Efficiency of Forest Carbon Policies on the Intensive Margin and Extensive Margin

Rong Li and Xiaohui Tian

Renmin University of China

Abstract

The economic potential of carbon sequestration in forests is widely acknowledged but there is no consensus on the policy instrument that should be adopted to promote it. This paper focuses on the comparison of efficiency of different forest carbon policies. We develop a dynamic framework that can be used to examine the effects and efficiencies of carbon policies in the forest sector. We first explore the issue analytically in a stylized optimal control model of timber market, which allows timber decision making of land owners in extensive margins (i.e., changing forest areas) and intensive margins (i.e., changing harvest ages) and timber market feedbacks. We then introduce carbon price projections and species-specific production information into a multi-ages timber market model. We numerically simulate the effects of five different carbon policies separately assuming the policies are imposed exogenously and land owners respond optimally. We find that policies that are incapable of increasing carbon updates at the intensive margin will result in very large inefficiency losses. A 'per hectare' land subsidy could be 5 to more than 10 times more costly than a 'per ton' carbon Tax & Subsidy or carbon subsidy policy depending on carbon prices. A carbon tax on forest emissions without compensating the sequestration leads to net carbon emissions and is thus the least efficient policy choice.

1. Introduction

The primary goal of this paper is to develop a dynamic framework that can be used to examine the effects and efficiencies of alternative carbon policies in the forest sector. This goal is motivated by the role of the forest sector in mitigating greenhouse gas (GHG) effects because trees absorb carbon dioxide while growing. It is estimated that forests could be efficient in contributing as much as one-third of total global carbon abatement (Sohngen and Mendelsohn 2003). Many countries can meet relatively stringent emission targets at relatively low costs by storing additional carbon in forests. Beyond their use as an efficient component of global climate policy, forests play an important role in the emerging regional and voluntary markets that have cropped up in the absence of an international regime for climate change. Many of these markets offer a possibility to finance forest carbon credits, most recently from reducing emissions from deforestation and forest degradation.

Although the economic potential of forest sequestration is widely acknowledged (Stavins, 1999; Plantinga et al., 1999; Sohngen and Mendelsohn, 2003; Richards and Stokes, 2004), there is no consensus on how to accomplish forest carbon sequestration. Different studies recommend different schemes that have varying levels of efficiency. Sohngen and Mendelsohn (2003) propose a carbon rental system with a payment for carbon permanently stored in wood products. van Kooten et al., (1995) suggest a carbon subsidy for growth and tax for net emissions at harvest time. Both approaches focus explicitly on measuring the carbon that is sequestered or emitted, whereas there are other approaches being proposed which deviate from accurate measurements of carbon to different extents. Searchinger et al., (2009) , for example, consider a form of carbon tax to deter land use change and GHG emissions due to expansion of wood-based biofuel production. Similarly, other approaches recommend a variety of subsidy schemes based on various discounting factors in order to account for problems like permanence, additionality, and leakage (see Dutschke 2001, 2002; Colombia Ministry of the Environment 2000; Blanco and Forner 2000; Chomitz 2000; and Kim et al., 2008). On the other hand, some approaches do not consider the level of carbon stored in forests (Stavins and Jaffe, 1999; Plantinga et al., 1999). These approaches provide a payment for land use change and vary the payment based on land opportunity costs. Although these approaches can sequester carbon, they are unlikely to be efficient[1].

The literature in environmental regulation has long established that the way to achieve efficient levels of pollution involves charging per unit of pollution based on damages caused by that unit (Helfand et al., 2003). By the same logic, the efficient carbon policies are those paying forest owners per ton of carbon sequestered, which are the carbon rental (C Rental) approach in Sohngen and Mendelsohn (2003) and the carbon tax and subsidy (C Tax & Subsidy) approach in van Kooten et al., (1995). Any proposal that incorporates forests into carbon markets using alternative methods will be more

[1] We do not consider command-and-control policies; rather, we only consider policies that intend to create economic incentives on carbon sequestration. Our primary focus is on how carbon credits are accounted in the forest sector. But there are other dimensions of issues relevant to carbon policy design, e.g., carbon price mechanism (cap-and-trade or fixed carbon price). Yet, the policies we discuss can be potentially incorporated into a carbon market.

costly, and it is important to understand the resulting cost differences due to policy choice.

We aim to compare and measure the differences in efficiency of alternative forest carbon policies, taking into account forest management in two dimensions. Carbon sequestration can be achieved through either increasing forestland (the extensive margin) or increasing carbon stocks on per unit of land (the intensive margin) by changing management practices including changing harvest ages, thinning, and fertilization, among other practices. The impacts of changes at extensive and intensive margins are not mutually exclusive. Instead, forestland owners react to carbon policies at both margins simultaneously and the reaction at each margin could be different across policies. Because these reactions all lead to changes in carbon consequences, it is important to consider effects on both margins when evaluating the efficiencies of carbon polices. However, few studies examining policy options comprehensively account for different management practices. Parks and Hardie (1997) compare the effectiveness of programs based on per-ton of carbon and per-acre of land for converting marginal agriculture lands into forests; but they ignore the role of management. Antle et al., (2003) show that 'per ton' carbon policies are less costly than 'per hectare' carbon policies, particularly in the presence of heterogeneous croplands. We extend the approach suggested by Antle et al., (2003) and examine differences in costs among per ton and per hectare policies under a circumstance where a stock resource is managed dynamically. Specifically, we focus on forests, where the decision on the age of harvesting the trees has important implications for carbon storage. We model harvest age as a continuous choice which can vary among tree classes and over time. In this way, we can better capture adjustments on the intensive margin of forest management in response to carbon policies.

Another contribution of this study is that we include policy-induced market effects. The market effects are derived from the systematic changes of timber supply at the aggregate level due to carbon policies. Although forests can produce timber and carbon services on the same site, providing additional carbon sequestration will not necessarily lower the level of timber supply per acre. On one hand, at the extensive margin, forestland could either expand or contract, depending on a carbon policy. At the intensive margin, even if there is no land use change, increasing carbon stocks in existing forests could lead to higher or lower timber supply, depending on the age of forests (Sohngen, 2007). These market effects will indirectly affect timber price and thus the efficiency of policies. Therefore, if timber prices are held constant and carbon benefits/debits have no effects on timber market, the net losses or gains in timber markets are not reflected.

