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Long-term versus temporary certified emission reductions in forest carbon sequestration programs*

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Under the Clean Development Mechanism (CDM) of the Kyoto Protocol, forest projects can receive returns for carbon sequestration via two crediting instruments: temporary or long-term certified emission reductions (tCERs or lCERs). This study shows the effect of lCERs on the private owner's forest rotation intervals decision and carbon credit generation in afforestation and reforestation projects. A credit verification mechanism with a harvest penalty implemented under the lCERs policy distorts the timber harvesting decision and the corresponding carbon credit supply. Two opposing incentives are created by the lCERs mechanism which leads to either longer or shorter rotations compared to the Faustmann rotation, depending on which incentive prevails. Our numerical results show that both lCERs and tCERs seem to have similar impacts on harvesting incentives, but the resulting carbon supply differs among the instruments owing to the credit verification mechanism. The tCERs carbon supply curve is monotonically increasing in the carbon price, while a lCERs carbon supply is non-monotonic and may have a backward bending region over a range of carbon prices.

Key words: carbon sequestration, forest rotation, long-term certified emission reductions (lCERs).

1. Introduction

Given the recent concerns over climate change, various programs have been proposed to mitigate greenhouse gas emissions. Afforestation and reforestation have the potential to sequester significant amounts of carbon through the absorption of carbon dioxide and other greenhouse gases (Sedjo and Solomon 1989; Nordhaus 1991; Richards 1992; Binkley and van Kooten 1994; Cacho *et al*. 2003; Lee *et al*. 2005). Under the Clean Development Mechanism (CDM) of the Kyoto Protocol, forest managers can enter into contracts to offset man-made carbon emissions and generate two different types of carbon credit, or *certified emissions reductions* (CERs), known

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respectively as *temporary* or *long-term certified emission reductions*: tCERs and lCERs (UNFCCC 2003).

A unit of CERs is equal to one metric ton of carbon dioxide equivalent (CO_2e) sequestered from trees (CDM Rulebook, 2009a). These CERs are verified by the CDM executive body every 5 years (UNFCCC 2003) and may be purchased by the users of carbon credits to meet their carbon emissions compliance requirements. Forest owners benefit from participation, because they are able to generate extra revenue from standing forest biomass. Seventeen tCERs projects had been approved by September 2010, and the first lCERs project was approved in December 2010 (UNFCCC, 2010).

With a tCERs project, the CDM executive verifies and issues tCERs based on the amount of total carbon stock sequestered in standing forest at a certain verification date. Verified tCERs are valid for use as carbon offsets by buyers during a 5-year period. The tCERs expires after the 5-year period, and the buyer must either contract for more tCERs or satisfy their emissions obligations in some other way.

While tCERs are based on the carbon stock at a given verification date, lCERs are based on a measure of the flow of carbon, which is the difference in the carbon stock between two verification periods. (UNFCCC 2006; CDM Rulebook, 2009b). Accrued lCERs can be used as valid CO_2e offsets from the verification period until the end of the project. However, if there is a biomass reduction event between verifications (such as harvest), there will be a penalty or reduction in valid accumulated lCERs equal to the reduction in CO_2e sequestered.[1] Contract producers are responsible to reimburse a loss to purchasers of lCERs.

This article develops a theoretical model to examine optimal harvesting strategies based on the value of harvested timber and revenues from sequestered carbon under lCERs. We simulate optimal rotation intervals and carbon supply curves under the lCERs instrument using our model and compare with those under tCERs.[2] The theoretical results are applied to Tanzania and the Philippines, two developing countries that have the potential to sponsor afforestation and reforestation projects to generate lCERs under the CDM. The study also provides a dynamic framework for measuring the feasibility of a given forest plantation that sequesters carbon under this instrument.

This paper extends a growing literature on carbon sequestration instruments for forestry. Attaching a positive value to a continuous flow of

[1] This is a stylistic representation of the harvest penalty based on the current conceptual framework outlined in the modalities and procedures for afforestation and reforestation project activities under the CDM (UNFCCC 2003). In practice, the penalty in a project depends on negotiations between the buyer and seller of the credits as well as the authorizing body under the CDM.

[2] Although the short-term nature of tCERs provides flexibility to program participants, they are not as compatible with credits generated from national or regional emissions trading schemes such as the European Union allowance (Bird *et al.* 2004). The lCERs instrument addresses this issue to some extent.

sequestered carbon dioxide emissions in forest rotation models is likely to result in optimal rotation intervals that are longer than the privately selected rotation interval (Plantinga and Birdsey 1994). Hoen and Solberg (1997) and van Kooten *et al.* (1995) derive the optimal carbon subsidy and tax mechanism to internalize the carbon sequestration function of the forest. Guthrie and Kumareswaran (2009) extend their models by incorporating timber price uncertainty to evaluate the costs and benefits of a hypothetical carbon credit certification scheme while Spring *et al.* (2005) examine the effect of wildfire risk in sequestering forest carbon.

Germain *et al.* (2007) and Olschewski *et al.* (2005) examine the economic feasibility of carbon credit projects for developing countries, given the current carbon crediting mechanisms for forest projects under the CDM. However, their model does not consider the dynamic aspects of rotation interval choices and corresponding carbon storage. Galinato and Uchida (2010, 2011) were the first to examine the effect of implementing the current tCERs mechanism on the choice of rotation intervals, the supply of carbon credits and social welfare. Both studies find that the tCERs instrument partially internalizes the carbon sequestration function of forests.

Our article is the first study that investigates the effect of lCERs, as outlined in the UNFCCC modalities and procedures for forest activities, on rotation intervals and carbon credit supplies of forestry projects. In the light of potential increasing reliance on lCERs in the future, there is a need to understand the incentives and management implications of lCERs. We are not aware of any study that has modelled the impact of lCERs on harvesting decisions and carbon credit supply. Understanding and comparing the tCERs and lCERs instruments which regulate these forestry projects will be important as the instruments are revised in the future.

As shown in this analysis, the discrete nature of verification periods under the CDM along with the other characteristics of lCERs leads to some idiosyncratic effects on rotation choice and carbon credit supply. The design of the penalty under lCERs in conjunction with the fixed verification periods is critical in determining the rotation length and carbon credit supply. Given the current guidelines for lCERs, the penalty creates opposing incentives on rotation length. The penalty is an increasing function of the difference in biomass before and after harvesting between verifications. Thus, the landowner can reduce the *nominal* value of the penalty by shortening the rotation interval. However, he can also reduce the *present* value by lengthening it so the penalty is received later rather than earlier. If the former effect outweighs the latter effect, the rotation interval is shorter than the case without a penalty but when the opposite holds rotations are longer.

