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Optimal Forest Management for Carbon Sequestration: A Case Study of *Eucalyptus urophylla* and *Acacia mangium* in Yen Bai Province, Vietnam

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October, 2013

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NPV	Net present value (million VND/hectare)
T	Rotation age (years)
VND	Vietnamese Dong
r	Discount rate

OPTIMAL FOREST MANAGEMENT FOR CARBON SEQUESTRATION: A CASE STUDY OF *EUCALYPTUS UROPHYLLA* AND *ACACIA MANGIUM* IN YEN BAI PROVINCE, VIETNAM

Nghiem Thi Hong Nhung

EXECUTIVE SUMMARY

Carbon trading may provide several benefits for developing countries that have extended their forest area. In Vietnam, there has been a large increase in productive planted forest areas in the last few years; hence, a management strategy to ensure that these forests achieve both timber production and carbon sequestration goals is important.

The main objective of this study is to find out optimal management strategies for productive planted forests when carbon benefits are considered. With a given initial state of forest, the research attempts to: a) determine the planting and harvesting patterns, which can maximize net returns from selling timber and sequestering carbon; b) compare the optimal management strategy when carbon has or does not have market value; c) compare the optimal management strategy for two dominant tree species; d) analyse the sensitivity of the optimal management strategy to forests' area, prices and discount rate; and e) identify the policy implications in further developing multiple-use forests in Vietnam.

The Faustmann formula was applied to find the optimal rotation age and the net present value (NPV) for planted forest at stand-level. We extended the Faustmann model to include multi-stands and spatial arrangement among forest stands in order to analyse the optimal strategy at forest-level. A simple search algorithm was used to look for optimal sets of planting and harvesting. The model was coded in GAMS. To evaluate the model, 293 household forest farmers who grow *Eucalyptus urophylla* and *Acacia mangium* in Yen Bai province, Northern Vietnam were interviewed.

Survey results show that the actual tree cutting age is five years. However, at the stand-level, we find that the optimal rotation age of *E. urophylla* (when only timber has market value) is 10 and 9 years for households and forest enterprises, respectively, at a 5% discount rate. For *A. mangium,* the optimal rotation age is 13 years for both households and forest enterprises. The NPV is VND 16 million per hectare for households of both *E. urophylla* and *A. mangium.* For forest enterprises, the NPV is VND 57 million and VND 62 million per hectare for *E. urophylla* and *A. mangium*, respectively.

Adding carbon values make the optimal rotation age slightly shorter and the NPV higher. Similarly, taking into account the spatial arrangement of forest stands shortens the rotation age and improves the NPV. Nevertheless, the rotation age, including carbon or forest-level, is still well-above the actual one. The optimal rotation age decreases with an increasing carbon price, planting subsidy level, constant timber price, and discount rate. The optimal rotation age increases with a rise in the level of increasing timber price, the level of economies to planting scale, and stochastic carbon price. The optimal rotation age is sensitive to the particular carbon payment scheme.

To encourage forest owners to lengthen the rotation age, the government can use a lump-sum payment of carbon benefits at the beginning of the rotation. Given that the majority of households cut their trees sooner based on their family's economic status, a planting cost subsidy will help to narrow the actual and the optimal rotation age. If the assumption of constant timber price is relaxed, the study finds that it is optimal to grow large-sized timber. It is suggested that cooperation or joint-venture among households, forest enterprises, and wood-processing companies may help to grow large-sized timber.

1.0 INTRODUCTION

1.1 Problem Statement

Productive planted forests[1] constitute approximately 13.1% of the total forest area in Vietnam and have increased by 11.9% per annum during the period of 2002-2006 (Forest Protection Department 2007). During a period of rapid climate change, managing planted forests for multiple-use purposes (i.e., timber production and carbon sequestration) is increasingly important. The global cost of a climate policy with forestry as an abatement option is USD 3 trillion cheaper than a policy without forestry (Tavoni *et al.* 2007). In addition, Vietnam can potentially gain a lot from engaging in the international carbon market; however, the benefits of carbon sequestration have not been adequately studied in the management of productive planted forests (Bui and Hong 2006).

In Yen Bai province, most of the fast-growing tree species in productive planted forests are cut at the age of five years (Nguyen *et al.* 2006). The cutting age is less than the optimal harvesting age that accounts for both timber production and carbon sequestration (Diaz-Balteiro and Rodriguez 2006; Van Kooten *et al.* 1995). Moreover, majority of forest farmers apply a clear-cut practice that destroys habitats and causes serious loss of biodiversity (Bui and Hong 2006; Pawson *et al.* 2006). These consequences result from forest farmers' daily basic needs and lack of investment capital as well as the lack of payment for environmental services, among others (Nguyen *et al.* 2006; Bui and Hong 2006).

Up to now, Vietnam does not have multiple-use planted forests (Forest Protection Department 2007; FAO 2006). Nevertheless, the Vietnamese government has recognized their importance, and two decisions signed by the Prime Minister regarding productive planted forests have recently been issued. Government Decision No. 100/2007/QD-TTg, dated July 2007, encourages forest owners to lengthen rotation ages (Vietnam 2007a). Government Decision No. 147/2007/QD-TTg, promulgated in September 2007, emphasizes that productive planted forests are multiple-use planted forests, and that the government subsidizes forest owners to partially compensate them for their environmental services and for the low profitability of planting trees (Vietnam 2007b).

During the period 2007-2015, the area of productive planted forests will continue to expand as the result of the government's Five Million Hectare Afforestation Program and because of a large domestic demand for wood (Vietnam 2007b; Department of Forestry 2006). To increase the value of carbon sequestration while ensuring timber production, there is an urgent need to adopt an optimal management strategy for productive planted forests.

1.2 Research Questions

The research attempts to answer the following questions:

1. Which pattern of planting and harvesting trees should a forest owner follow in order to maximize the net present value (NPV) from timber harvesting and carbon sequestration?
2. What are the differences in NPV and rotation age (T) between two optimal management strategies that consider or do not consider the value of carbon sequestration?
3. What are the differences in NPV and T of the optimal management strategies for two dominant tree species (i.e., *Eucalyptus urophylla* and *Acacia mangium*) for households and forest enterprises?
4. How does the optimal management strategy vary with a change in forest area, timber price, carbon price, and discount rate *ceteris paribus*?
5. What are the gaps in NPV and T between the current forest management strategy and the optimal strategy? What policy instruments are relevant to fill the gaps?

[1] This is a new term used in State of the World Forest (FAO 2007).

1.3 Literature Review

The optimal management strategy for a single stand forest was developed by Faustmann (1849). Let *V(t)* be the value of bare land, the Faustmann formula is as follows:

$$(1) \qquad V(t) = \frac{(p-c)g(t)e^{-rt} - k}{1 - e^{-rt}}$$

where: *t* is stand age, *k* planting cost, *p* price of timber, *c* harvesting cost, *g(t)* timber growth function, and *r* interest rate. The optimal rotation is increasing in *k* and decreasing in *p* and *r.*

Hartman (1976) extended the Faustmann model to include the amenity value of forests. He found that the optimal rotation is longer or shorter than the Faustmann rotation if environmental values increase or decrease with stand age. With the growing concern over climate change, Englin and Callaway (1993) included carbon value into the Faustmann rotation and found that the optimal rotation differs from the standard Faustmann rotation. Interestingly, they showed that the optimal rotation increases as discount rate goes up. They explained that as the discount rate rises, carbon emission after harvest lengthens, rather than shortens, the optimal rotation. Moreover, van Kooten *et al.* (1995) studied the effect of carbon taxes and subsidies on the optimal forest rotation age and concluded that the carbon optimal rotation is a bit longer than the Faustmann rotation age. Diaz-Balteiro and Rodriguez (2006) employed a dynamic programming approach and showed that the optimal rotation age for the same dominant tree species is different in two countries; and that the rotation age is sensitive to the changes in discount rate and carbon price. Again, Gutrich and Howarth (2007) confirmed that when carbon storage brings benefits to society, optimal rotation ages are extended depending on the forest types. They also pointed out that in the absence of policies to promote forest carbon storage, forest owners employ clear-cut harvesting regimes with a relatively short rotation age. In conclusion, literature on single stand forests shows that carbon rotation age differs from timber rotation age.