This study also provides an application of dynamic models into the design of policies in forestry. Forest management is a long term behavior in which the current stocks and decisions not only rely on but also have consequences for future timber prices and carbon polices. The literature in policy design for environment regulations suggests that the intertemporal nature of environmental and resource externalities affects the choice of optimal policy (Farzin 1996, Benchekroun and Van Long 1998, Chakravorty et al., 2006). Furthermore, a number of studies that focus on optimal policy have taken into account the stock effects of various pollutants or renewable resources in a dynamic context. Issues examined include nonpoint-source pollution (e.g., see Xepapadeas 1992), carbon dioxide emissions (Farzin and Tahvonen 1996, Jaffe and Stavins 1995), nonrenewable resources (Rubio and Escriche 2001, Strand 2010) and fishing regulations (Hansen et al., 2008). Although the methods of dynamic modeling in forestry have been established (Lyon and Sedjo 1998; Sohngen and Mendelsohn, 1998), policy studies in forestry, including carbon policies, are either static (Parks and Hardie, 1995) or steady state analysis (van Kooten et. al., 1995, Koskela, and Ollikainen 2001, Kim et al., 2008). This study provides a dynamic framework examining policy instruments in the forest sector.

Our results demonstrate the importance of focusing on dynamic adjustments in management (i.e., the intensive margins) for designing sequestration policies. First, we find that policies that are incapable to increase carbon updates at the intensive margin will result in large inefficiency losses. A ‘per hectare’ policy could be 5 to 10 times more costly than a ‘per ton’ policy depending on the carbon prices and land use conditions because a ‘per hectare’ policy could not effectively create adequate incentives to sequester more carbon at the intensive margin. Second, a particular concern is raised with respect to the policy that taxes emissions from the forests without subsiding sequestration, because we find such policies lead to net carbon emissions per unit land in addition to contraction of forestland area.

The rest of the paper is organized as following. Second 2 develops a stylized optimal control model of the timber market which allows dynamic decision making. Five policy instruments are examined: a subsidy to carbon sequestration, a tax to carbon emissions, Carbon Tax & Subsidy, Carbon Rental and a ‘per hectare’ forestland subsidy. Second 3 introduces carbon price projections and species-specific production information into the numerical model. We compute the intertemporal paths of timber sector responses and carbon supply in a one region, multi-age class context for regularly managed southern pine. The reasons we focus on southern pine are: these forests play an important role in storing carbon, greater than other regions of the US and a significant amount of similar forests are found in developed countries where economic incentives are likely be implemented. Section 4 compares the marginal cost curves of different scenarios. Section 5 concludes the paper.

2. The optimal control model of the timber market

In this section, we present a dynamic model of the timber market based on that used by Sohngen and Sedjo (1998). We modify the model by introducing carbon policies. In this model, we consider a social planner may harvest, replant trees and manage forestland in any period. The objective of the social planner is to maximize the net present value of net surplus in the timber market over infinite time periods, $\sum_0^\infty \rho^t w_t$. The net surplus for a given period t is derived from the consumer surplus determined by an exogenous timber demand function ($\mathrm{D}(\cdot)$) of total quantity harvested (q_t) minus the sum of total costs due to harvests ($c^h(q_t)$), replants ($p^m g_t$), and cost of land use plus the carbon benefit (or minus carbon cost, f_t^c). That is,

$$w_t = \int_0^{q_t} [\mathrm{D}(\mathrm{u}, \mathrm{y_t}) - c^h(u)]\, du - p^m g_t - R\left(\sum\nolimits_a x_{a,t}\right)\sum\nolimits_a x_{a,t} + f_t^c \qquad (1)$$

The total harvested quantity of timber in a period is derived from the harvested hectares in each age group and average yield at each age. That is,

$$q_t = \sum_a V(a)\, h_{a,t} \tag{2}$$

The cost of land use is represented by the opportunity cost of forestland use. Specifically, for holding the current amount of land in forests rather than alternative uses (for example: cropland or pasture land), the social planner needs to pay land rent per hectare according to land supply function (R(·)). The land supply function rises with total forestland area, capturing the opportunity cost of introducing additional land into the forest sector. At the beginning of each period, the social planner faces a given amount of forestland indexed by age ($x_{a,t}$), where a is denoted as age class. The social planner chooses how much to harvest from each age group, $h_{a,t}$. He can choose to harvest all, a part, or none of an age group. Once harvest occurs, he may choose the area to plant with new seedlings, g_t. If the area of replants exceeds the total harvested area, it must be the case that non-forestland is converted to forestland. Additional land costs would occur. On the contrary, if the replanted area is less than the total harvested area, this implies deforestation and lower cost associated with land rent.

Formally, the social planner's objective function is thus:

$$\text{Max} \sum_0^\infty \rho^t \left\{ \int_0^{q_t} [\mathrm{D}(\mathrm{u}, \mathrm{y_t}) - c^h(u)]\, du - p^m g_t - R\left(\sum_a x_{a,t}\right) \sum_a x_{a,t} + f_t^c \right\} \tag{3}$$

where

$$w_t = \int_0^{q_t} [\mathrm{D}(\mathrm{u}, \mathrm{y_t}) - c^h(u)]\, du - p^m g_t - R\left(\sum_a x_{a,t}\right)\sum_a x_{a,t} + f_t^c \tag{4}$$

$$q_t = \sum_a V(a)\, h_{a,t} \tag{5}$$

subject to

$$\begin{cases} x_{a,t+1} = x_{a-1,t} - h_{a-1,t}, for\ a > 1\ and\ t > 0 \\ x_{1,t+1} = g_t, for\ \mathrm{t} = 0 \end{cases} \tag{6}$$

and $h_{a,t} \leq x_{a,t}$, and $h_{a,t}, x_{a,t}, g_t > 0$

The total harvested quantity of timber in a period is derived from the harvested hectares in each age group and average yield at each age. A key of the dynamic feature of this model is that we represent the complicated dynamic transition of forest stocks. The trees grow as they age according to an exogenous yield function. As a result, our transitions are able to capture both changes in total area and volume changes of the forest stocks.

Having constructed the model, we now turn to analyze the impacts of carbon policies. Four carbon policy scenarios are considered here: one 'Reference scenario' case where no carbon policy exists; and two first best policies in which credits are given by measuring the flow of carbon accurately and three non-first best policies: two focusing on measuring only parts of the carbon flows and one focusing on measuring the size of enrolled land. Specifically, the model scenarios are:

- Reference scenario: no carbon credits are available. land owners only receive revenue from timber market.