Increasing the sequestration of carbon is the stated goal of CERs, but the structure of the lCERs penalty leads to some potentially undesired carbon sequestration outcomes. We show that in some cases, there is a backward-bending region in the carbon sequestration supply curve. Under certain circumstances, the lCERs instruments induce very little increase in carbon

sequestration for a given forest stand. However, a higher carbon price increases land rents for stands under the lCERs certification rule, so lCERs provide an incentive for land conversion from other uses to forestry. The results of our model suggest a need to carefully design the penalty mechanism in afforestation and reforestation projects that generate lCERs.

The rest of the paper proceeds as follows: the next section provides an overview of the current guidelines for generating lCERs with afforestation and reforestation programs under the CDM and compares it with tCERs. Section 3 presents the theoretical model for lCERs that solves for optimal rotation intervals under an infinite rotation horizon. Section 4 summarizes results from simulations in the Philippines and Tanzania. Section 5 concludes the study.

2. An overview of temporary and long-term certified emission reductions

Under the CDM, forestry projects that generate tCERs or lCERs are subject to a number of participation criteria and technical standards. The host country must have ratified the Kyoto Protocol and established a Designated National Authority (DNA) that determines the feasibility of crediting projects within the country. To be eligible, a proposed forest project must not be required by national or local law, and the targeted land must be without forest cover between 31 December 1989 and the starting date of the project. Under the current rules, tCERs and lCERs forest projects can last from 20 to 60 years depending on the type of trees and other economic and environmental factors (UNFCCC 2003).

Figure 1 demonstrates how lCERs are generated under a multiple rotation system for a hypothetical forest project. The example in Figure 1 assumes a 30-year crediting period, which is the total number of years that the project may generate lCERs. The project begins in the year 2010, and the landowner is allowed to choose the first crediting verification of sequestered carbon at any point after the forest project starts (UNFCCC 2003). The first verification

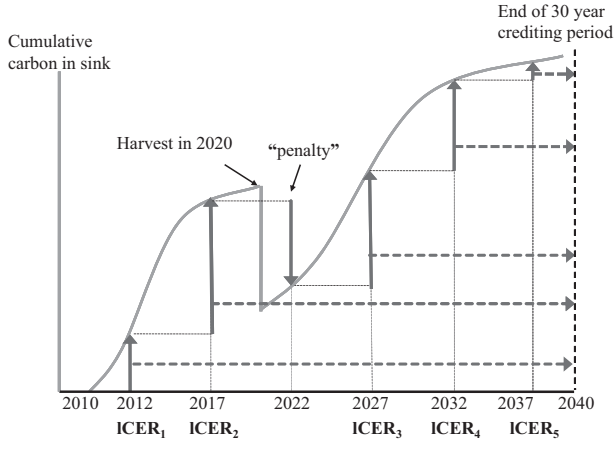

Figure 1 The lCERs mechanism.

period is selected in year 2012 in the example. After the first verification, the subsequent verification periods take place every 5 years in 2017, 2022 and so on until the last verification in 2037, before the end of the project in 2040 (UNFCCC 2003). At each verification period, the DNA verifies and issues lCERs based upon the additional carbon sequestered from the previous verification period to the current verification period. Suppose that all trees are harvested in year 2020, and a decrease in the carbon stock is observed.[3] The penalty is then imposed in the next verification in year 2022 and is equal to the value of the difference in carbon stock in year 2022 and 2017. The solid vertical arrows indicate the amount of accredited carbon sequestered, the downward arrow in year 2020 displays the penalty, and the dashed horizontal arrows indicate the years each unit of lCERs is valid for sale, purchase and use as a carbon offset.

Issued lCERs that are purchased by firms are valid as CO_2e offsets through the end of the crediting period and depends on incremental gains and losses in the carbon stock of the project sink. If a landowner sells lCERs early in the crediting period based on expected carbon stock accumulation and there is a subsequent loss in carbon stock because of harvesting or any other events, the landowner is required to replace or remunerate the buyer for the reversed units of lCERs (UNFCCC 2003; Bird *et al*. 2004). Alternatively, the landowner may choose not to sell lCERs that would be reversed in the verification following harvest. The landowner can still earn additional revenue from sequestered carbon in subsequent verifications as long as the volume of trees in subsequent verifications is larger than in previous verifications.

Projects that adopt tCERs are subject to the same participation criteria and technical standards as lCERs. While verification periods also occur in 5-year intervals, tCERs are generated based on *total* amount sequestered at a verification period and not the incremental gain since the last verification. Figure 2 illustrates a project generating tCERs where the first verification occurs in year 2012 with subsequent verification periods every 5 years until the end of the crediting period in 2040. The amount of tCERs accrued at verification is measured by the vertical arrows. Loss in carbon stock after a verification owing to harvesting has no impact on the validity of tCERs already issued, but can affect the amount of tCERs generated in the next verification cycle (UNFCCC 2006). Also, tCERs expire for use by the buyer as an offset after 5 years once the subsequent tCERs have been issued in the next verification period; thus, they are termed 'temporary' (UNFCCC 2003).

3. Infinite rotation model for long-term certified emission reductions

We integrate two important characteristics of the lCERs instrument into an optimal rotation model. First, lCERs are based on additional carbon sequestered from one verification period to the next. Second, we account for the loss

[3] Note that in Figure 1, carbon stock in tree biomass does not go to zero due to harvest in practice. This is because some amount of carbon is stored in the soil.

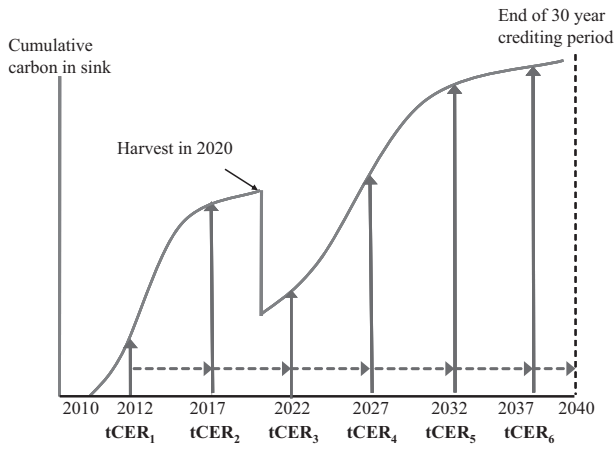

Figure 2 The tCERs mechanism.

of any biomass during harvest as a penalty based on the reduction in carbon sequestered between the adjacent verification periods.

We suppose that a landowner maximizes the net present value of forest activities by selecting optimal forest rotation intervals in an infinite time horizon for an even-aged stand that is clear-felled at harvest.[4] We assume that timber revenues and verified lCERs are the primary benefits for the landowner. The lCERs revenue is earned over a 60-year crediting period during the forest project. We identify three types of rotations in our infinite rotation model: (i) rotations within the crediting year period; (ii) a rotation that could be in transition from the crediting period to the post-crediting period; and (iii) rotations after the crediting period. We first solve the harvesting decision without carbon credits to derive the value function after the 60-year crediting period. Then, we substitute the value function back into the main objective function to solve for the rotations during the crediting period as well as the transitional rotation.