In fact, a forest usually consists of many stands. A forest stand is defined as “a contiguous group of trees sufficiently uniform in species composition, arrangement of age classes, site quality, and condition to be a distinguishable unit” (Smith *et al.* 1997). The optimal management strategy for a multiple stand forest was first introduced by Mitra and Wan (1985). They applied a dynamic programming approach and found that: a) if the utility function is linear, the Faustmann periodic solution is optimal; and b) if the utility function is increasing and strictly concave, an optimal solution converges to the maximum sustained yield[2] solution. Besides timber value, management strategies for multiple stand forests have taken into account non-timber benefits, such as carbon sequestration, biodiversity, and old-growth values. Tahvonen (2004) included old-growth values into his model as follows:

$$(2) \qquad Max\ V = \sum_{t=0}^{\infty} \left[U(c_t) + A(h_t)\right](1+r)^{-t}$$

where *U* denotes a utility function for timber output and c_t the volume of timber, *A* is the utility function related to environmental characteristics, and h_t a function of old growth conservation. The results of Tahvonen’s analysis showed the existence of an optimal long-run stationary continuum for land allocation between timber production and old-growth conservation. At each point in the continuum, timber is produced under the Faustmann rotation[3]. However, the studies of Mitra and Wan, and Tahvonen were based on the assumption that there are no spatial interactions among forest stands.

Spatial interactions can be either biological or financial interactions. To capture biologically spatial interactions, Swallow *et al.* (1997) employed a dynamic programming approach and allowed optimization of timber harvesting decisions in a forest consisting of two stands. In their study, spatial interactions among forest stands refer to the dependence of the non-timber benefit function for any stand on its own age and the ages (or conditions) of the neighbouring stands. Their results showed that the nature of stand interactions may alter the optimal management plan substantially. Koskela and Ollikainen (2001) considered a forest as including one focal stand and an exogenous adjacent stand, which affects the amenity production of the focal stand. They showed that the rotation age may increase with timber price, rather than

[2] Maximum sustainable yield stands for maximizing the mean annual increment (Hyytiainen and Tahvonen 2003).

[3] This means that the optimal management strategy divides forest land into two regions: one is for timber production and follows Faustmann rotation, and the other is for old growth conservation and applies an extended rotation.

decrease, as in the Faustmann model. However, their models included only two stands, while in reality, the number of stands in forests may go up to several thousand.

Financially spatial interactions refer to economies of harvesting or planting scale. At stand level, Termansen (2007) included economies of harvesting scale to his analysis and found that harvest costs have significant impacts on the optimal harvest strategy. His results also suggested that optimal rotation does not always decrease with interest rate, as in the Faustmann model. At forest level, Rose and Chapman (2003) analyzed the role of economies of adjacent harvesting scale in timber and non-timber management strategies. Their results showed that the manager's decisions can be misleading if spatial interactions are ignored.

Gutierrez *et al.* (2006) used a genetic algorithm to find the optimal management regimes for multiple stand forests under the Clean Development Mechanism (CDM)[4]. They discovered that the optimal rotation age is increasing in carbon price and the profitability of a project is very sensitive to its size, especially when project size is less than 2,000 ha. They also concluded that information on carbon sequestration in the tropics is scarce. In their study, however, all forest stands are at the initial age of zero and the study is based on the assumption of no spatial interdependence of forest stands.

In Vietnam, the optimal rotation age which maximizes the NPV from timber production for some main dominant tree species has been identified. Nguyen and Doan (2005) showed that rotation age for *hybrid Acacia* is 7-8 years for small-sized timber and 14-15 years for large-sized timber. Nguyen *et al.* (2006) proved that the optimal age for *A. mangium* should be longer than the rotation age that is applied by forest farmers. However, the optimal management strategy for planted forests when carbon sequestration is considered remains unknown in Vietnam.

In conclusion, the optimal rotation age for both single and multi-stand forests when carbon value is included is widely known, based on literature. Literature also shows that carbon rotation length may differ from the Faustmann rotation. However, those models have not yet been applied in a Vietnamese context. This study will apply the extension of the Faustmann model to find the carbon optimal rotation in planted forests in Vietnam. Further, the inclusion of spatial interactions in carbon optimal age for multi-stand forests remains unknown in the surveyed literature. This research therefore investigates the impacts of the spatial interactions among forest stands to the carbon optimal rotation. In this context, spatial interactions are defined as the economies of planting scale. This implies an arrangement of forest stands in relation to stand ages, which may contribute to large harvested areas and, hence, large planted areas. As a result, it will help to reduce planting cost.

1.4 The Study Area

1.4.1 General condition

Yen Bai is 180 km northwest of Hanoi with a total area of 688,630 ha, of which more than 70% covered by mountains and highlands (Figure 1). Yen Bai is characterised by a monsoon tropical climate with a mean annual temperature of 22-23°C, mean annual rainfall of 1500-2200 mm and mean annual humidity of 83-87% (Yen Bai Statistical Office 2010).

1.4.2 Forest resource and property rights

Yen Bai is a major source of timber supply in northern Vietnam. The area of productive planted forest in Yen Bai is 116,000 ha, accounting for 59% of the total area and 6.9% of the total productive planted forest area in Vietnam (Forest Protection Department 2007). Nine state enterprises and 41,000 households are involved in forest plantations (Yen Bai Forestry Department 2008; Nguyen *et al.* 2006). In Yen Bai, 50% of the productive forest area is managed by the Commune Committee, 42% by households, and 7.6% by forest enterprises with that remaining belonging to other institutions (Figure 2). Planted forests are dominated by

[4] "CDM is an arrangement under the Kyoto Protocol allowing industrialised countries with a greenhouse gas reduction commitment (called Annex B countries) to invest in projects that reduce emissions in developing countries as an alternative to more expensive emission reductions in their own countries" ("Clean Development Mechanism" 2009).

fast-growing trees such as *Eucalyptus spp.*, *Acacia spp.*, *Styrax tonkinensis, Manglietia conifera,* and *Cinnamomun cassia Blume* (Yen Bai Forestry Department 2008).