- Carbon subsidy (Subsidy): this scenario only subsidizes carbon updates by measuring growths according to current carbon price. No tax on emissions.
- Carbon tax (Tax): only taxes emissions upon harvests and burning wood for energy.
- Carbon Tax&Subsidy (Tax&Subsidy): this policy was proposed by van Kooten et al., (1995), and it is a combination of the carbon tax policy and the carbon subsidy policy. Carbon sequestered each year through forest growth is paid the current carbon price while carbon emissions are taxed at the current carbon price upon harvest
- Carbon Rental(C Rental): this policy proposes another approach to solve the impermanence of carbon storage in forests by treating the carbon service as temporary. Under the carbon rental system, forest owners are compensated by annual rents for providing annual carbon storage services; At harvest, landowners are paid the carbon price for carbon stored permanently in wood products.
- Land subsidy (Land): this policy gives a subsidy to each unit of forested land as long as the land is not clear cut. The rate of subsidy equals to the carbon offsets value per unit of land in the baseline case

Different economic incentives can affect harvest decisions and replant decisions due to carbon benefits introduced by different policies. Table 1 summarizes the first order conditions for harvest decisions under a variety of policies. The general form of the first order conditions is given by:

$$P_t V(a) + \frac{\partial f_t^c}{\partial \mathrm{h}_{\mathrm{a,t}}} = \rho \left(P_{t+1} V(a+1) - R' \left(\sum_a x_{a,t+1} \right) + \left(\frac{\partial f_{t+1}^c}{\partial \mathrm{h}_{\mathrm{a+1,t+1}}} + \frac{\partial f_{t+1}^c}{\partial \mathrm{x}_{\mathrm{a+1,t+1}}} \right) \right) \qquad (7)$$

where P_t is the market price minus harvest cost for per unit of timber harvested at t.

Equation 7 must be satisfied at all times and for all age classes if harvest occurs. The first order condition indicates that the harvest occurs when the sum of marginal benefit of harvesting an additional unit of tree of age a at t equal the sum of marginal the benefit of harvesting this unit of tree at t+1 (yet, this unit of tree would be at age a+1 at t+1). The left hand side represents the marginal benefit of harvesting an additional unit of stocks of age a at time t plus the marginal changes from carbon benefit at time t due to this additional unit of harvest. The opportunity cost has three components: (1) the marginal benefit from revenues of harvesting this unit of trees at t+1 ($P_{t+1}V(a+1)$); (2) the marginal benefit from avoiding additional land rental cost for postponing the harvest for another period; (3) the marginal changes of carbon benefit of harvesting this unit one period later, through an additional unit of tree stocks of age a+1 at time t+1 and an additional unit of harvest of age a at t+1.

As illustrated in Table 1, each policy differs in how carbon benefits/costs affect optimal decision making. Under the carbon subsidy policy, we subsidize growth each year. Hence, there are additional opportunity costs from harvesting earlier as one land owner can earn more subsidy from additional growth if he/she postpones harvest. Under carbon taxes, one has to pay some amount of taxes, depending the amount of carbon emissions due to harvests for each period. So when one postpones harvest, a land owner faces additional benefits i.e., less carbon taxes for the current period as well as additional costs i.e., extra carbon taxes in the next period. The carbon benefits and costs will coexist if a combination of carbon subsidy and carbon tax is introduced. Under the carbon rental system, forest owners get paid for each unit of carbon conserved by their forests in each period as well as a one-time payment if they harvest. This policy gives economic incentive to delay harvests as they can earn additional revenue from the two parts of payments. For the land subsidy scenario, land owners receive subsidies as long as they maintain the forested land regardless the actual amount of carbon that is conserved. This policy mainly provides extensive margin incentives as it ignores the difference in the abilities of absorbing and storing carbon across age classes.

The optimal conditions illustrate the importance of comparing alternative carbon policies. While van Kooten et al., (1995) only focus on the Tax and Subsidy scenario, we show that the optimal harvest ages change differently with carbon policies despite of same carbon prices p_c because channels transmitting those effects are very different. Carbon benefits can be introduced via land (Scenario 5), forest stocks, i.e., $x_{a,t}$ (Scenario 1), or harvests i.e., $h_{a,t}$ (Scenario 2) or both (Scenario 3 and 4). So we have different first order conditions governing the decision making on optimal harvest ages. Consequently, the results of carbon uptakes should also be different among carbon policy scenarios. Moreover, price changes over time and across scenarios and these changes are also reflected in the first order conditions. Prices of timber (p_t) are no longer constant here; instead, they are results of a series of timber market equilibrium. It is important to take into account market effects when modeling the effects of carbon policies, because under some the direction of change would be different from the case where prices are constant. We will show the effects in the numerical studies in the next section.

3. Simulation results and the effects of carbon policies

Using the model described above, we can simulate the effects of alternative carbon policies on timber management as well as on the timber market. We focus on dynamic timber market responses to exogenous policy shocks, i.e., carbon policies. The future path of timber prices, supply and forest stocks are determined endogenously and simultaneously for each scenario. The model keeps track of forest stocks by age class. Accordingly, carbon update results can also be inferred by timber harvests and forest stocks. All results are reported in aggregate numbers, though they are consistent with individual land owner's optimization behavior in a competitive timber market.

We first characterize the initial conditions. The forest stocks we modeled are US Southern pine plantation, which is a representative species for saw timber production in the US. There are 9.84 million hectares of forestland with 28 evenly distributed age classes. The forest is homogeneous with a yield function applied to each hectare (ha). A detailed description of the parameters and initial conditions of this analysis are given in Table 2. The parameters are calibrated so that both the Reference scenario and the other scenarios start from the initial steady state. The social planner faces a calibrated constant elasticity timber demand function which remains unchanged over time. Forest area is adjusted via harvests and regenerations according to a constant elasticity increasing land supply function, so land will be more expensive to rent if new land is introduced to forest production. The discount rate is assumed to be 0.95, implying a real interest rate of 5%.

As for the carbon calculation, the amount of carbon captured is a fixed percentage of the forest volume. It is assumed that a fixed percentage of carbon (pickling rate) in the wood harvest is stored in the wood permanently. The carbon prices are estimated from the optimal carbon tax scenario of DICE-2010 Model (Nordhaus 2010), which represent the social optimal marginal costs of an additional ton of CO_2 emissions to the atmosphere. The increase path of carbon price is displayed in Fig. 1. The projection uses the carbon price in 2010 as the starting level and the price rises to as high as $700 per ton C until 2110. The carbon conversion rate applied is 0.20 tC/m^3 for standing volume and for harvested wood as well.