3.1. Rotations after the carbon crediting period

After the maximum 60-year crediting period, the landowner earns a profit only from timber. Assuming a constant net timber price, discount rate and planting cost, the discounted future profit from forest rotations after the crediting period at the time when the transitional rotation ends, π_a, is equal to[5]

[4] Note that we assume zero carbon left at harvest although some residuals of carbon are stored in the soil or harvested timber. This simplifies our model but does not affect our results.

[5] Various forms of uncertainty pertaining to tree growth and prices of timber and carbon are relevant in analyzing the landowner's rotation decision. Some of these issues are modeled in real options theory as applied to forest management. However, it is difficult to derive a meaningful analytical formula, particularly in our infinite horizon formulation involving both continuous and discrete choices as described below. Rather than introducing these complications in an already complicated model, we provide sensitivity analyses in the simulation section that show the effect of changes in discounting and timber and carbon prices.

$$\max_{t_f} \pi_a = \frac{p_v V(t_f) - Q}{e^{rt_f} - 1} - Q \tag{1}$$

where $V(\cdot)$ is timber volume at time t_f, p_v is the net price of timber, Q is the fixed cost of planting and r is the discount rate. The optimal rotation interval after the crediting period is characterized as the Faustmann rotation, t_f, where the marginal value of timber equals the marginal opportunity cost of timber and land. Note that the optimal value π_a* starts when the last rotation interval during the 60-year crediting period or the transition rotation ends. Thus, π_a* occurs any time after year 60 and does not necessarily start in year 61.

3.2. Rotations during the carbon crediting period

During the 60-year crediting period, the landowner earns revenues from timber and verified lCERs. The number of lCERs accrued in each verification period amounts to the additional carbon biomass accumulated through the growth in wood mass since the previous verification period. Because the verification intervals are fixed at 5 years, the timing of the first verification period determines the timing of all the subsequent verification dates during the 60-year crediting period.

The present value of carbon revenue generated during the first stand rotation, R_1, is

$$R_1 = p_c \alpha V(t_v) e^{-rt_v} + p_c \alpha \sum_{j=0}^{n_1-1} \Delta V(J_1) e^{-r(t_v+5(j+1))} \tag{2}$$

where p_c is a constant carbon market price per unit of sequestered carbon, α is the carbon conversion coefficient of tree volume, t_v is the initial date of verification, j is an index for the verification period, n_1 is the number of verification periods after t_v, and $\Delta V(J_1) \equiv V(t_v + 5(j + 1)) - V(t_v + 5j)$ is the difference in the volume of timber between the jth and the $(j + 1)$th verification. The first verification generates the first carbon revenue of $p_c\alpha(V(t_v) - V(0))e^{-rt_v}$ which is equal to the first term in (2) because $V(0) = 0$. Carbon revenues during subsequent verifications are provided by the second term in (2).

For the subsequent forest stand rotations, carbon revenues continue to be earned based on incremental carbon sequestration between verification periods. However, a penalty is imposed in the following verification period after harvest because the current stock of carbon biomass is less than at the verification period prior to harvest. Given this penalty mechanism, the net carbon revenues during any subsequent forest stand rotation interval i during the 60-year crediting period, R_i, can be written as:[6]

[6] Note that Equation (3) assumes $n_i > 1$. If $n_i = 1$, Equation (3) consists only of the second term.

$$
\begin{aligned}
R_i = p_c\alpha \sum_{j=1}^{n_i-1} \Bigg(& V\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + j + 1\right) - \sum_{l=0}^{i-1} t_l\right) \\
& - V\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + j\right) - \sum_{l=0}^{i-1} t_l\right)\Bigg) e^{-r\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + j + 1\right)\right)} \\
& + p_c\alpha\left(V\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + 1\right) - \sum_{l=0}^{i-1} t_l\right) - V\left(t_v + 5\sum_{l=0}^{i-1} n_l - \sum_{l=0}^{i-2} t_l\right)\right) \\
& \times e^{-r\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + 1\right)\right)} \quad \forall i = 2, \ldots, m
\end{aligned}
\tag{3}
$$

where t_i is the ith timber rotation length, n_i is the number of verifications during the ith rotation and m is an index for the final forest rotation before the crediting period ends. The rotation intervals may vary because the fixed and discrete 5-year verification intervals can influence the timing of harvesting differently across rotations. The first term of (3) represents carbon revenues generated from additional carbon sequestered between the verification periods within the ith forest rotation. The second term represents the penalty that the landowner incurs during the verification period after timber harvest. Note that the first expression in the penalty denotes tree volume at the first verification following stand harvest while the second expression denotes volume at the last verification before harvest.

By compactly defining the timber volume differences in the first term and the second term of Equation (3) as $\Delta V(J_2)$ and $\Delta V(J_3)$ where the former is the difference between verification periods while the latter is the difference between the last verification period in one rotation and the first verification period in the next rotation, respectively, we can rewrite Equation (3) as:[7]

$$
\begin{aligned}
R_i = p_c\alpha \sum_{j=1}^{n_i-1} (\Delta V(J_2)) e^{-r\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + j + 1\right)\right)} \\
+ p_c\alpha(\Delta V(J_3)) e^{-r\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + 1\right)\right)} \quad \forall i = 2, \ldots, m
\end{aligned}
$$

The total value of the forestry project during the 60-year project is the sum of the net present value of carbon revenues in Equations (2) and (3) and timber revenues:[8]

[7] Definition of important parameters and indexes is summarized in Table 1.
[8] We define the parameters n_0 and t_0 to be equal to 0.

Table 1 Definition of variables and indexes in the theoretical model

Variable	Definition
n_1	Number of verification periods after t_v in the first rotation
n_i	Number of verifications in the ith timber rotation from rotations $i = 2$ to m
t_i	Length of the ith timber rotation
t_f	Length of the Faustmann rotation
t_v	Initial verification year
i	Index for timber rotations, $i = 1,\ldots,m$
j	Index for credit verifications

$$\pi_b = R_1 + \sum_{i=2}^{m} R_i + \sum_{i=1}^{m} \left(p_v V(t_i) e^{-r \sum_{l=1}^{i} t_l} - Q e^{-r \sum_{l=0}^{i-1} t_l} \right) \tag{4}$$

Note that the final rotation during the crediting period, t_m, is a transition rotation from the crediting period to the non-crediting period, where the forest stand is not necessarily harvested in year 60 but can continue to grow before the Faustmann rotation t_f starts.