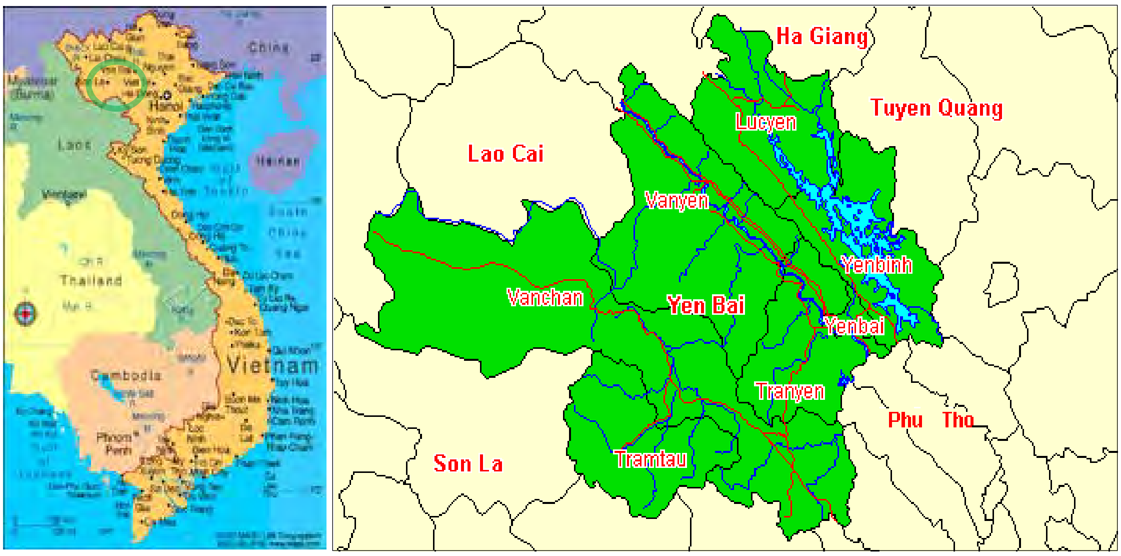

Figure 1. Map of Yen Bai province

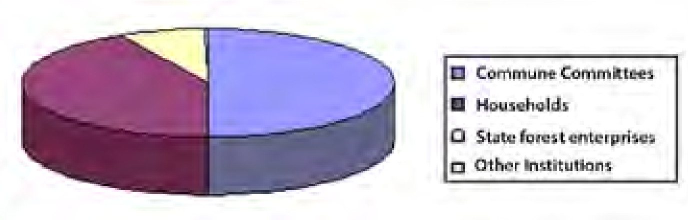

Figure 2. Proportion of forest land ownership in Yen Bai province

1.4.3 Legal framework and institutions

In Vietnam, all forest land is under state ownership. According to Government Decree No. 163/1999/ND-CP (1999), forest land is allocated and leased to individuals and organizations for long-term forestry purposes. Forest land allocated to households shall not exceed 30 ha and a fifty-year use right. After 50 years, the right to use the land can be extended at the request of the forest owner. Government Decree No. 135/2005/ND-CP (2005c) allows state forest enterprises to contract their land to households for a maximum of 30 years. Therefore, in principle, forest owners have sufficient land to apply sustainable management and longer rotation intervals; that is, to grow multiple age class species and delay harvest more than its actual harvesting age (i.e., five years).

According to Government Decree No. 23/2006/ND-CP,(2006) forest owners can exchange, transfer, rent, inherit or mortgage the right to use the land they have been allocated. They can also use their lands as capital for joint ventures. Therefore, forest owners can pool their land for carbon sequestration management. However, they cannot change the purpose of land use unless approved by government.

Government Decision No. 147/2007/QD-TTg (2007b) states that forest farmers who are allocated forest land are given a subsidy of VND 1.5 million per hectare per rotation and can keep 100% of the forest products. However, they have to pay a duty of 80 kg rice per hectare per rotation (approximately VND 0.24 million per hectare per rotation). Forest owners are required to replant the forests within 12 months after harvest. According to Government Decrees No. 106/2004/ND-CP (2004) and No. 20/2005/ND-CP, (2005d) feasible forestry projects can borrow up to 85% of the total project's capital and for up to 15 years. The more recent Decision No. 443/2009/QD-TTg (2009) states that the government will subsidize interest rates from bank loans up to 4% per year and for a period of two years.

1.4.4 Market conditions

As stated in Government Decree No. 23/2006/ND-CP (2006), forest owners are free to sell their forest products. Prime Minister Decision 661/1998/QD-TTg (1998) encourages forest owners to plant tree species that have high economic value. Decision No. 40/2005/QD-BNN (2005b) allows forest owners to make their own decisions about harvest age of timber and clear-cutting trees. Decision No. 100/2007/QD-TTg (2007a) states that the government encourages forest owners to lengthen the rotation ages. However, there is no specific policy to encourage forest owners to maintain longer rotation.

According to Nguyen *et al.* (2006), there are two types of timber dominant in Yen Bai: small-sized timber used for making wood-chips, pulp and construction work; and large-sized timber, around 13-15 years, for making exported products. End users of small-sized timber include local small-scale wood-processing units, wood-chip factories, Bai Bang paper mill, and Cau Duong match factory. End users of large-sized timber are wood-processing factories, local carpenters, and construction companies. Timber can be sold directly from forest owners to timber end-users or through timber collectors, timber wholesalers, and/or licensed trade individuals and organizations.

According to some forest owners, they have no difficulty selling their timber, and timber price varies with tree age or diameter[5]. Forest management costs include planting cost, tending cost, protection cost, land tax and bank interest. There are three main types of timber price: stumpage price, price at landing 1, and price at buyer's place[6]. Transportation costs make up a large proportion of the timber price. Growers also recognize that selling large-sized timber is more profitable than small-sized timber. However, they don't harvest trees later because of bank loans that need paying, the occurrence of illegal logging in forest enterprises, and because of the necessity to cover daily basic household needs.

Nguyen's study (2006) shows that export revenue of processed-wood products has increased dramatically over the last several years. However, 80% of the raw wood used to produce these processed-wood products is imported. The import price of *Eucalyptus* is VND 2.9 million per cubic meter while that of *Acacia* is VND 1.5 million per cubic meter; these are much higher than domestic timber prices for the same tree species. Moreover, transportation cost accounts for 27% of total import price, which is significant as 80% of wood-processing factories are located in the southern part of Vietnam.

1.5 Contribution of the Study

The study applied a theoretical model of optimal forest management developed by Faustmann (1849) (i.e., stand-level model) and by Tahvonen (2004)[7] (i.e., multiple stand or forest-level model) to analyse real data from Vietnam. Results are used to make policy recommendations to further develop multiple-use forests in Vietnam.

Determining the optimal forest management strategy would help forest owners make their plans and manage their forests profitably when carbon sequestration has market value. The results would be used to recommend policy to the Ministry of Agriculture and Rural Development (MARD) to develop the optimal management strategy for different tree species and ownership; to cope with change in market conditions; and to encourage carbon storage in Vietnam. The optimal forest management strategy can also be used to evaluate CDM projects in terms of the NPV and the amount of carbon sequestered.

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[5] Personal communication

[6] Landing 1 is a place near forests where forest owners in this region unload their raw timber for businessmen to buy and transport to wood-processing companies or other users. Buyer's place refers to the location of wood-processing companies or of other users. It means that raw timber is transported to their door.

[7] Should economies of scale exist, the study used the model of Tahvonen (2004) to analyse the actual data. Tahvonen's model does not include spatial arrangement among forest stands, while the model used in this study does.

2.0 METHODOLOGY

2. 1 The Model

2.1.1 Variables

Assume a forest consist of *n* stands with *n* equals to 1 for the Faustmann model, and is greater than 1 for the forest-level model. The objective of the model is to maximize the NPV from harvesting timber and sequestering carbon. The dependent variables (i.e., the optimal management strategy) include NPV and its associated rotation length.

Let $v(.)$: the discounted sum of timber and carbon values;
a_s: the area of stand *s* in hectares;
x_{st}: age of stand *s* in period *t*.

The model objective is to maximize the discounted revenue from timber and carbon[8]:

$$v(a_1,..a_n; x_{10},..,x_{n0}) = max \sum_{t=0}^{50} (1+r)^{-t} \, [U_t + A_t] \qquad (3)$$

Subject to:

$d_{st} = 0$ or $1, s = 1,..,n,$	binary decision variables
$x_{s,t+1} = (x_{st} + 1).(1 - d_{st}), s = 1,..,n,$	age of stand *s* at period *t+1*
$x_{st} \geq 0, s = 1,..,n,$	nonnegative constraint of ages

Where:

r — discount rate

$U_t = \sum_{s=1}^{n} [q(x_{st}). a_s . d_{st}.P(x_{st})] - G(h_t)$ — timber value at the period *t*

$q(x_{st})$ — timber volume per hectare of stand *s* in period *t*

d_{st} — the binary decision variable, $d_{st} = 1$: stand *s* is clear-cut in period *t*
$d_{st} = 0$: stand *s* is kept in period *t*.

$P(x_{st})$ — price of timber per unit volume, which varies with timber's age

$G(h_t)$ — planting cost of timber at period *t*, which varies with planting size[9],
$G(h_t) = \beta h_t^{\lambda}$, β and λ are estimated from survey data.

$h_t = \sum_{s=1}^{n} d_{st}.a_s$: — planting size in hectare in period *t*

$A_t = [\sum_{s=1}^{n} Qc(x_{st}). a_s . d_{st}]. Pc$: — amount of carbon sequestered at period *t*. We assume no carbon tax is imposed on forest owner at harvest. The carbon emission and transaction cost are also neglected. This formula implies carbon sequestration is calculated at the end of rotation for simplicity. Sensitivity to different payment schemes will be provided in the section of sensitivity analysis.