The model is solved in GAMS using its nonlinear optimization solver. We solve the model by annual steps for 150 years in total. The resulting paths of harvest age, timber output, forest area and carbon updates for all scenarios are shown from Fig. 2 to Fig. 7, with each scenario labeled differently. All results are generated endogenously by the dynamic system.

The Reference scenario produces the same output, harvests and inventory paths as the initial steady state level over the projection period. The forestland stays at 9.84 million hectares. The optimal harvest age in the baseline is thus chosen as 28 and the replant area equal the harvest area. The carbon updates per year do not vary as the annual growth just equals the amount of timber that is withdrawn from forests. The equilibrium timber price stabilizes at $58/$m^3$ over time. We compare the effects of each policy scenario over the Reference Scenario.

3.1. Scenario 1: Carbon Subsidy

In this scenario, we assume that a subsidy is given per unit of carbon sequestration according the growth of forest inventories over the projection period. The rate of subsidy is consistent with the carbon price path we described above. The subsidy is irrelevant to the harvests. We first calculated the average harvest ages for each year. As the model allows harvests from different age classes during the same year, the average harvest age illustrated is calculated as the sum of actual harvest ages weighted by the harvest area for each age class (Fig. 2). The introduction of the carbon subsidy extends the harvest age. The average harvest ages rises from 28 years initially to 40 till 2055 and continues rising to higher levels. The forest area (Fig.3) expands dramatically to 16.17 million hectares by 2055. This is consistent with expectation as the subsidy brings additional revenue to forestland and thus encourages afforestation through land conversion from other sectors.

Interestingly, Fig. 5 shows that wood output decreases relative to the Reference scenario initially, and then gradually increases and surpasses that of the Reference scenario. This is due to the effects from perfect foresight on the optimal control model. When forest owners foresee the carbon subsidy for annual growth, they need to increase the annual growth of trees by two dimensions. First, at the extensive margin, they increases the forest area as mentioned above; land owners realize that future carbon prices are higher, so they begin taking advantage of higher carbon prices earlier than the schedule of carbon price increases. Second, at the intensive margin, they shift harvest ages to elder classes. But in order to do that, one needs to hold part of the stocks from harvest till they get older because it takes time for trees to mature. This explains the lower level of output initially relative to the baseline. Also the output does not rise as fast as the carbon prices. Given the feedback from timber market, producers realize that prices will be lower so there are some advantages of not increasing harvest too fast.

Our principle interest is how carbon policies affect carbon contents in the forest sector. Fig. 7 shows the schedules of effects on carbon offsets. The carbon gains are calculated as the differences in net carbon sequestration every year between each scenario and the Baseline. The net carbon sequestration captures the carbon uptakes due to growths as well as the carbon emissions due to harvests. The carbon subsidy has positive effects on net carbon sequestrations. The effects enlarge as the carbon price rises over time. Similarly, the effects on carbon stocks are results of two margins: (1) the average carbon gains on per hectare of forests increases (Fig. 8) as the harvest ages become older and (2) the total area of forests increases. In sum, both margins lead to positive carbon gains.

3.2. Scenario 2: Carbon Tax

Here, only a carbon tax on per unit of carbon emissions upon harvest is imposed on producers. No subsidy is given to sequestration at all. The rationale is to limit carbon emissions by discouraging harvest. We find that the schedule of average harvest age for each year is below that in the baseline case. This is surprising at first glance because in a Faustmann model, a harvest tax is expected to delay the harvest age (Koskelaa and Ollikainenb, 2001). Note that the Faustmann model is based on the assumption of fixed timber price and the inclusion of carbon prices is essentially equivalent to a decrease in timber price. However, the timber price in our model is endogenously determined by the timber market. The introduce of this carbon tax is equivalent to a upward shift of the supply curve as it increases the producer's cost. Hence, total output decreases relative to that of the Reference scenario and the equilibrium timber price is higher than that of the Reference scenario. As a result, the higher timber prices give incentives of harvesting faster.

The effects on forest area are as expected. Total forest area shrinks further and further as the carbon price rises (Fig. 4). In other words, more forestland are clear cut than replanted every year. The changes in harvests and replants bring in changes in inventories as well as carbon uptakes. Beyond the decrease in total forest area, less carbon is being sequestered on each unit of land on average (Fig. 4). In general, the Carbon Tax scenario leads to more net carbon emissions than the baseline case.

The rationale to promote a carbon tax is to reduce net carbon emissions from the forest sector by creating disincentive on emissions associated with harvests or other uses of wood (Searchinger et al., 2009). Unfortunately, the tax also reduces the rate of carbon sequestration via two channels: (1) the tax drives more forestland into alternative uses, which reduces forest inventories as a whole; (2) the market induced effects on timber price push down harvest age thereby resulting in negative effects on carbon sequestration at the intensive margin. As a result, the total rate of net carbon sequestration decreases because of the tax.

3.3. Scenario 3: Tax & Subsidy and Scenario 4: C Rental

Unlike the other scenarios, both of these scenarios pay for carbon sequestrations by explicitly tracking the carbon flows in and out of forests. The differences between them are only in their accounting methods: the Tax & Subsidy scenario directly trades carbon credits while the Carbon Rental scenario rents the emission credits. Though the actual payments would be different, the two scenarios should create the same marginal incentives in managing forests and sequestrating carbon. Consistently, the simulation results reveal that the two scenarios have identical effects on all management practices. The effects of both scenarios on harvest ages and forest area are similar to those of Scenario 1(Carbon Subsidy). These policies have positive effects on both harvest ages and forest area (Fig. 3 and 4). Yet, their harvest age effects are larger than those of the Carbon Subsidy scenario while the forest area effects are smaller. This is not unexpected, because without considering the timber market effect, a carbon tax delays harvest age and squeezes forest area. So combining the carbon tax with subsidy should strengthen the harvest age effects and weaken the forest area effects.