Two sets of constraints are faced by the landowner. The first set of constraints requires that the last verification during the rotation interval must take place no later than the harvesting date. For the first harvest, this implies $t_1 \geq t_v + 5n_1$, and for the second harvest, $t_1 + t_2 \geq t_v + 5(n_1 + n_2)$. This is generalized for the ith rotation as

$$\sum\nolimits_{l=1}^{i} t_l \geq t_v + 5 \sum\nolimits_{l=1}^{i} n_l \quad \forall i = 1, \ldots, m \tag{5}$$

In addition to the first set of constraints, the last verification period of the project must not go beyond year 60, implying

$$60 \geq t_v + 5 \sum\nolimits_{i=1}^{m} n_i \tag{6}$$

The landowner's problem is to select all m rotation intervals, $t_1,\ldots,t_m$, and the initial verification period, t_v, to maximize the net present value of his profit, which is equal to (4) plus the value function of (1) discounted to present value terms:

$$\max_{t_1,\ldots,t_m,t_v} \left\{ \pi_b + \pi_a^* e^{-r \sum_{i=1}^{m} t_i} \right\} \tag{7}$$

subject to constraints (5) and (6).

The Lagrangian of the landowner's problem is formulated as

$$L = \pi_b + \pi_a^* e^{-r \sum_{i=1}^{m} t_i} + \sum\nolimits_{i=1}^{m} \lambda_i \left(\sum\nolimits_{l=1}^{i} t_l - t_v - \sum\nolimits_{l=1}^{i} 5n_l \right) + \lambda_z \left(60 - t_v - \sum\nolimits_{l=1}^{m} 5n_l \right)$$

where λ_i's and λ_z are the respective Lagrangian multipliers of the constraints on the choice variables t_i's and t_v. The corresponding Kuhn–Tucker conditions that solve the problem are the following.
For $i = 1$ to $m - 1$ (if $m \geq 2$):

$$\begin{aligned}\frac{\partial L}{\partial t_i} &= p_v V'(t_i) e^{-r\sum_{l=0}^{i} t_l} + r\left(\sum_{k=i}^{m} Q e^{-r\sum_{l=0}^{k} t_l} - p_v \sum_{k=i}^{m} V(t_k) e^{-r\sum_{l=1}^{k} t_l} - \pi_a e^{-r\sum_{l=1}^{m} t_l}\right) \\ &\quad - p_c \alpha \sum_{k=i}^{m-1} \sum_{j=1}^{n_k} \left(\Delta V'(J_{k1}) e^{-r\left(t_v + 5\left(\sum_{l=0}^{k} n_l + j + 1\right)\right)}\right) \\ &\quad - p_c \alpha \left(V'\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + 1\right) - \sum_{l=0}^{i-1} t_l\right) e^{-r\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + 1\right)\right)}\right. \\ &\quad \left. + \sum_{k=i+1}^{m-1} \left[\Delta V'(J_{k2}) e^{-r\left(t_v + 5\left(\sum_{l=0}^{k} n_l + 1\right)\right)}\right]\right) \\ &\quad + \sum_{k=i}^{m} \lambda_k \leq 0, \text{ with } t_i \geq 0,\ t_i \frac{\partial L}{\partial t_i} = 0\end{aligned} \tag{8}$$

For $i = m$:

$$\begin{aligned}\frac{\partial L}{\partial t_m} &= p_v (V'(t_m) e^{-rt_m} - rV(t_m)) e^{-r\sum_{l=1}^{m} t_m} \\ &\quad - r\left(\frac{p_v V(t_f) - Q}{e^{rt_f} - 1} - Q\right) e^{-r\sum_{l=1}^{m} t_l} + \lambda_m \leq 0, \text{ with } t_m \geq 0,\ t_m \frac{\partial L}{\partial t_m} = 0\end{aligned} \tag{9}$$

$$\begin{aligned}\frac{\partial L}{\partial t_v} &= p_c \alpha \sum_{i=2}^{m} \left(\sum_{j=1}^{n_i - 1} (\Delta V'(J_2) - r\Delta V(J_2)) e^{-r\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + j + 1\right)\right)}\right. \\ &\quad \left. + (\Delta V'(J_3) - r\Delta V(J_3)) e^{-r\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + 1\right)\right)}\right) \\ &\quad + p_c \alpha (V'(t_v) - rV(t_v)) e^{-rt_v} + p_c \alpha \sum_{j=0}^{n_1 - 1} \left(\Delta V'(J_1) - r\Delta V(J_1)\right) \\ &\quad \times e^{-r(t_v + 5(j+1))} - \sum_{i=1}^{m} \lambda_i - \lambda_z \leq 0, \text{ with } t_v \geq 0,\ t_v \frac{\partial L}{\partial t_v} = 0\end{aligned} \tag{10}$$

$$\frac{\partial L}{\partial \lambda_i} = \sum_{l=0}^{i} t_l - t_v - \sum_{l=0}^{i} 5n_l \geq 0,\ \lambda_i \geq 0,\ \text{with}\ \lambda_i \frac{\partial L}{\partial \lambda_i} = 0 \quad \forall i = 1, \ldots, m \tag{11}$$

$$\frac{\partial L}{\partial \lambda_z} = 60 - t_v - 5\sum_{l=1}^{m} n_l \geq 0,\ \lambda_z \geq 0,\ \text{with}\ \lambda_z \frac{\partial L}{\partial \lambda_z} = 0 \tag{12}$$

where

$$\Delta V'(J_{k1}) \equiv V'\left(t_v + 5\left(\sum_{l=0}^{k} n_l + j + 1\right) - \sum_{l=0}^{k} t_l\right) - V'\left(t_v + 5\left(\sum_{l=0}^{k} n_l + j\right) - \sum_{l=0}^{k} t_l\right)$$

and

$$\Delta V'(J_{k2}) \equiv V'\left(t_v + 5\left(\sum_{l=0}^{k} n_l + 1\right) - \sum_{l=0}^{k} t_l\right) - V'\left(t_v + 5\sum_{l=0}^{k} n_l - \sum_{l=0}^{k-1} t_l\right)$$

are the derivatives of the additional growth of volume over time.

When all constraints are non-binding, all the Lagrangian multipliers are equal to zero. In this case, the initial verification period is chosen such that the marginal opportunity cost of carbon revenues equals the value of the marginal product of carbon biomass as shown in (10). Equation (9) indicates that the transition rotation interval, t_m, becomes the Faustmann rotation interval. This occurs because there is no impact of carbon revenues on the rotation interval when the last verification period in the last rotation does not coincide with the harvest date.