Qc — amount of carbon sequestered, metric tonne per hectare

P_c — carbon price per metric tonne

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[8] In Vietnam, forest owners can use their lands for 50 years at most. After 50 years, land rent may be extended at renter's request otherwise it is reverted back to the government. Based on preliminary results from the models, I used a 50-year planning horizon, since rotation age patterns are likely similar, but NPV is a big difference between infinitive and 50 years. Moreover, a fifty-year planning horizon is long enough for Vietnamese farmers since they are generally poor.

[9] There are no economies to planting scale in the Faustmann model.

2.1.2 Data

To estimate the cost functions for the two species, we adjusted planting costs obtained from the survey by inflation rates (Table 1). We ran the models with fixed carbon prices of USD 3 (equivalent to VND 51,000)[10] per ton CO_2.

Table 1. Inflation rate in Vietnam

Year	2000	2001	2002	2003	2004	2005	2006	2007
Inflation rate (%)	-1.6	-0.4	4.0	4.3	7.8	8.4	6.6	8.2*

**Source:* World Bank (2008) and ADB (2007)

Timber growth functions of *E. urophylla* and *A. mangium* for Site index II are estimated from data obtained from MARD (2003).

E. urophylla: (4) $q(x_{st}) = -1.38x_{st}^2 + 40.33x_{st} - 94.07$, $R^2 = 0.99$

A. mangium: (5) $q(x_{st}) = -0.3x_{st}^2 + 28.06x_{st} - 63.33$, $R^2 = 0.99$

where x_{st} denotes timber age and $q(x_{st})$ represents timber volume at age x_{st}.

The survey showed that a household's timber productivity is approximately one-third of the productivity provided in the Yield table (MARD 2003). We therefore used timber volume of household equals to $q(x_{st})/3$. This fact is also reported by the Vietnam Ministry of Natural Resources and Environment (2005).

To identify the amount of carbon uptake, carbon sequestration functions from Vo *et al.* (2009) are used. Since the carbon sequestration functions from Vo *et al.* are not suitable for planted forests beyond seven years of age, we therefore adjusted their carbon sequestration functions. First, we used tree density data from Tables of Site Index (MARD 2003) and tree density at planting from our survey[11] to calculate the relationship between stand age and tree density for households and enterprises. Second, we ran the carbon sequestration functions from Vo *et al.* with respect to stand age and tree density for site index I[12] for *E. urophylla* and site index II for *A. mangium*[13]. Finally, based on these figures, we re-estimated the carbon sequestration functions with respect to stand age only in order to use in our analysis. The final functions are as follows:

For households of *E. urophylla*:

(6) $Qc(x_{st}) = -0.071x_{st}^2 + 6.0155x_{st} + 11.567, R^2 = 0.9633$

For enterprises of *E. urophylla*:

(7) $Qc(x_{st}) = -0.1101x_{st}^2 + 9.3232x_{st} + 17.928, R^2 = 0.9633$

For households of *A. mangium*:

(8) $Qc(x_{st}) = -0.0305x_{st}^2 + 4.9714x_{st} + 66.114, R^2 = 0.9921$

For enterprises of *A. mangium*:

(9) $Qc(x_{st}) = -0.0271x_{st}^2 + 4.42x_{st} + 58.781, R^2 = 0.9921$

where x_{st} denotes timber age and $Qc(x_{st})$ represents the carbon amount (tonne per hectare) sequestered up to age x_{st}.

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[10] We use USD 3 per ton of carbon and 1 USD=17,000 VND

[11] From our survey, tree density of both species at planting is 2189 and 1660 trees per hectare for households and enterprises, respectively.

[12] The carbon sequestration from Vo *et al.*, is *LnQc=22.036 + 0.313lnX-1.584lnN*, where *Qc* is amount of carbon uptake (kilograms per hectare), *X* is age of tree, and *N* is tree density (per hectare).

[13] We used tree density at age 12/13 for *E. urophylla/A. mangium* for the rest of rotation so that the amount of carbon sequestered does not increase too high, say 30 thousand tonnes per hectare.

As mentioned above, we had to adjust the carbon sequestration functions from Vo *et al.* (2009) so that these functions fit in our study. In the sensitivity analysis section, we provided the model's results with other carbon sequestration functions from Vo *et al.* for *E. urophylla*, namely:

(1) $Qc(x_{st}) = 15.987e^{0.1516x_{st}}$

(2) $Qc(x_{st}) = e^{22.036+0.313\ln(x_{st})-1.584\ln(N)}$

(3) $Qct(x_{st}) = (e^{(4.1343-4.6438/x_{st})})/1000$

where $Qct(x_{st})$ is carbon amount uptake by individual trees (kilograms per tree) and *N* denotes tree density (trees per hectare). The equation (10) is carbon sequestration function for households and is adjusted from the equation (11). In the equation (12), we assumed tree density is 1000 trees per hectare. We cannot use tree density data as suggested above because in carbon function (12) the higher the tree density, the greater the amount of carbon uptake.

2.1.3 Algorithm

The model described in Section 2.1.1 was solved by the following procedure. To find the optimal strategy, all scenarios with different rotation ages were compared based on the objective variable. The scenario that had the highest NPV was chosen as the optimal strategy. The model was coded in GAMS and was used to analyse the optimal forest management strategy for case studies in Yen Bai province, Vietnam.

2.2 Questionnaire Development

Draft questionnaires for forest households and enterprises were developed based on the model specification and on a previous study on timber production in Yen Bai province (Nguyen *et al.* 2006). The questionnaires were sent to researchers in the forestry sector in Vietnam for further comments. The questionnaires were revised as follows: inclusion of more details in the cost section; provisions of simple explanations in the carbon sequestration section; and addition of questions regarding household labour and financial status in the general section. The questionnaires were tested in 10 households and forest enterprises in Yen Bai province. Respondents had no idea about the site index of their land and often grow several species in their forests. This was taken into account in finalizing the questionnaires.

The final quesionnaires included five parts. Part I obtained information about age, gender, ethnicity, education, size of household, labour and financial status. Part II included questions about sizes of forest lands and other lands, cutting practice, initial stage of forest, and understorey plants. Part III requested information about timber production costs, capital and subsidy from the government. Part IV was focused on income from forest and other sources in 2007. Part V investigated the management strategy regarding rotation length, government subsidy, method of payment for carbon sequestration, and carbon pooling.

2.3 Survey Implementation

The study sites included Tran Yen, Van Yen, and Yen Binh districts. Two communes in each of the three districts were selected based on consultations with local government officials. These are Viet Cuong and Cuong Thinh in Tran Yen district; Ngoi A and Yen Thai in Van Yen district; and Vu Linh and Vinh Kien in Yen Binh district.

The sample population consisted of households who grow *E. urophylla* or *A. mangium* and own a productive forest of at least 0.5 ha (Table 2). Households were selected randomly. Surveys were implemented in September 2008. Enumerators included students and lecturers from Vietnam Forestry University, and staff from the Institute of Environment and Ecology in Xuan Mai, Hanoi. A total of 271 usable questionnaires out of 291 distributed were collected. We interviewed four state forest enterprises (i.e., Viet Hung, Thac Ba, Van Yen, and Yen Binh). We also interviewed a private forest enterprise, a special management board, the Yen Bai Forestry Department, and other forestry department at district-level and commune-level to get further data for the research.

Table 2. Location and sample size

Location	Sample size		
	Total household	*E. urophylla*	*A. mangium*
Viet Cuong and Cuong Thinh communes, Tran Yen district	93	1	92
Ngoi A and Yen Thai communes, Van Yen district	88	6	101
Vu Linh and Vinh Kien communes, Yen Binh district	90	79	44
Total	**271**	**86**	**237**

3.0 RESULTS AND DISCUSSION

3.1 General

3.1.1 Descriptive data

The results of some descriptive data used in models are shown in Table 3. Almost all (85%) respondents are male with an average age of approximately 46 years and an average level of education of 8 per scale of 12. Nearly half (47%) of forest households belong to minority groups, namely Tay, Cao Lan, Dao, and Nung; the rest is Kinh group. Household size is five, three of which constitute household labor. Majority (80%) of the households are middle-class, 6.3% are poor, and the rest are well-off. Almost all (267/271) households can own their forest land for 50 years or more. Majority (91%) of the owners apply a clear-cut practice to manage their forests. Among the 271 respondents, 32 grow *E. urophylla* only, 78 grow *A. mangium* only, and 171 grow mixed species but in single stands. The average planted forest area is 3.95 ha, 20 times and 3 times higher than agriculture land and other lands, respectively. Agriculture activities bring 14 times higher revenue per hectare compared with forestry. This result is consistent with forest farmers' desire, noted during household interviews, to shift their land use to agriculture.