Accordingly, their trend in the carbon offset effects is similar with the Carbon Subsidy scenario as well. More carbon offsets are accomplished in the forest sector relative to the Reference scenario (Fig. 7). Moreover, we find that their effects on carbon gains are smaller than the Carbon Subsidy scenario before 2031, but larger from 2031 to the end of the simulation, with the differences continuing expanding. That is due to the effects from dynamic adjustments of the forest sector. As we described above, compared with the Carbon Subsidy one, these two scenarios have larger impacts on extending harvest ages (i.e., the intensive margin) but smaller impacts on enlarging forest area (i.e., the extensive margin). The carbon intensity on per unit of forestland is driven by changes in harvest ages. Because land adjustments are usually accomplished instantly while it takes time to accumulate carbon on the site, the impacts on extensive margin dominate in the short term while the impacts on the intensive margin dominate the other in the longer term. Consequently, compared with the Carbon Subsidy scenario, these two scenarios sequester less carbon in the near term and more carbon the longer term.

3.4. Scenario 5: Land Subsidy

Different from the scenarios examined above, this scenario compensates carbon sequestration according to total forested land. The subsidy is not contingent on management practices on the site as long as the forests are not clear cut and converted to non-forest uses. The rate of subsidy equals to the corresponding average value of carbon sequestration on per hectare of forests in the Reference scenario. So the rationale is to boost carbon uptake by introducing more land into forests or avoiding deforestation. The advantage of this approach is its low measurement costs. The most important effects on management practices are the positive effects on forest area (Fig 4). The total forest area enlarges over time. How about the effects on harvest ages? Results from Faustmann model state that lump-sum transfers by forestland (e.g., a lump-sum tax illustrated by Koskelaa and Ollikainenb 2010) have no incentive on the harvest ages as they do not create any incentive to management on the stands. Yet, we find that the per hectare policy causes changes on the average harvest age in the short term, although the changes are minor (the harvest age decreases about one year). The short run changes can be explained by inventory adjustments (Fig. 3) and they are much smaller compared with the scales of effects under other scenarios. In general, the land subsidy does not create significant effects on the intensive margins.

The carbon effects are positive and significant. Again, the effects are increasing over time. However, the carbon gains from land subsidy is much smaller than under the Tax & Subsidy and the Carbon Rental scenarios. The carbon gains are less than 10% of the level under the Tax & Subsidy Scenario and around 15% of the level under the Carbon Subsidy scenarios. The gaps cannot be fully explained by their land expansion schedules as the rates of land expansion of the other scenarios are only around twice of that of the Land Subsidy one. This indicates that most of the differences in total carbon offsets stem from their variances on the intensive margins. As discussed above, Land Subsidy provides limited economic incentives at the intensive margins, thereby it losses the large potential to promote carbon sequestration by changing management practices compared with those ‘per ton' policies. As a result, the effectiveness of the land subsidy is largely diminished. We will further demonstrate the efficiency losses from land subsidy by comparing different marginal cost curves.

4. The costs of carbon sequestration

In this section, we apply the same dynamic analysis framework to an analysis of the costs of carbon sequestration. We do this by projecting the marginal cost functions of carbon sequestration under different policies. For each policy, we run multi-simulations by varying the carbon prices. We first compute an implicit cost which equals the social welfare losses of the timber sector at each carbon price. The implicit cost is then matched with its level of carbon gain at that given carbon price. Finally, the marginal cost per ton is found by linking each increment of the implicit cost with the additional carbon sequestration which is triggered by this specific increment. The marginal cost for per ton carbon sequestered for each type of policy is presented in Fig. 8. Note that the Carbon Tax scenario is not examined because it leads to negative carbon gains.

For all scenarios which create positive carbon offsets, the lowest marginal cost occurs with the Tax & Subsidy and the Carbon Rental policy. As discussed earlier, these two policies are the only policies that pay by explicitly measuring carbon flows, hence they are the most efficient polices in promoting carbon sequestration. The Carbon Subsidy policy is relatively inefficient, with a marginal cost curve higher than under the two optimal policies. The marginal cost of the Land Subsidy policy is substantially higher than both the two optimal ones and the carbon subsidy one. Moreover, the efficiency loss enlarges as carbon price rises. For example, at a carbon price of \$112/MtC (equivalent to \$30/ Mt CO_2), the carbon supply under the Land Subsidy scenario is 10.1% of that under the Tax&Subsidy scenario and 14.1% under the Carbon Subsidy scenario; at \$224/MtC (equivalent to \$60/ Mt CO_2), its carbon supply is only 6.3% of that under the Tax & Subsidy scenario and 9.1% under the Carbon Subsidy scenario.

One potential concern is whether the result depends on the assumption of land uses. So far we have assumed an afforestation situation where the total size of forestland is stable without carbon polices, and it could potentially be increased as much as possible with a carbon incentive. For robustness, we examine the costs of carbon sequestration under two other land use situations. Fig. 9 presents the results under a deforestation situation where the forest area decreases in the absence of carbon policies. This mimics the cases where forests are currently being converted to agriculture or other land uses due to high opportunity costs of forestland. Fig. 10 shows the results of the case where we reduce the elasticity of land supply to reflect a high land competition case. The results are consistent with the previous findings. In both cases, the marginal cost curve of the Land Subsidy is higher than that of Tax & Subsidy and diverges at high carbon quantity. The cost curve of Carbon Subsidy is between the Tax & Subsidy and the Land Subsidy scenarios while it almost overlaps with the curve of Tax & Subsidy in the case of land boundary. In general, the results reflect that the 'per hectare' policy (Land Subsidy) bears significant efficiency losses compared with the 'per ton' policies (Tax & Subsidy, Carbon Rental and Carbon Subsidy) at every level of payments. More than that, the efficiency losses drastically increase with carbon quantities, with a marginal cost as high as 4.1 times of that of the 'per ton' policies for carbon supply of 1 million MtC to 14.6 times for carbon supply of 5 million MtC.

Now we compare our results with Antle et. al. (2003). They also find that the 'per ton' policy is more efficient than the 'per hectare' policy but the two marginal cost curves converge at high carbon quantity. This controversy can be resolved by comparing their reasons causing the efficiency differences with the reasons here. The efficiency differences in Antle et. al. (2003) are explained by spatial heterogeneity, so the differences would diminish at the point where all land participates in the carbon programs. However, the differences are caused by the failure of 'per hectare' policy to create carbon on the intensive margin. Thus, the inefficiency exists regardless of their effects on extensive margins. Even if the same forests are enrolled, as in the case with a land boundary, the effects on the harvest ages are still dramatically different between the two types of policy. In sum, our findings provide implications to carbon policy design with land use sectors in two aspects. First, the findings indicate that the policy makers or carbon contracting parties could potentially bear significant measurement costs for the 'per ton' policy if there is a possibility of multi-choice or multi-dimension management practices relevant to carbon sequestration. Second, the efficiency gains from 'per ton' policies are especially large at high carbon prices or for large scale programs.