For all other rotation intervals $i = 1$ to $m - 1$, manipulation of (8) provides

$$\begin{aligned}
&p_v V'(t_i) e^{-r\sum_{l=0}^{i} t_l} - \sum_{k=i+1}^{m-1} p_c \alpha \Delta V'(J_{k2}) e^{-r(t_v + 5(\sum_{l=0}^{k} n_l + 1))} \\
&\quad = r\left(p_v \sum_{k=i}^{m} V(t_k) e^{-r\sum_{l=1}^{k} t_l} - \sum_{k=i}^{m} Q e^{-r\sum_{l=0}^{k} t_l} + \pi_a e^{-r\sum_{l=1}^{m} t_l}\right) \\
&\qquad + p_c \alpha \left(V'\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + 1\right) - \sum_{l=0}^{i-1} t_l\right) e^{-r\left(t_v + 5\left(\sum_{l=0}^{i-1} n_l + 1\right)\right)}\right) \\
&\qquad + p_c \alpha \sum_{k=i}^{m-1} \sum_{j=1}^{n_k} \left(\Delta V'(J_{k1}) e^{-r\left(t_v + 5\left(\sum_{l=0}^{k} n_l + j + 1\right)\right)}\right)
\end{aligned} \tag{13}$$

This implies that for each ith rotation, the marginal revenue of harvesting is equated to the marginal opportunity cost of harvesting. On the left-hand side of the equation, the marginal revenue from harvest consists of the marginal value of timber as well as the marginal return from delaying the penalty for reductions in timber volume owing to harvest. On the right-hand side, the opportunity cost of harvesting includes the foregone interest from the opportunity of investing timber revenues at interest rate r in the current and all other future rotations (first term), as well as the foregone opportunity for carbon revenues during all future verification periods (second and third terms).

The lCERs penalty from reduced carbon storage via harvest can be mitigated in two ways. First, because the penalty is based on the difference in tree volume between the verification period before harvest and the verification period after harvest, the landowner can reduce the nominal value of the penalty by harvesting earlier in a verification period, as hinted by the second term on the left-hand side of (13). Harvesting earlier reduces the difference between biomass volumes from the two surrounding verification periods, because the average rate of carbon sequestration over a verification period is higher for younger trees. On the other hand, the number of times a penalty is incurred and the present value of each of the penalties can be reduced by delaying the harvesting date as shown by the third term on the right-hand side of (13). In the extreme case where the penalty is large, the harvest date may be postponed until after the last verification date of the project to avoid the penalty.

When the first set of constraints are all binding ($\lambda_i > 0$ for $i = 1,\ldots,m$) and the second constraint is not binding ($\lambda_z = 0$), the optimal rotation intervals, except the first rotation, can be solved independently from the choice of the initial verification date. When the first m constraints are binding, we have $t_i = 5n_i$ for $i = 2$ to m which solve for the optimal rotation intervals after the first rotation. The two remaining choice variables, t_1 and t_v, have the relationship $t_1 = t_v + 5n_1$. Solving for $\sum_{i=1}^{m} \lambda_i$ in (10) and substituting into (8) along with the binding constraints $t_i = 5n_i$ yields the optimal condition of the first rotation interval as,

$$
\begin{aligned}
rp_c\alpha\Bigg(& V(t_v)e^{-rt_v} + \sum_{j=0}^{n_1-1} \Delta V(J_1)e^{-r(t_v+5(j+1))} \\
& + \sum_{i=2}^{m}\left(\sum_{j=1}^{n_i-1} \Delta V(J_2)e^{-r\left(t_v+5\left(\sum_{l=0}^{i-1} n_l+j+1\right)\right)} + \Delta V(J_3)e^{-r\left(t_v+5\left(\sum_{l=0}^{i-1} n_l+1\right)\right)}\right)\Bigg) \\
& + rp_v\sum_{k=1}^{m}\left(V(t_k)e^{-r\sum_{l=1}^{k} t_l} - Qe^{-r\sum_{l=0}^{k} t_l}\right) + r\pi_a e^{-r\sum_{l=1}^{m} t_l}
\end{aligned}
$$

$$
\begin{aligned}
&= p_v V'(t_1)e^{-rt_1} + p_c\alpha\left(\sum_{i=2}^{m}\left(\sum_{j=1}^{n_i-1}\Delta V'(J_2)e^{-r\left(t_v+5\left(\sum_{l=0}^{i-1}n_l+j+1\right)\right)}\right.\right.\\
&\quad\left.\left.+\Delta V'(J_3)e^{-r\left(t_v+5\left(\sum_{l=0}^{i-1}n_l+1\right)\right)}\right)+V'(t_v)e^{-rt_v}+\sum_{j=0}^{n_1-1}\Delta V'(J_1)e^{-r(t_v+5(j+1))}\right)\\
&\quad -p_c\alpha\left(V'\left(t_v+5\left(\sum_{l=0}^{i-1}n_l+1\right)-\sum_{l=0}^{i-1}t_l\right)e^{-r(t_v+5)}\right.\\
&\quad\left.+\sum_{k=1}^{m-1}\sum_{j=1}^{n_k}\Delta V'(J_{k1})e^{-r\left(t_v+5\left(\sum_{l=0}^{k}n_l+j+1\right)\right)}+\sum_{k=2}^{m-1}\Delta V'(J_{k2})e^{-r\left(t_v+5\left(\sum_{l=0}^{k}n_l+1\right)\right)}\right)
\end{aligned}
\tag{14}
$$

The left-hand side of (14) states that the marginal opportunity cost of harvesting is comprised of three elements: the opportunity cost of carbon revenues (first bracketed term), the opportunity cost of timber during all rotations (second bracketed term) and the opportunity cost of land (last term). These are equated to the summation of the marginal benefit of timber (first term), the marginal value of carbon biomass in the first rotation (second term) and the marginal value of delaying the penalty (third term) on the right-hand side of the equation. Note that even though the marginal opportunity cost and the marginal benefit of harvest are equal in the first rotation, this may not be the case for subsequent rotations. This is because when the binding constraints hold in the subsequent rotations, the marginal opportunity cost does not have to equal the marginal benefit of harvest.[9] In this case, the choice of the initial verification influences the timing of harvest, especially in the first rotation interval, but it is not clear whether rotation intervals are longer or shorter rotation interval compared with the case when the first set of constraints are not binding.

The lCER structure characterized above is similar to the subsidy and tax policy proposed by van Kooten *et al.* (1995) in that carbon sequestration credits are based on incremental additions to carbon, and penalties are accrued for incremental losses. However, lCERs are different because the inflexible and discrete 5-year verification intervals in the lCERs mechanism can introduce incentives to deviate from the optimal rotation interval and the carbon credit supply.

[9] We derive t_v by replacing the first rotation interval into the binding constraint.

4. Simulations

The theoretical model is used to simulate rotation intervals, an initial verification period, and consequent carbon supply under the lCERs policy. Galinato and Uchida (2011) investigate the effect of the tCERs policy by simulating stylized plantations from two tree species: mahogany, a slow-growing tree species in the Philippines, and neem, a fast-growing tree species in Tanzania. We use these same tree species to compare the effects of lCERs and tCERs.