Table 3. Descriptive data

Variable	Unit	Mean (Standard deviation)
Age	years	46 (10.45)
Sex	female=1	15 % (36%)
Ethnic	minority groups =1	47% (50%)
Education	years	8/12 (2.96)
Household size	people	5 (1.46)
Household labor	people	3(1.21)
Financial status	well-off =1, poor =2, and average =3	2.67 (0.7)
Productive planted forest's area	hectare	3.95 (4.62)
Agriculture land	hectare	0.19 (0.13)
Other lands	hectare	1.18 (7.18)
Distance from planted forest to the main road	kilometre	1.11 (1.27)
Number of stands in planted forest	stands	2.54 (1.04)
Harvest age	years	5.17 (1.47)
Agriculture revenue per agriculture land	million VND per hectare	134 (174.31)
Planted forest revenue per forest land	million VND per hectare	9.9 (8.15)

The survey shows that 4.8% of households receive a subsidy from government to grow their trees. Most (73.4%) households use their own capital to invest in their forests, so lower interest rates from bank loans may not be relevant to the big population of forest households. Forty-eight percent (48.3%) based their decision to cut on timber age, 28.4% on family economic status, and 12.2% on timber price. Family economic status, the second main reason to cut their trees, relates to the 80% of forest households that are middle-class. The decision on tree species largely depends on profitability of the species (48%), on family economic status (25.5%), and on the decision of adjacent households (12.2%), with 14.4% on other reasons. Almost all (93.4%) forest owners would delay their harvest if they are financially supported from the government with an average amount of VND 5.5 million per hectare per year. The reasons why they chose that level of compensation amount are living costs and debt (46.2%), production costs or other incomes (20.6%), price and volume uncertainties (10.3%), and other reasons (22.9%). Again, family economic status plays an important role in the decision of household forest owners regarding tree cutting.

The two proposed carbon payment schemes are weighted almost similarly, 51.7% and 48.3% for annual and lump sum payment, respectively. For annual payment, forest farmers would be given annual carbon service payments from forest canopy closure or from year four onwards until forest harvesting. For lump sum payment, forest farmers would be paid for carbon service in full during forest establishment and they have to sign a pledge to keep their forests until it reaches a certain age. Forest owners wish to receive an average amount of VND 21.4 million per hectare per rotation from carbon benefits for them to keep their trees till age 11 years on average. Should an investor want to establish forests in an area with the participation of households, besides income from timber selling, the participants would be given some payments from keeping their forests for carbon sequestration. Results show that nearly 89% of households agree to this carbon pooling arrangement. This is because they believe that they would: benefit from technical support, forest protection, and economies of scale (42.9%); have more capital to invest in their forest (5%); receive environmental benefits (13.4%); and other reasons (38.7%). Regarding carbon pooling, almost half (47.3%) of respondents said that a contract is necessary, 21.8% need a discussion, and 31% have no ideas on the paper work needed. When we asked forest owners if they could foresee any obstacles for a carbon pooling agreement, 22.9% said there were no obstacles, 15.9% worried about catastrophic risks and price uncertainty, 8.1% were afraid of the infeasible plan of the investors, 4.8 % answered that poor households may cut trees earlier, and 48.3% gave other reasons. Household answers showed little worry about their ability to engage in a carbon pooling project.

3.1.2 Planting cost and timber revenue

For households, planting cost of *E. urophylla* is VND 6.85 million per hectare, which is VND 0.07 million higher than that of *A. mangium* (Table 4). We calculated the planting cost as per 2007 Vietnamese Dong based on the inflation rate of Vietnam as shown in Table 4.

For forest enterprises, we took the average figures of planting costs (including planting cost, tending cost up to year three, and other costs) collected from enterprises. It comes to planting costs of VND 17.02 million per hectare for *E. urophylla* and VND 14.09 million per hectare for *A. mangium*. These costs are higher than those of households since enterprises use more fertilizers and bear other associated costs such as management, design, and interest rate. We used these costs to calculate the Faustmann rotation for households and for enterprises.

Table 4. Planting costs

Species	Household's planting cost (million VND per hectare)	Enterprise's planting cost (million VND per hectare)
E. urophylla	6.85	17.02
A. mangium	6.77	14.09

Table 5 shows that timber revenue per hectare per rotation for *E. urophylla* is nearly VND 7 million higher than that for *A. mangium.* We used the average timber price of VND 0.37 million and VND 0.33 million per cubic meter for *E. urophylla* and *A. mangium* to calculate Faustmann rotations for both households and enterprises.

Table 5. Timber price and revenue in 2007

Species	Selling place	Average timber revenue per hectare (million VND)	Average timber price per m^3 (million VND)
E. urophylla	Stumpage price	19.38	**0.37**
	Landing 1	22.06	0.44
A. mangium	Stumpage price	12.89	**0.33**
	Landing 1	10.39	0.35

From household survey data, we estimated the following function of economies to planting scale[14] for *E. urophylla* (Figure 3):

(13) $G(h_t) = 5.16h_t^{0.98}$, $R^2 = 0.66$

where h_t denotes planted area (hectare) and $G(h_t)$ represents planting cost (million VND per hectare). In this case, the level of economies of scale λ equals to *0.98.*

Similarly, the cost function for *A. mangium* is as follows (Figure 4).

(14) $G(h_t) = 4.56h_t^{1.07}$, $R^2 = 0.66$

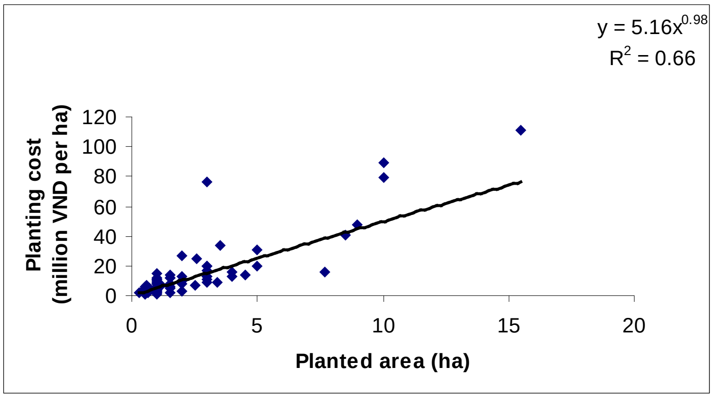

Figure 3. Economies to planting scale for *E. urophylla*

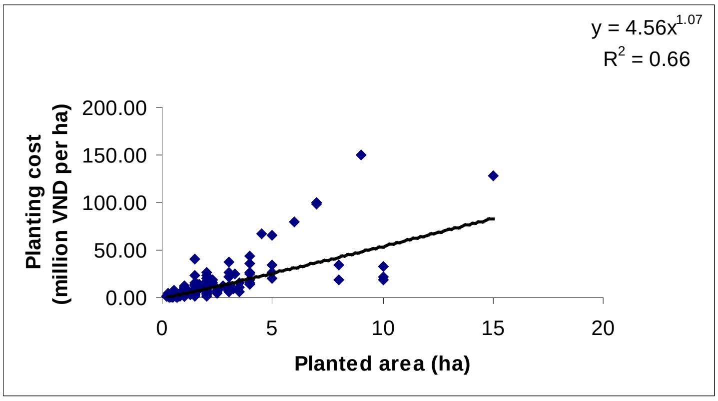

Figure 4. Economies to planting scale for *A. mangium*

In the case of *A. mangium,* the cost function exhibits increasing planting cost to scale. Intuitively, since households who have a large area of planted forests may have more money to invest in their

[14] Majority of forest households sell stumpage trees; hence, we do not have data to estimate economies of harvesting scale.

plantations or do it as a real business, increasing cost to scale exists. Further, it is hard to find economies of scale since households employed different techniques, amount of capital, labour, and fertilizer in their forests. Finally, since more than 70% of Yen Bai province is mountains and highlands, the far distance among forest stands of the same owners, and the low level of machine application make the level of economies to planting cost nearly one in both tree species. However, we still used the function of economies to planting scale of *E. urophylla* to calculate forest-level rotation. Sensitivity of the optimal rotation age to the value of λ is presented in the section of sensitivity analysis.