5. Conclusion

The aim of this study is to evaluate the effects of different policy instruments used to promote carbon sequestrations on both intensive and extensive margins, taking into consideration of the policy induced market effects and intertemporal changes. The analysis considers five policy options by employing an optimal control model of the timber market. We investigate the dynamics of the policy effects on forest inventory, the timber market and carbon consequences for five policy options. There are a 'per ton' carbon tax, a 'per ton' carbon subsidy, a 'per hectare' land subsidy and two optimal policies which pays by explicitly measuring carbon in and out of forests: the Carbon Tax & Subsidy policy and the Carbon Rental policy. We find that under the same carbon price path, the two optimal policies lead to the largest carbon sequestration among all scenarios. However, the Carbon Tax scenario causes carbon losses at both intensive and extensive margins after considering the market effects.

We then apply the intertemporal model to compare the marginal costs of sequestration of the five policies under different land use situations. The findings illustrate that the most efficient systems are the two optimal policies regardless of land use situations. The sub efficient policy choice is the Carbon Subsidy, which slightly deviates from the optimal policies. The ‘per hectare’ Land Subsidy is substantially less efficient than the other three ‘per ton’ policies and the efficiency losses are especially significant at high carbon quantities. The results indicate its marginal cost ranges from 4 to more than 10 times of that for the Carbon Tax & Subsidy policy and the Carbon Rental policy. The least efficient carbon policy is the Carbon Tax policy because it leads to simultaneous losses in social welfare and forest carbon.

This study provides practical implications for carbon policy design with the land use sectors. First, the results show that the government can achieve more carbon sequestration efficiency on both the intensive margin and the extensive margin. While the potential on the extensive margin is constricted to the regional land conditions, the potential on the intensive margin is substantial and should not be ignored. Second, it is worthwhile to implement a ‘per ton’ policy instead of a ‘per hectare’ policy as long as the administration costs do not exceed the efficiency losses. A ‘per ton’ carbon subsidy policy may be an appropriate choice if taking into consideration of measurement costs because it provides the close approximation in efficiency to the optimal policies and it avoids measurement costs on actual emissions from harvest. Third, when designing climate policies, a recommended policy choice is to treat the land use sector differently from the other emission sectors. While it is correct to directly tax carbon emissions from energy uses, taxing emissions from the forest sector without compensating sequestration leads to inefficient outcomes because the carbon tax reduces the rate of carbon sequestration as well.

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Scenarios	Description	Carbon Benefits/Costs	Optimal conditions for harvest
Reference	No carbon policy	None	$\boldsymbol{P_t V(a) = \rho\left(P_{t+1}V(a+1) - R'\left(\sum_a x_{a,t+1}\right)\right)}$ [2]
Scenario 1	Carbon Subsidy (Subsidy)	$p_c\delta \sum_a x_{a,t}\hat{V}_a$ [3]	$\boldsymbol{P_t V(a) = \rho\left(P_{t+1}V(a+1) - R'\left(\sum_a x_{a,t+1}\right)\right.} + p_c\delta\hat{V}_{a+1}\Big)$
Scenario 2	Carbon Tax (Tax)	$-p_c\delta(1-\sigma)q_t$ [4]	$\boldsymbol{P_t V(a)} - p_c\delta(1-\sigma)\boldsymbol{V(a)} = \boldsymbol{\rho}\left(\boldsymbol{P_{t+1}V(a+1)} - p_c\delta(1-\sigma)\boldsymbol{V(a+1)} - \right.$ ***R′axa,t+1***
Scenario 3	Carbon Tax&Subsidy(Tax&Subsidy)	$p_c\delta \sum_a x_{a,t}\hat{V}_a - p_c\delta(1-\sigma)q_t$	$\boldsymbol{P_t V(a)} - p_c\delta(1-\sigma)\boldsymbol{V(a)} = \boldsymbol{\rho}\left(\boldsymbol{P_{t+1}V(a+1)} - p_c\delta(1-\sigma)\boldsymbol{V(a+1)} - \right.$ ***R′axa,t+1****+pcδVa+1*
Scenario 4	Carbon Rental (C Rental)	r_c[5]$\delta \sum_a x_{a,t}V(a) + p_c\delta\sigma q_t$	$\boldsymbol{P_t V(a)} + p_c\delta\sigma\boldsymbol{V(a)} = \boldsymbol{\rho}\left(\boldsymbol{P_{t+1}V(a+1)} + p_c\delta\sigma\boldsymbol{V(a+1)} - \boldsymbol{R'}\left(\sum_a \boldsymbol{x_{a,t+1}}\right) + \right.$ *rcδ*Va
Scenario 5	Land Subsidy(Land)	$l\sum_a x_{a,t}$ [6]	$\boldsymbol{P_t V(a) = \rho\left(P_{t+1}V(a+1) - R'\left(\sum_a x_{a,t+1}\right)\right.} + l\Big)$

Table 1 Carbon benefit/cost and first order conditions for harvest decisions under alternative scenarios

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[2] P_t is the net price of raw timber at t. The formula to calculate is $P_t = D(q_t, y_t) - c^h(q_t)$

[3] p^c is the social cost of per unit of additional carbon emissions i.e., the current carbon price; $\widehat{V}_a$ is the growth rate per ha for age class a. δ is the carbon conversion rate for wood products.

[4] σ is the proportion of permanently stored carbon in wood products.

[5] $r_c = p^c\left(r - \frac{dp^c}{dt}p^c\right)$

[6] l is the subsidy rate per hectare.