4.1. Parameters and functional forms

Mahogany (*Swietenia macrophylla*) has the largest potential for carbon sequestration among all tropical trees in the Philippines (Covar 1998), with a volume function

$$V = 10^{[1.7348-(6.6721/A)+(0.053801\times S)-(0.78406\times S/A)]} \tag{15}$$

where V is the standing timber volume in cubic meters per hectare, A is timber age in years and S is the site index value (Revilla *et al*. 1976).

The growth function of Tanzanian neem (*Azadirachta indica*) is (Tewari and Kumar 2002)

$$V = 105.84133 \times [1 - \exp(-0.10582 \times \mathrm{A})]^{2.11913} \tag{16}$$

The amount of carbon sequestered for each tree species is calculated using

$$\mathrm{TC} = V \times \mathrm{WD} \times C\mathrm{s} \times C\mathrm{w} \tag{17}$$

where TC is the carbon coefficient in tonnes of carbon per hectare (tC/ha), WD is the wood density, C_s is the conversion factor to compute whole stand biomass from stemwood biomass and C_w is the conversion factor to estimate the carbon content of whole stand biomass of carbon per ton (Winjum *et al.* 1992).

Table 2 summarizes the parameters used in the model for the two species. The discount rate and the price of carbon are important in determining rotation intervals, the initial verification period and the feasibility of establishing carbon forest plantations. A competitive carbon price is assumed equal to the marginal damage from a unit of carbon. Tol (2005) provides the mean estimated marginal damage as \$93 per ton of permanent carbon (tC).[10] We set

[10] Carbon uptake into biological sinks is usually measured in tonnes of carbon while emissions reductions are in tonnes of carbon dioxide. By using the conversion factor of 12 tC/44 tCO_2, \$93/tC is equal to about \$25/tCO_2. This is within the range of the strike price (and slightly higher than the average spot price) of CERs in European Carbon Exchange in 2009 (ECX, 2009).

Table 2 Parameters of the simulation model

Parameter definition	Mahogany in the Philippines	Neem in Tanzania
Timber price per cubic meter (*ptim*)	171.47	106.67
Harvesting cost per cubic meter	35.23	21.33
Net timber price per cubic meter (p_v)	136.24	85.34
Fixed cost of planting per hectare (Q)	803.97	156.89
Site index (I)	25	N/A
Wood density tonnes per cubic meter (WD)	0.56	0.52
Conversion factor to compute whole-stand biomass from stem wood biomass (Cs)	1.6	1.2
Conversion factor to estimate the carbon content of whole stand biomass (Cw)	0.5	0.5

Sources: Galinato and Uchida (2011).

$100/tC as baseline price for our simulation and use a range of carbon prices from $0 to $100/tC to examine the effects of carbon price differences. We also allow for low and high discount rates using 5% and 10% as well as different timber prices for each species.

4.2. Economic feasibility of lCERs

In order for the host country to establish forest plantations in a particular site, the project needs to be economically feasible. The forest project is economically feasible in an infinite rotation model if the soil expectation value (SEV), which is the maximum present value of net benefits during all rotations from Equation (7), is positive. Table 3 presents the SEVs in the Philippines and Tanzania.

For the lCERs projects, the SEV for Philippine mahogany is larger than that of Tanzania neem given a 5% discount rate, but smaller given a 10% discount rate. This indicates that slow-growing trees species are favoured by a low project discount rate, while fast-growing trees are favoured by a high discount rate. The positive SEVs also indicate that the lCERs forest projects are economically feasible even without additional revenue from carbon sequestration. However, without carbon revenue, the landowner may bear negative annual returns because no profits are gained until the optimal harvesting date. Carbon revenue during each verification period can increase the SEV and thus offset some of the opportunity cost of the land (Sedjo 1999).

It is not clear *a priori* whether the SEV from lCERs is greater than or less than that from tCERs because of the difference in the credit prices between the instruments. We convert the 5-year rental price of carbon to the market price of permanent carbon to make the carbon prices of tCERs and lCERs comparable.[11] The SEVs under the lCERs and tCERs projects are similar,

[11] The annual rental rate of carbon credit is computed by multiplying the market price of carbon by the discount rate. The 5-year rental rate is adjusted accordingly by 5-year interest increments.

Table 3 Per hectare soil expectation value (SEV) of carbon forest plantations with lCERs using Philippine Mahogany and Tanzanian Neem in an infinite rotation planning horizon (2001 US$)

	Long-term certified emission reductions (lCERs)								Temporary certified emission reductions (tCERs)*							
Discount rate	5%				10%				5%				10%			
Permanent carbon price (rental carbon price) ($/tC)	$0	$20	$50	$100	$0	$20	$50	$100	$0	$20 ($4)	$50 ($11)	$100 ($22)	$0	$20 ($8)	$50 ($20)	$100 ($39)
Philippine Mahogany (*ptim* = 171.47)																
Net timber benefits	5249	5245	5219	5160	429	415	410	383	5249	5243	5209	5160	429	428	419	378
Net carbon benefits with penalty	0	298	781	1650	0	92	237	510	0	257	691	1464	0	85	224	501
SEV	5249	5543	6000	6810	429	507	647	893	5249	5500	5901	6624	429	512	643	879
Tanzanian neem (*ptim* = 106.67)																
Net timber benefits	5245	5244	5243	5243	1964	1962	1925	1920	5245	5244	5244	5243	1964	1962	1925	1920
Net carbon benefits with penalty	0	125	314	627	0	75	235	478	0	128	320	642	0	74	234	476
SEV	5245	5369	5557	5871	1964	2037	2162	2398	5245	5371	5564	5885	1964	2036	2160	2396

*Simulation results for tCERs are updated estimates of those in Galinato and Uchida (2011). Note that the rental carbon price is adjusted from the permanent (market) carbon price and used in tCERs calculation.

but the lCERs projects seem to generate larger SEVs for the slow-growing species with higher carbon prices.

4.3. Optimal rotation intervals and initial verification period with lCERs

Tables 4 and 5 summarize optimal rotation intervals and an optimal initial verification period under lCERs for Philippine mahogany and Tanzanian neem, respectively.[12] We also re-estimated values for tCERs from Galinato and Uchida (2011) and present the results for comparison.

Under the baseline timber prices, the Faustmann rotation age is 31.5 years for mahogany and 9.8 years for neem with a 5% discount rate, and 24.2 and 7.9 years with a 10% discount rate. The optimal rotation intervals are longer with higher carbon prices, lower timber prices and lower discount rates. Also, the rotation intervals during the crediting project are not equal in length as suggested in the theoretical model.

Based on our simulations, under the lCERs program, the initial verification period tends to be chosen so the harvest date during the first rotation interval coincides with the last verification period. The initial verification period starts as early as year 0.1 of the first rotation or as late as year 5. The initial verification choice, however, does not guarantee that the last verification period during each subsequent rotation interval corresponds to the harvest date. This result is similar to what the tCERs program yields.