We were unable to estimate function of economies to planting scale for forest enterprises. Based on planting costs determined by the Vietnamese government (Vietnam 2005a), each forest enterprise developed beforehand tables of estimated planting cost for each species per hectare.

3.2 Faustmann Rotation

The optimal ages for both species are higher than the actual harvesting ages (i.e., five years) shown by the survey (Table 3). At positive discount rates, the optimal rotation length ranges from 8 to 10 years and the NPV is between VND 3 and 189 million per hectare for *E. urophylla*; and from 9 to 17 years and between VND 3 and 209 million per hectare for *A. mangium*. The Faustmann rotation of households is a little bit longer than that of enterprises, but the NPV is much smaller. This result is interesting since most planted forest areas of forest enterprises are contracted to households. The terms of conditions vary among forest enterprises. The NPV of forest enterprises is higher than that of households because of timber growth. Households whose land are allocated from the government tend to plant trees with higher density, use less fertilizer, and may apply incorrect growing techniques.

When carbon has value, the household's rotation and the enterprise's rotation are nearly identical. As mentioned in Section 2.1.2, we used the carbon price of USD 3 per metric tonne. For both households and enterprises, the carbon optimal rotation is slightly shorter compared to the Faustmann rotation but the carbon NPV is higher than the Faustmann's NPV (Tables 6 and 7). This finding (i.e., carbon sequestration makes rotation age shorter) contrasts with the result of van Kooten *et al.* (1995). This is because of the nature of fast-growing trees in our study, where carbon uptake and timber growth are stronger in its early years; while the native tree species in van Kooten *et al.* have totally different patterns of growth throughout its life[15]. Therefore, it is optimal to cut and replant trees sooner to maximize profit from selling timber and sequestering carbon.

Table 6. Faustmann rotation age with and without carbon value for *E. urophylla* in forest households and enterprises

Discount rate (%)	Households				Enterprises			
	Timber only		With Carbon		Timber only		With Carbon	
	T (years)	NPV (m. VND/ha)	T	NPV	T	NPV	T	NPV
1	10	51.97	10	64.44	10	170.52	10	189.85
2	10	38.17	10	47.82	10	126.86	10	141.81
3	10	28.41	10	36.03	10	95.87	10	107.68
4	10	21.36	10	27.49	10	73.42	10	82.92
5	10	16.15	**9**	21.24	9	56.86	9	65.17
6	10	12.24	**9**	16.68	9	44.90	9	51.84
7	9	9.36	9	13.15	9	35.61	9	41.48
8	9	7.10	9	10.35	9	28.25	9	33.29
9	9	5.29	8	8.15	9	22.35	**8**	27.04
10	9	3.81	8	6.42	8	17.78	8	21.95

Note: Carbon price is VND 51,000 (USD 3) per metric tonne.

[15] The first derivative of timber growth function for *E. urophylla* is $q'(x_{st})=-2.76\ x_{st} +40.33$. Van Kooten *et al.*, used the timber growth function $q(x)=0.000573\, x^{3.7819}e^{-0.030965x}$, with the first derivative $q'(x)=[\, 0.002167\, x^{2.7819}e^{-0.030965x}] - [(1.77429E\text{-}0.5)x^{3.7819}e^{-0.030965x}]$.

Table 7. Faustmann rotation age with and without carbon value for *A. mangium* in forest households and enterprises

Discount rate (%)	Households				Enterprises			
	Timber only		With Carbon		Timber only		With Carbon	
	T (years)	NPV (m. VND/ha)	T	NPV	T	NPV	T	NPV
1	17	59.95	17	75.65	17	195.76	17	209.71
2	17	42.60	13	55.22	17	141.63	13	153.24
3	17	30.51	13	41.19	13	105.76	13	115.57
4	13	22.34	13	31.06	13	80.58	13	88.33
5	13	16.60	10	24.11	13	62.00	10	68.52
6	13	12.30	10	18.87	11	48.23	10	54.53
7	13	9.01	10	14.83	10	38.27	10	43.73
8	11	6.55	9	11.71	10	30.59	10	35.26
9	11	4.67	9	9.29	10	24.46	9	28.51
10	10	3.15	9	7.32	10	19.49	9	23.27

3.3 Forest-level Rotation

To estimate forest-level rotation, we used Microsoft Excel to randomly choose five case studies for *E. urophylla* from the survey data. The number of stands ranges between one and five in our database. We therefore randomly chose one case each that has two, four, and five stands; and two cases that have three stands (Table 8). For the initial ages of forest stands, we analysed two cases: a) zero initial ages and b) actual initial ages. Forest stand areas are the actual households' stand areas.

Table 8. Case studies of forest-level rotation for *E. urophylla*

Cases	Codes*	No. of stands	Area of stands (ha)					Age of stands (years)				
			S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
1	A086	5	3.1	2.9	1	0.8	0.8	3	3	3	3	3
2	A086	5	3.1	2.9	1	0.8	0.8	0	0	0	0	0
3	A075	4	1	0.3	0	0.3	…	4	2	2	2	…
4	A075	4	1	0.3	0	0.3	…	0	0	0	0	…
5	A038	3	3	1	1	…	…	1	1	1	…	…
6	A038	3	3	1	1	…	…	0	0	0	…	…
7	A017	3	2	0.5	1	…	…	2	1	1	…	…
8	A017	3	2	0.5	1	…	…	0	0	0	…	…
9	A007	2	1	1	…	…	…	4	2	…	…	…
10	A007	2	1	1	…	…	…	0	0	…	…	…

*Note: This is a coding number we used in our database.

For *E. urophylla*, in all 10 cases, the optimal rotation age with or without carbon is shorter by up to two years than the Faustmann rotation and the NPV is greater than that of the Faustmann NPV. In particular, when the initial age of the forest is greater than zero (i.e., cases 1, 3, 5, 7, and 9), at a 5% discount rate, carbon sequestration makes rotation age shorter. When the initial age equals zero, at an 8% discount rate, adding carbon value shortens the rotation age. The optimal rotation decreases with an increasing discount rate, as in the Faustmann model (Table 9).

Table 9. Forest-level rotation with and without carbon value for *E. urophylla*

Case	5% discount rate				8% discount rate			
	Timber		Carbon		Timber		Carbon	
	T (years)	NPV (m. VND/ha)	T	NPV	T	NPV	T	NPV
1	10	21.42	8	26.81	8	12.16	8	15.93
2	9	17.82	9	22.48	9	8.64	8	11.47
3	10	21.27	8	26.64	8	12.08	8	15.93
4	9	17.42	9	22.08	9	8.34	8	11.14
5	10	18.51	9	23.32	8	9.52	8	12.75
6	9	17.70	9	22.36	9	8.55	8	11.37
7	10	19.12	8	24.01	8	10.07	8	13.44
8	9	17.61	9	22.27	9	8.48	8	11.30
9	10	20.97	8	26.27	8	11.79	8	15.57
10	9	17.48	9	22.14	9	8.38	8	11.19

Note: Carbon price is VND 51,000 (USD 3) per metric tonne.

