uncertainties requires less payments when attempting to avoid a switch from forest to agriculture. Second, higher uncertainties would require more payments in order to induce a switch from agriculture to forest, i.e. via afforestation. Thus, higher uncertainties imply that the conventional net present value approach overestimates the costs of REDD and underestimates the costs of afforestation schemes.

Towards the end of Sections 2 and in 3 we investigate the cost-effectiveness of different pairs of the fixed and variable components of the REDD payment. First, where there is little or no correlation between a proposed payment index and landowner's opportunity cost then in order to meet the permanence criterion, cost-effectiveness would require a fixed rather than a variable payment. This result is relevant when considering aligning payments with the carbon market price and where it may be impossible to rigorously determine a correlation between existing indices and the alternative land use. In these cases, the policy regulator should design a payment scheme with a fixed component only.

But where the landowner's opportunity cost can be shown to be relatively highly correlated with a particular index, such as for soy bean, the higher the correlation the lower the cost of the policy overall. Our simulations suggest that cost savings from the latter approach can be up to a third compared with alternative payment approaches whether fixed payments or indexing to a carbon market. For policy, however, there will always be some degree of information asymmetry in the form of knowing the true opportunity cost and hence, the level of correlation. But even where it could be estimated with a crude degree of precision, e.g. using auctions, there is still the problem of discerning the balance between the variable and fixed components of the payment. One way around this is to measure the volatility of alternative returns from land use. Where the volatility of the index is relatively lower than the volatility of the landowner's opportunity cost the cost-effective policy would be one with a higher variable payment in return for a lower fixed payment. In a context of volatile commodities' markets such as for beef, cattle and oil palm, this kind of payment approach might even help mitigate some of the risk associated with uncertain incomes and returns from agriculture, particularly for poorer landowners.

Finally, we note a number of limitations and ideas for future research. First, landowners' opportunity costs are unlikely driven by a single factor such as prices of alternative land uses. Second, we focus on landowner-scale PES schemes but it is not yet clear that these be a significant feature of a future, international-level REDD+ scheme. While PES may play a role in project-scale pilot activities, perhaps in national-level schemes, other policy instruments are also likely to come into play in the short-term. Third, where these schemes are used a variable payment may be more costly to implement than a fixed payment alone. This could be subject to future, empirical research.

References

Behan, J., McQuinn, K., and Roche, M. (2006). Rural land use: Traditional agriculture or forestry? *Land Economics*, 82(1):112.

Benítez, P., Kuosmanen, T., Olschewski, R., and van Kooten, G. (2006). Conservation payments under risk: a stochastic dominance approach. *American Journal of Agricultural Economics*, 88(1):1–15.

Boerner, J. and Wunder, S. (2008). Paying for avoided deforestation in the Brazilian Amazon: from cost assessment to scheme design. *International Forestry Review*, 10(3):496–511.

Bulte, E., van Soest, D., Van Kooten, G., and Schipper, R. (2002). Forest conservation in Costa Rica when nonuse benefits are uncertain but rising. *American Journal of Agricultural Economics*, 84(1):150–160.

Busch, J., Strassburg, B., Cattaneo, A., Lubowski, R., Boltz, F., Ashton, R., Bruner, A., Creed, A., Obersteiner, M., and Rice, R. (2009). Collaborative modeling initiative on REDD economics. In *IOP Conference Series: Earth and Environmental Science*, volume 6, page 252019. IOP Publishing.

Butler, R., Koh, L., and Ghazoul, J. (2009). REDD in the red: palm oil could undermine carbon payment schemes. *Conservation Letters*, 2(2):67–73.

Dangl, T. and Wirl, F. (2004). Investment under uncertainty: calculating the value function when the Bellman equation cannot be solved analytically. *Journal of Economic Dynamics and Control*, 28(7):1437–1460.

Dixit, A. (1989). Entry and Exit Decisions under Uncertainty. *Journal of Political Economy*, 97(3):620–638.

Dixit, A. K. and Pindyck, R. S. (1994). *Investment under Uncertainty.* Princeton University Press, Princeton, New Jersey.

Dohlman, E., Schnepf, R., and Bolling, C. (2001). Soybean Production Costs and Export Competitiveness in the United States, Brazil, and Argentina. *Oil Crops Situation and Outlook*, pages 16–24.

Dutschke, M. and Angelsen, A. (2008). How do we ensure permanence and assign liability. *Moving Ahead with REDD: Issues, Options and Implications*, pages 77–86.

Dutschke, M. and Wong, J. (2003). Can Permanence Be Insured? Consideration of Some Technical and Practical Issues of Insuring Carbon Credits from Afforestation and Reforestation. HWWA Discussion Paper No. 26270.

Engel, S., Pagiola, S., and Wunder, S. (2008). Designing payments for environmental services in theory and practice: An overview of the issues. *Ecological Economics*, 65(4):663–674.

Gregersen, H., El Lakany, H., Karsenty, A., and White, A. (2010). Does the opportunity cost approach indicate the real cost of redd+. *Rights and Resources Initiative*.

Guthrie, G. and Kumareswaran, D. (2009). Carbon Subsidies, Taxes and Optimal Forest Management. *Environmental and Resource Economics*, 43(2):275–293.

Isik, M. and Yang, W. (2004). An analysis of the effects of uncertainty and irreversibility on farmer participation in the conservation reserve program. *Journal of Agricultural and Resource Economics*, 29(02).

Kim, M., McCarl, B., and Murray, B. (2008). Permanence discounting for land-based carbon sequestration. *Ecological Economics*, 64(4):763–769.

McDonald, R. and Siegel, D. (1986). The value of waiting to invest. *The Quarterly Journal of Economics*, 101(4):707–728.

Mehta, A., S. C. and Capoor, K. (2003). Contracting for carbon. *Environmental Finance*, pages 28–29.

Miranda, M. J. and Fackler, P. L. (2002). *Applied Computational Economics and Finance*. MIT Press.

Nepstad, D., Soares-Filho, B., Merry, F., Moutinho, P., Rodrigues, H., Schwartzman, S., O., A., and S., R. (2007). *The costs and benefits of reducing carbon emissions from deforestation and forest degradation in the Brazilian Amazon*. Woods Hole Research Center.

Palmer, C. and Silber, T. (2010). Trade-offs between carbon sequestration and poverty alleviation in community-based land use systems: Preliminary evidence from Mozambique. *Research Papers in Spatial and Environmental Analysis*, 130.

Pindyck, R. S. (1988). Irreversible investment, capacity choice, and the value of the firm. *American Economic Review*, 78:969–985.

Pindyck, R. S. (1991). Irreversibility, uncertainty, and investment. *Journal of Economic Literature*, 29:1110–1148.

Schatzki, T. (2003). Options, uncertainty and sunk costs: an empirical analysis of land use change. *Journal of environmental economics and management*, 46(1):86–105.

Streck, C. (2005). World bank carbon finance business: Contracts and emission reductions purchase transactions. In Freestone, D. and Streck, C., editors, *Legal aspects of implementing the Kyoto Protocol mechanisms: making Kyoto work*. Oxford University Press.

Watson, R., Noble, I., Bolin, B., Ravindranath, N., Verardo, D., and Dokken, D. (2000). Land use, land-use change and forestry: a special report of the intergovernmental panel on climate change. *Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change*.

Wiemers, E. and Behan, J. (2004). Farm forestry investment in Ireland under uncertainty. *The Economic and Social Review*, 35(3):305–320.