For Philippine mahogany in Table 4, only one rotation is fully incorporated in the 60-year crediting period when the discount rate is 5%, while there are two complete rotations with a 10% discount rate. Because a positive carbon price provides an additional incentive to sequester carbon, the rotation length during the crediting period is generally longer than that of the Faustmann rotation. This is the case for most parameterizations in Table 4. However, the rotation length is actually shorter when the discount rate is 5%, the carbon price is $20 and the timber price is $342.94. One possible explanation for this case is that shortening the rotation length at the margin decreases the difference in the volumes of carbon stock before and after harvest, thereby decreasing the nominal penalty.

Penalty avoidance influences the timing of harvest in other instances as well. A large penalty can be avoided by delaying harvest until the end of the last verification of the project. For example, with a 10% discount rate and a timber price of $342.94, the last penalty before the end of the project can be avoided by delaying the second harvest until year 55.1 to coincide with the last verification period. Note also that in this case, the second rotation is longer than the first rotation. Without a penalty as implemented on fixed verification periods, optimal rotation lengths would tend to be equalized.

[12] We use Mathematica 7 in our simulations. The notebook files are available from the authors upon request.

Table 4 Optimal rotation and initial verification periods for Philippine Mahogany in an infinite rotation planning horizon under lCERS and tCERs

	Long-term certified emission reductions (lCERs)								Temporary certified emission reductions (tCERs)*							
Discount rate	5%				10%				5%				10%			
Permanent carbon price (rental carbon price) ($/tC)	$0	$20	$50	$100	$0	$20	$50	$100	$0	$20 ($4)	$50 ($11)	$100 ($22)	$0	$20 ($8)	$50 ($20)	$100 ($39)
ptim = 171.47																
Initial verification year (tv)	N/A	2.2	3.5	5.0	N/A	0.1	0.7	2.2	N/A	2.4	3.8	5.0	N/A	4.8	0.7	2.4
1st rotation length (t_1)	31.5	32.2	33.5	35.0	24.2	25.1	25.7	27.2	31.5	32.4	33.8	35.0	24.2	24.8	25.7	27.4
2nd rotation length (t_2)	31.5	(31.5)	(31.5)	(31.5)	24.2	30.0	30.0	30.0	31.5	(31.5)	(31.5)		24.2	25.0	25.0	30.0
3rd rotation length (t_3)						(24.2)	(24.2)	(24.2)					24.2	(24.2)	(24.2)	(24.2)
Rotations after the crediting period (t_f)	31.5	31.5	31.5	31.5	24.2	24.2	24.2	24.2	31.5	31.5	31.5	31.5	24.2	24.2	24.2	24.2
ptim = 342.94																
Initial verification year (t_v)	N/A	5.0	1.9	2.8	N/A	0.1	0.1	0.1	N/A	1.5	2.1	3.1	N/A	4.0	4.4	5.0
1st rotation length (t_1)	31.1	30.9	31.9	32.8	23.8	25.1	25.1	25.1	31.1	31.5	32.1	33.1	23.8	24.0	24.4	25.0
2nd rotation length (t_2)	31.1	(31.1)	(31.1)	(31.1)	23.8	30.0	30.0	30.0	31.1	(31.1)	(31.1)	(31.1)	23.8	25.0	25.0	25.0
3rd rotation length (t_3)						(23.8)	(23.8)	(23.8)					23.8	(23.8)	(23.8)	(23.8)
Rotations after the crediting period (t_f)	31.1	31.1	31.1	31.1	23.8	23.8	23.8	23.8	31.1	31.1	31.1	31.1	23.8	23.8	23.8	23.8

Note: N/A indicates not applicable. Rotation intervals in the parenthesis indicate the rotations in transition that start during the 60-year crediting period and continue in the post-crediting period. *Simulation results for tCERs are updated estimates of those in Galinato and Uchida (2011). Note that the rental carbon price is adjusted from the permanent (market) carbon price and used in tCERs calculation.

Table 5 Optimal rotation and initial verification periods for Tanzanian Neem in an infinite rotation planning horizon under lCERS and tCERs

	Long-term certified emission reductions (lCERs)								Temporary certified emission reductions (tCERs)*							
Discount rate	5%				10%				5%				10%			
Permanent carbon price (rental carbon price) ($/tC)	$0	$20	$50	$100	$0	$20	$50	$100	$0	$20 ($4)	$50 ($11)	$100 ($22)	$0	$20 ($8)	$50 ($20)	$100 ($39)
ptim = 106.67																
Initial verification year (tv)	N/A	4.9	5.0	5.0	N/A	3.1	3.4	3.8	N/A	4.9	4.9	5.0	N/A	3.0	3.4	3.8
1st rotation length (t_1)	9.8	9.9	10.0	10.0	7.9	8.1	8.4	8.8	9.8	9.9	9.9	10.0	7.9	8.1	8.4	8.8
2nd rotation length (t_2)	9.8	10.0	10.0	10.0	7.9	7.9	10.0	10.0	9.8	10.0	10.0	10.0	7.9	7.9	10.0	10.0
3rd rotation length (t_3)	9.8	10.0	10.0	10.0	7.9	8.1	10.0	10.0	9.8	10.0	10.0	10.0	7.9	8.1	10.0	10.0
4th rotation length (t_4)	9.8	10.0	10.0	10.0	7.9	9.0	10.0	10.0	9.8	10.0	10.0	10.0	7.9	9.0	10.0	10.0
5th rotation length (t_5)	9.8	10.0	10.0	10.0	7.9	7.9	10.0	10.0	9.8	10.0	10.0	10.0	7.9	7.9	10.0	10.0
6th rotation length (t_6)	9.8	10.0	10.0	10.0	7.9	8.1	10.0	10.0	9.8	10.0	10.0	10.0	7.9	8.1	10.0	10.0
7th rotation length (t_7)	9.8	(9.8)			7.9	9.0	(7.9)	(7.9)	9.8	(9.8)	(9.8)		7.9	9.0	(7.9)	(7.9)
8th rotation length (t_8)	9.8				7.9	(7.9)			9.8				7.9	(7.9)		
Rotations after crediting period (tf)	9.8	9.8	9.8	9.8	7.9	7.9	7.9	7.9	9.8	9.8	9.8	9.8	7.9	7.9	7.9	7.9
ptim = 213.34																
Initial verification year (t_v)	N/A	4.4	4.6	4.8	N/A	2.7	2.8	3.1	N/A	4.4	4.7	4.8	N/A	2.7	2.8	3.1
1st rotation length (t_1)	9.5	9.6	9.6	9.8	7.5	7.7	7.8	8.1	9.5	9.6	9.7	9.8	7.5	7.7	7.8	8.1
2nd rotation length (t_2)	9.5	9.8	10.0	10.0	7.5	7.5	7.5	7.5	9.5	9.8	10.0	10.0	7.5	7.5	7.5	7.1
3rd rotation length (t_3)	9.5	10.0	10.0	10.0	7.5	7.5	7.5	7.5	9.5	10.0	10.0	10.0	7.5	7.5	7.5	7.9
4th rotation length (t_4)	9.5	10.0	10.0	10.0	7.5	7.5	7.5	7.5	9.5	10.0	10.0	10.0	7.5	7.5	7.5	7.1
5th rotation length (t_5)	9.5	10.0	10.0	10.0	7.5	7.5	7.5	7.5	9.5	10.0	10.0	10.0	7.5	7.5	7.5	7.9
6th rotation length (t_6)	9.5	10.0	10.0	10.0	7.5	7.5	7.5	7.5	9.5	10.0	10.0	10.0	7.5	7.5	7.5	7.1
7th rotation length (t_7)	9.5	(9.5)	(9.5)	(9.5)	7.5	7.5	7.5	7.5	9.5	(9.5)	(9.5)	(9.5)	7.5	7.5	7.5	7.9
8th rotation length (t_8)	9.5				7.5	(7.5)	(7.5)	(7.5)	9.5				7.5	(7.5)	(7.5)	(7.5)
Rotations after crediting period (t_f)	9.5	9.5	9.5	9.5	7.5	7.5	7.5	7.5	9.5	9.5	9.5	9.5	7.5	7.5	7.5	7.5