Parameters	**Value**	**Source**
Yield function	$\ln(V(a)) = 7.82 - 52.9/a$	Sohngen and Sedjo, 1998
Pickling rate	0.35	Daigneault et al., 2010
Carbon price	The optimal carbon tax scenario	DICE-2010 Model
Interest rate	5%	
Carbon conversion rate	0.20 tC/m^3	eg. van Kooten et al., 1995
Price elasticity for wood products	-0.5	Simangunsong and Buongiorno,2001 Newman, 1987
Land supply elasticity	0.33	Lubowski et al., 2006

Table 2 Key parameters and sources

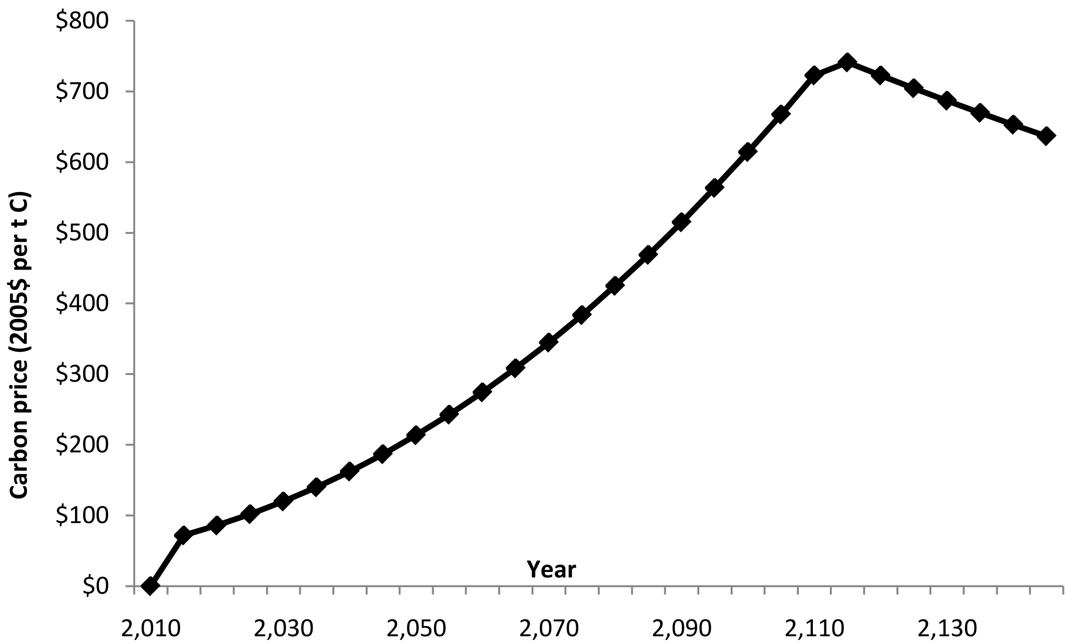

Figure 1 Global carbon price path

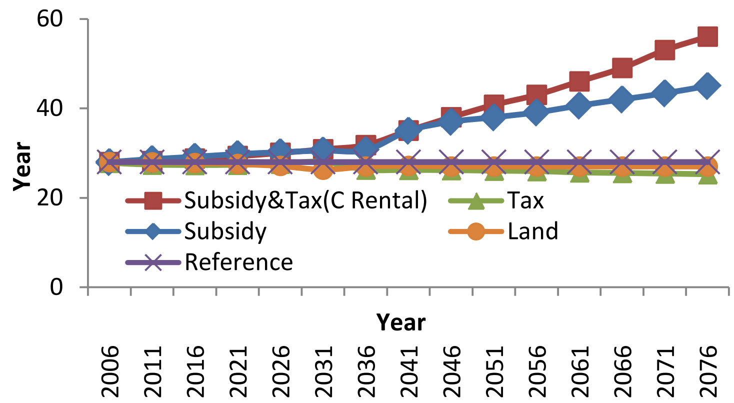

Figure 2 Paths of Average Harvest Age

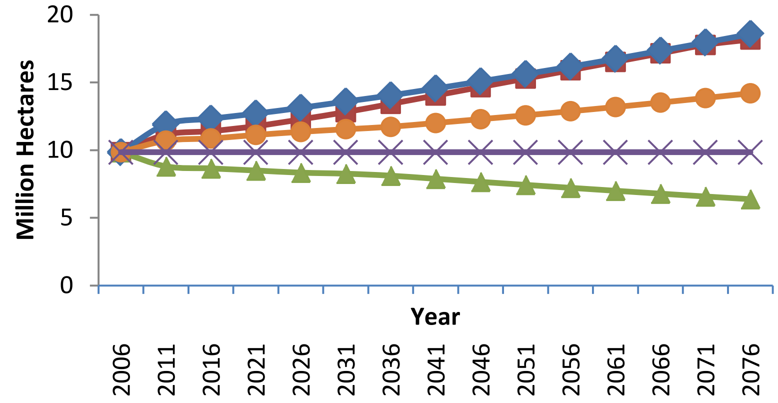