3.4 Sensitivity Analysis

3.4.1 Carbon price

We did a sensitivity analysis of the Faustmann model with a carbon price from USD 3 (VND 0.051 million) to USD 70 (VND 1.19 million) per metric tonne and with the carbon price assumed to be constant over the planning horizon. In the case of *E. urophylla* (Table 10), the carbon rotation age decreases significantly with an increasing carbon price (up to 75%) and moderately with discount rate (up to 33%). The level of decrease is slightly different between households and enterprises. For example, at a USD 3 carbon price, the households' rotation age is 10 years at a 1% discount rate, and 8 years at a 10% discount rate, while the rotation length for enterprises is 10 and 7 years in both cases, respectively. In general, the rotation age ranges from 2 to 10 years. For *A. mangium* (Table 11), the relationship between the carbon rotation age and the carbon price or the discount rate is similar to that of *E. urophylla.* However, the households' rotation age is very sensitive to carbon price. It decreases to one year at the carbon price of USD 20 per tonne at all discount rates. The spread of the optimal rotation age is larger than that of *E. urophylla*, ranging from 1 to 17 years.

Table 10. Sensitivity analysis of Faustmann rotation age with constant carbon price for *E. urophylla* in forest households and enterprises

Discount rate (%)	Carbon price (USD/tonne)	Households		Enterprises	
		T (year)	NPV (m. VND/ha)	T	NPV
1	3 (0.051 m. VND)	10	64.44	10	189.85
	10 (0.17)	10	93.54	10	234.95
	20 (0.34)	9	135.70	10	299.37
	70 (1.19)	4	385.18	6	645.93
5	3 (0.051)	9	21.24	9	65.17
	10 (0.17)	9	33.75	9	84.56
	20 (0.34)	7	52.75	8	112.56
	70 (1.19)	3	174.62	5	277.39
8	3 (0.051)	9	10.35	9	33.29
	10 (0.17)	8	18.43	8	45.92
	20 (0.34)	6	31.22	7	64.72
	70 (1.19)	3	115.12	5	174.52
10	3 (0.051)	8	6.42	8	21.95
	10 (0.17)	7	12.91	7	31.69
	20 (0.34)	6	23.20	7	46.92
	70 (1.19)	2	92.84	4	135.57

Table 11. Sensitivity analysis of Faustmann rotation age with constant carbon price for *A. mangium* in forest households and enterprises

Discount rate (%)	Carbon price (USD/tonne)	Households		Enterprises	
		T (year)	NPV (m. VND/ha)	T	NPV
1	3 (0.051 m. VND)	17	75.65	17	209.71
	10 (0.17)	6	123.87	13	245.22
	20 (0.34)	1	533.47	10	304.19
	70 (1.19)	1	2924.46	1	1953.58
5	3 (0.051)	10	24.11	10	68.52
	10 (0.17)	4	51.29	10	86.71
	20 (0.34)	1	258.31	7	117.21
	70 (1.19)	1	1416.04	1	945.93
8	3 (0.051)	9	11.71	10	35.26
	10 (0.17)	3	31.84	8	47.31
	20 (0.34)	1	178.04	6	70.15
	70 (1.19)	1	976.01	1	651.99
10	3 (0.051)	9	7.32	9	23.27
	10 (0.17)	3	24.81	8	33.29
	20 (0.34)	1	146.97	5	52.77
	70 (1.19)	1	805.67	1	538.20

The relationship between the rotation length and the carbon price contrasts with the findings of van Kooten *et al.* (1995) but is in agreement with the results of Englin and Callaway (1993) (with amenity value). Diaz-Balteiro and Rodriguez (2006) found that carbon price has little effect with no clear pattern to the optimal rotation. The relationship between the rotation age and discount rate agrees with the literature, with the exception of Englin and Callaway, in which carbon rotation (without timber value) increases with discount rate. For *E. urophylla,* at a 5% discount rate and carbon price of USD 20 per metric tonne, the difference of the NPV between with and without carbon scheme is approximately VND 21 million per hectare, just about equal to the compensation level required by households to lengthen the rotation age.

We also analysed the optimal management strategies under stochastic carbon prices. Carbon prices were generated randomly in GAMS over a fifty-year planning horizon, and then were used to run the optimization model. We ran this procedure 10 times. We chose three magnitudes of carbon price: from VND 0 to 1.2 million per metric tonne (equal to USD 0 to 70 per tonne), from VND 0 to 0.5 million per tonne (equal to USD 0 to 29.5 per tonne), and from VND 0 to 0.3 million per tonne (equal to USD 0 to 17.7 per tonne). Details of carbon prices for the first run are provided in Appendix 1.

The relationship between the optimal rotation age and carbon price is the same as in the case of a constant carbon price (Tables 12 and 13). That is, the optimal rotation age decreases as the maximum value of carbon price increases. *A. mangium*'s optimal rotation age is more sensitive to carbon price than that of *E. urophylla.* At the maximum carbon price of VND 1.2 million per tonne (or USD 70 per tonne), the rotation age of *A. mangium* is reduced to one year for all 10 runs. In general, the optimal rotation age is shorter with an increasing discount rate. The speed with which the optimal rotation age shortens with an increasing discount rate is smaller compared to the case of a constant carbon price. Moreover, stochastic carbon price lengthens the optimal rotation age. For example, for *A. mangium,* at a constant carbon price of VND 0.34 million per tonne, all rotation ages are one year (Table 11), while at a stochastic price of VND 0.3 to 0.5 million per tonne, many rotation ages are greater than one year (Table 13). For *E. urophylla,* at a constant price of VND 1.19 million per tonne, the rotation ages are four years or less, while at a stochastic price, they are almost greater than five years. This agrees with the results of Chladna (2007) and Thomson (1992).

Table 12. Sensitivity analysis of Faustmann rotation age with stochastic carbon price for *E. urophylla*

Maximum Carbon Price (m. VND/tonne)	Order of run (out of 10)	T (year) Discount rate (%)					NPV (m. VND/ha) Discount rate (%)				
		1	3	5	8	10	1	3	5	8	10
1.2	First run	7	7	6	6	6	238.7	148.6	98.9	62.1	47.6
	Fourth run	10	10	10	10	10	221.1	140.4	95.5	58.6	44.0
	Tenth run	10	10	5	5	5	282.5	176.1	126.3	84.8	68.1
0.5	First run	9	9	9	6	6	122.2	73.5	46.9	27.0	20.2
	Seventh run	12	8	8	8	8	124.8	76.0	52.4	32.5	24.4
	Tenth run	9	11	6	6	6	113.8	66.2	44.4	27.7	21.0
0.3	First run	8	8	8	8	7	89.0	52.8	33.1	17.5	12.2
	Third run	14	14	11	7	9	101.4	56.7	35.1	19.2	13.2
	Fifth run	10	11	11	6	6	103.5	58.7	35.8	18.5	13.1
	Tenth run	10	10	8	8	8	96.3	56.2	37.2	21.9	15.9

Table 13. Sensitivity analysis of Faustmann rotation age with stochastic carbon price for *A. mangium*

Maximum Carbon Price (m. VND/tonne)	Order of run (out of 10)	T (year) Discount rate (%)					NPV (m. VND/ha) Discount rate (%)				
		1	3	5	8	10	1	3	5	8	10
1.2	First run	1	1	1	1	1	1159.2	791.7	583.0	411.1	343.9
	Fifth run	1	1	1	1	1	1055.2	740.7	555.2	395.3	329.8
	Eighth run	1	1	1	1	1	1067.2	700.7	498.9	339.0	278.4
0.5	First run	1	1	2	2	2	302.3	199.2	143.5	103.2	86.9
	Third run	2	2	1	1	1	195.9	126.8	92.9	66.2	56.4
	Ninth run	1	1	1	1	1	356.5	232.6	161.8	103.3	80.4
0.3	First run	14	10	5	5	5	124.5	72.1	50.8	32.7	25.3
	Second run	11	9	9	5	5	139.7	84.5	55.6	34.3	26.7
	Fourth run	1	1	1	1	1	1159.2	791.7	583.0	411.1	343.9
	Fifth run	1	1	1	1	1	1055.2	740.7	555.2	395.3	329.8

3.4.2 Carbon payment scheme

We analysed the impacts of various carbon payment schemes on the optimal management strategy (Tables 14 and 15). Carbon value can be paid to forest owners at the beginning of the rotation (with an expectation of rotation age), every year, or at the end of the rotation.