Note: N/A indicates not applicable. Rotation intervals in the parenthesis indicate the rotations in transition that start during the 60-year crediting period and continue in the post-crediting period. *Simulation results for tCERs are updated estimates of those in Galinato and Uchida (2011). Note that the rental carbon price is adjusted from the permanent (market) carbon price and used in tCERs calculation.

For Tanzanian neem in Table 5, there are 6–8 complete rotations within the 60-year project, depending on the price parameters and discount rate. The rotation length during the crediting period is longer than that of the Faustmann rotation as expected. Unlike the Philippine mahogany case, the incentive to reduce the penalty appears weaker. This may stem from the inflexibility of rotation choices of fast-growing tree species. Under the lCERs program for neem, the initial verification period is chosen so that the harvest date and the last verification period coincide during the first rotation interval. They are less likely to coincide during the subsequent rotations and verification periods. This result is similar to the tCERs program.

Our numerical results show that lCERs and tCERs seem to have similar impacts on harvesting incentives. However, as the timber price and discount rate increase for the slow-growing tree, the two instruments exhibit different carbon price elasticities of timber rotation length. For example, in the case of Philippine mahogany with a 10% discount rate and a timber price of $342.94, the tCERs rotations are monotonically increasing in carbon price while the lCERs rotations are not. This is because the tCERs mechanism induces the landowner to postpone the harvesting date to coincide with the verification date to earn more carbon credit revenues but the lCERs mechanism creates an incentive to either delay or advance the harvest to reduce or avoid penalty losses.

4.4. Supply of carbon sequestration from lCERs

Carbon supply based on CERs is a function of the price of carbon and other parameters of the model. The supply of CERs is affected by the rotation length during the 60 year crediting period as well as the initial verification choice. Although the rotation decision seems numerically similar with lCERs and tCERs, accredited carbon supply differs. A tCERs carbon supply curve is monotonically increasing in carbon price until the maximum volume is achieved (Galinato and Uchida 2011). However, a lCERs supply may increase, remain stationary or even decrease as the carbon price increases. We calibrate the amount of accredited carbon supply with respect to the carbon price for the Philippine mahogany case.

Figure 3 illustrates simulated lCERs supply curves for Philippine mahogany based on two different timber prices and discount rates. Note that the lCERs supply curve includes discrete jumps at certain carbon prices. For example, when the timber price is $171.47, the carbon credit supply with a 5% discount rate at a carbon price of $120/tC jumps to a higher level but then remains unchanged. We also observe the same result at a timber price of $342.94 with a 5% discount rate and high carbon price. This type of a supply jump can be caused when the incentive prevails to reduce or avoid a penalty by postponing harvest. A supply jump in the other direction is observed at a low carbon price, a timber price of $342.94 and a 5% discount rate and when the price of timber is $171.47, carbon price is $210/tC and a 10% discount

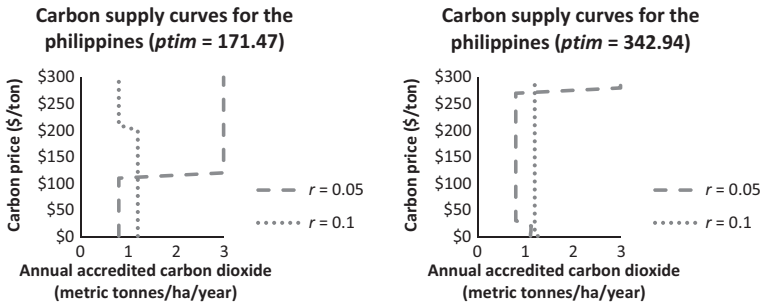

Figure 3 Carbon Supply Curves for Philippine Mahogany. Note: The variable *ptim* stands for the timber price and *r* is the discount rate.

rate. This jump can result from the incentive to mitigate a penalty by shortening the timber rotation interval.

5. Conclusion

Implementing long-term certified emission reductions under the CDM has some interesting but, for practical policy implementation, problematic effects on forest rotation intervals and carbon credit generation. Adopting lCERs could result in heterogeneous rotation intervals because verification periods are administered in fixed 5-year intervals. The structure of the credit verification with the harvest penalty could induce additional incentives to shorten or lengthen rotation intervals than the case without the penalty. Given a constant penalty amount, the landowner can decrease the present value of the penalty by delaying harvest. However, the nominal value of the penalty is increasing in rotation interval length within a verification period because it is based on the difference in volume before and after harvest. Because of this interplay between the timing of penalties *vis-à-vis* harvest, prediction of specific forest owner sequestration behaviour at the intensive margin is likely to be difficult.

Our numerical results show that both lCERs and tCERs have similar impacts on harvesting incentives. However, we find that the carbon supply at the intensive margin under the tCERs and lCERs instruments is very different. Unlike the tCERs supply, which is a monotonic function of the carbon price, the lCERs supply may increase, decrease or remain stationary over the carbon prices. The contrasts in the carbon credited supply curves are because of the different verification mechanism in each instrument.

Despite the complications and the drawbacks of tCERs and lCERs, they do increase SEVs from forestry projects. To the extent that standing forests are an effective medium for sequestering carbon relative to other land uses, remuneration for carbon sequestration via these instruments will tend to result in land conversion toward forestry in response to this increase in SEVs.

One interesting question from a welfare standpoint is to derive how far the lCERs mechanism is from maximum social welfare and compare these results with tCERs. Even in the presence of inefficiencies from tCERs, the tCERs policy creates only a 2% loss in socially optimal welfare under certain conditions (Galinato and Uchida 2010). It would be useful to measure such welfare loss for the lCERs policy.

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