Figure 3 Path of Forest Area

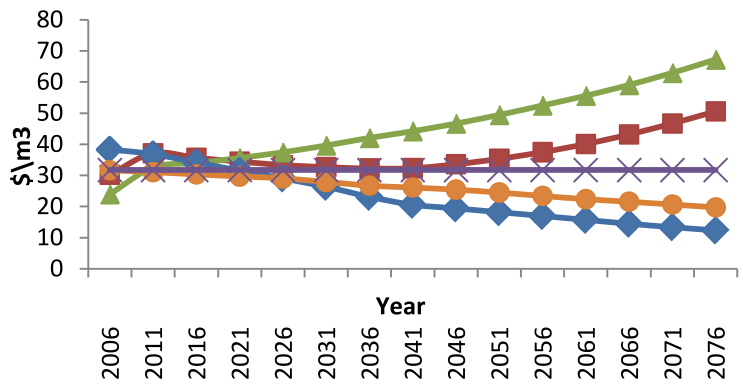

Figure 4 Paths of Timber Prices

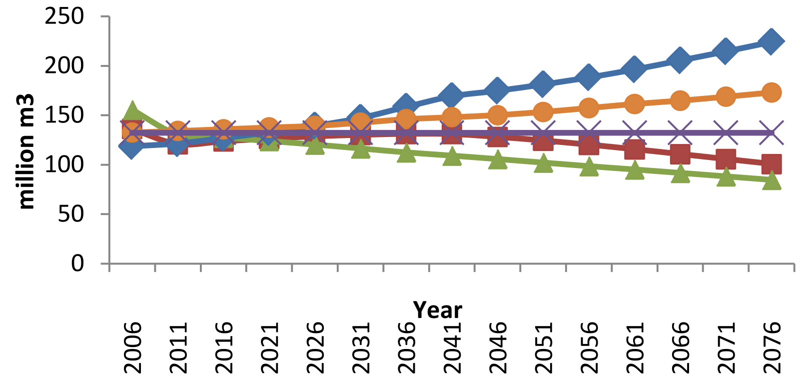

Figure 5 Path of Wood Products Outputs

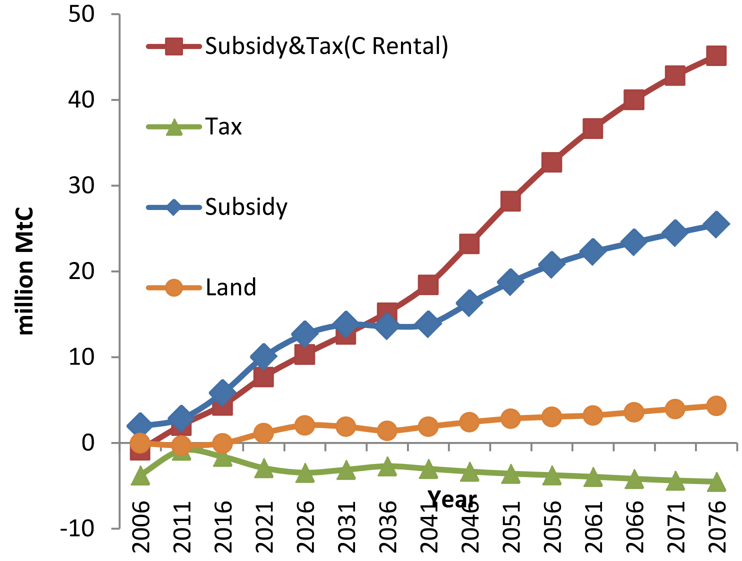

Figure 6 Path of Total Carbon offsets

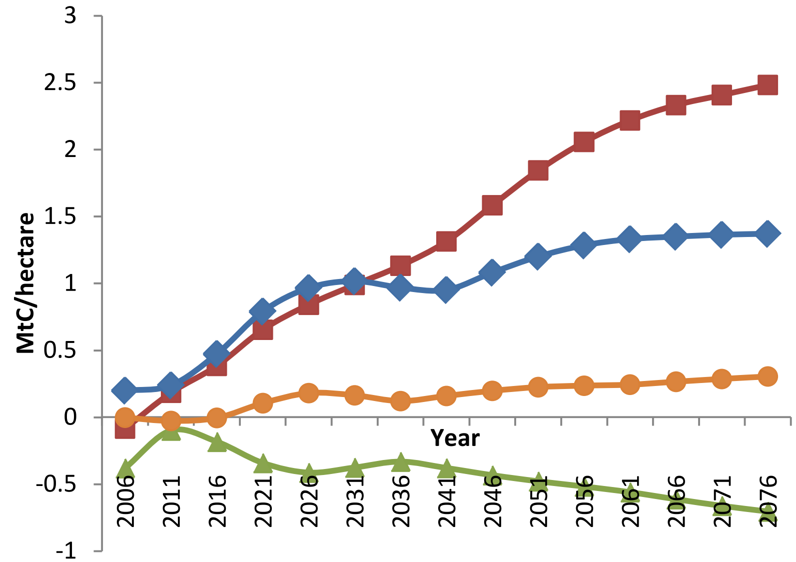

Figure 7 Path of per ha Carbon Offsets

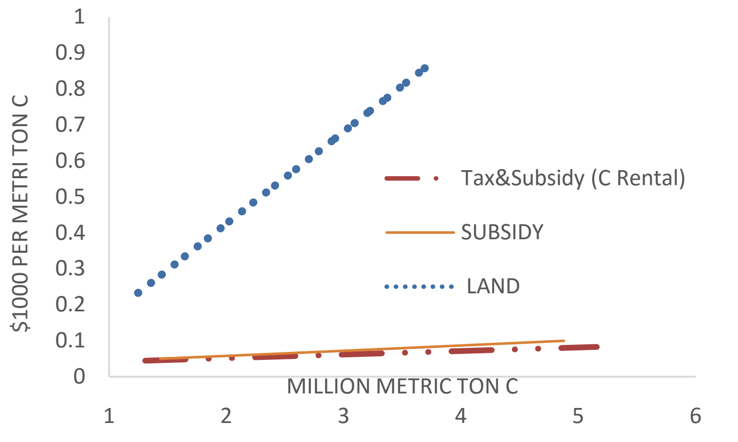

Figure 8 Margical Cost Curves-Afforestation

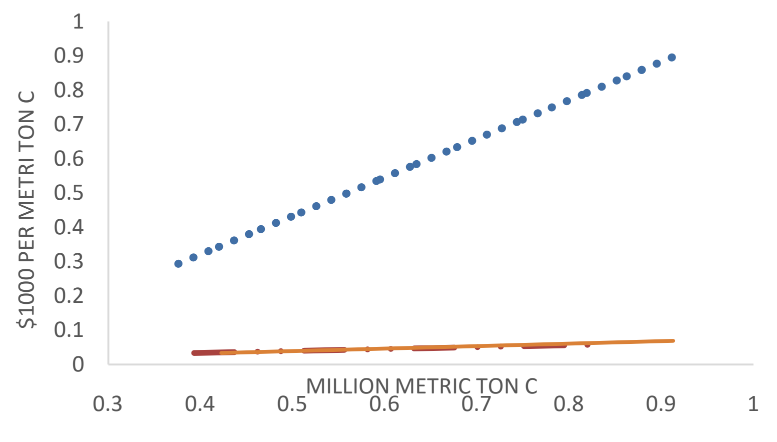

Figure 9 Marginal Cost Curves-High land competition

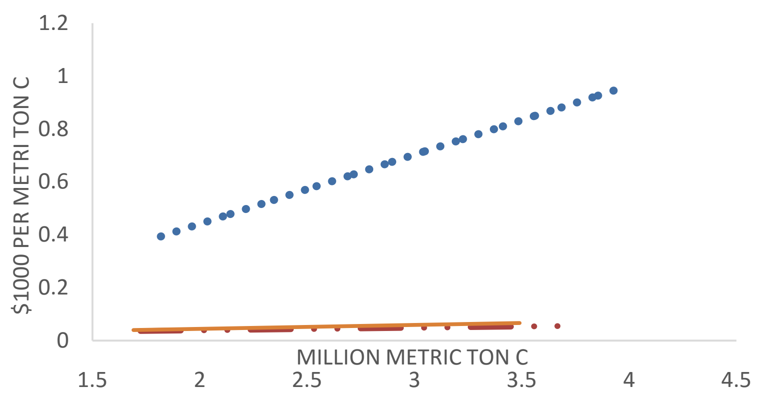

Figure 9 Marginal Cost Curves-Deforestation