We found that a lump-sum payment at the beginning of the rotation lengthens the optimal rotation age and increases the NPV compared to an annual payment and a payment at the end of the rotation. Interestingly, for *E. urophylla*, giving a lump-sum payment at the beginning of the rotation at the carbon price of VND 1.19 million (USD 70) per tonne increases the optimal rotation age with a rise in the discount rate. Intuitively, this result follows from having the payment at the beginning of the rotation in combination with a high carbon price, making carbon benefits greater than timber value, and making the farmer believe that it is worth it to lengthen the rotation age.

Table 14. Sensitivity analysis of Faustmann rotation age with carbon payment scheme for *E. urophylla*

Carbon price (m. VND/tonne)	Discount rate (%)	End payment T (year)	End payment NPV (m. VND/ha)	Annual payment T	Annual payment NPV	Beginning payment T	Beginning payment NPV
0.051	1	10	64.44	10	65.15	10	65.61
	5	9	21.24	10	22.79	10	23.95
	8	9	10.35	9	11.94	9	13.09
	10	8	6.42	8	7.90	9	9.08
0.17	1	10	93.54	10	95.89	10	97.43
	5	9	33.75	9	38.71	10	42.13
	8	8	18.43	8	23.33	9	27.07
	10	7	12.91	8	17.63	9	21.36
0.34	1	9	135.70	9	139.93	10	142.90
	5	7	52.75	8	61.63	9	68.37
	8	6	31.22	7	39.99	9	47.04
	10	6	23.20	7	31.78	10	38.93
1.19	1	4	385.18	4	393.22	5	397.99
	5	3	174.62	4	191.27	5	202.53
	8	3	115.12	4	132.22	37	157.95
	10	2	92.84	4	109.35	41	157.83

Table 15. Sensitivity analysis of Faustmann rotation age with carbon payment scheme for *A. mangium*

Carbon price (m. VND/tonne)	Discount rate (%)	End payment T (year)	End payment NPV (m. VND/ha)	Annual payment T	Annual payment NPV	Beginning payment T	Beginning payment NPV
0.051	1	17	75.65	17	77.61	17	78.30
	5	10	24.11	10	27.90	13	29.10
	8	9	11.71	10	15.73	10	16.90
	10	9	7.32	9	11.31	10	12.43
0.17	1	6	123.87	9	128.57	9	129.77
	5	4	51.29	5	61.05	6	62.71
	8	3	31.84	5	41.73	5	43.43
	10	3	24.81	4	34.36	5	36.04
0.34	1	1	533.47	1	533.47	1	533.47
	5	1	258.31	1	258.31	1	258.31
	8	1	178.04	1	178.04	1	178.04
	10	1	146.97	1	146.97	1	146.97
1.19	1	1	2924.46	1	2924.46	1	2924.46
	5	1	1416.04	1	1416.04	1	1416.04
	8	1	976.01	1	976.01	1	976.01
	10	1	805.67	1	805.67	1	805.67

4.3 Planting cost subsidy

We presented a sensitivity analysis of the carbon rotation age with a planting cost subsidy in Tables 16 and 17. Planting costs for both species are around VND 6 million. Based on this, we used VND 0.5 as the lowest subsidy level. VND 6.77 million and VND 6.85 million per hectare per rotation were used as the full subsidy level for *A. mangium* and *E. urophylla*, respectively.

Results show that the larger the planting cost subsidy, the shorter the rotation age. In particular, for *E. urophylla,* a full subsidy always makes the rotation age shorter and a subsidy VND 0.5 million only shortens the rotation at a 5% discount rate. Moreover, at a 5% discount rate, all subsidy levels induce forest owners to shorten the rotation age. The NPV is higher with the lower discount rate and the higher subsidy level.

Table 16. Sensitivity analysis of Faustmann carbon rotation age with planting cost subsidy for *E. urophylla*

Discount rate (%)	Subsidy level (m. VND/ha)	T (year)	NPV (m. VND/ha)
1	6.85	9	94.44
	4	10	81.00
	2	10	72.72
	1	10	68.58
	0.5	10	66.51
5	6.85	7	40.44
	4	8	31.76
	2	9	26.47
	1	9	23.85
	0.5	9	22.55
8	6.85	6	25.91
	4	7	18.96
	2	8	14.54
	1	8	12.39
	0.5	9	11.33
10	6.85	6	20.38
	4	7	14.21
	2	8	10.15
	1	8	8.29
	0.5	8	7.35

Table 17. Sensitivity analysis of Faustmann carbon rotation age with planting cost subsidy for *A. mangium*

Discount rate (%)	Subsidy level (m. VND/ha)	T (year)	NPV (m. VND/ha)
1	6.77	10	99.60
	4	13	88.38
	2	13	81.72
	1	13	78.39
	0.5	17	76.92
5	6.77	6	42.66
	4	9	33.90
	2	10	28.84
	1	10	26.47
	0.5	10	25.29
8	6.77	5	27.55
	4	7	20.15
	2	8	15.69
	1	9	13.68
	0.5	9	12.69
10	6.77	5	21.85
	4	6	15.14
	2	8	11.02
	1	8	9.16
	0.5	8	8.22

3.4.4 Timber price

Timber of different sizes is sold at different prices. We therefore employed a non-constant timber price. We assumed harvest size is strongly correlated to timber age. We also made assumptions based on our preliminary field work and our interviews during the survey. We used real timber prices-*P* (i.e., VND 0.37 million per cubic meter for *E. urophylla* and VND 0.33 million per cubic meter for *A. mangium* based on survey data) as the price for timber that was seven years old. If timber harvest age (T) is smaller than five years, timber price equals: $P_t = P-0.15$. If timber age is between five and six years, timber price equals: $P_t = P-0.05*(7-T)$. If timber age is from 7 to 14 years, timber price equals: $P_t = P+0.1*(T-7)$. If timber age is greater than 14 years, then $P_t = P+0.8$. We varied the real timber price from VND 0.1 to VND 3 million per cubic meter for sensitivity analysis.

For *E. urophylla* (Table 18), we found that when the real timber price is low, it is optimal to grow large-sized timber (i.e., the rotation age is around 13-15 years) at all discount rates. Moreover, at the real timber price (VND 0.37 million) or at the price of VND 0.1 million, the rotation age remains the same for all discount rates. The higher timber price decreases the rotation age. Only at a 8 % discount rate and at a VND 3 million timber price is it optimal to grow small-sized timber (i.e., eight years). So, assuming a non-constant timber price makes the rotation age (i.e., almost from 13 to 15 years) significantly longer than with the constant price Faustmann solution (i.e., from 8 to 10 years). The NPV increases with rising timber price and decreases with increasing discount rate. The relationships between the optimal rotation/the NPV and timber price for *A. mangium* are similar to those for *E. urophylla* (Table 19).

Table 18. Sensitivity analysis of Faustmann carbon rotation age with timber price where timber price is non-constant for *E. urophylla*

Discount rate (%)	Timber price (m. VND/m^3)	T (year)	NPV (m. VND/ha)
1	0.1	15	140
	0.3	15	174
	0.37	14	186
	0.5	14	210
	1	14	302
	3	10	700
5	0.1	15	46
	0.3	14	58
	0.37	14	63
	0.5	14	72
	1	13	107
	3	9	280
8	0.1	15	22
	0.3	14	29
	0.37	14	32
	0.5	13	37
	1	11	59
	3	**8**	168

Table 19. Sensitivity analysis of Faustmann carbon rotation age with timber price where timber price is non-constant for *A. mangium*

Discount rate (%)	Timber price (m. VND/m^3)	T (year)	NPV (m. VND/ha)
1	0.2	17	232.52
	0.33	17	262.95
	0.5	17	302.76
	2	17	653.96
	3	17	888.10
5	0.2	15	79.55
	0.33	15	90.68
	0.5	15	105.22
	2	15	233.58
	3	14	320.94
8	0.2	15	40.61
	0.33	15	46.72
	0.5	15	54.71
	2	13	127.08
	3	11	180.91
10	0.2	15	26.67
	0.33	15	30.98
	0.5	15	36.62
	2	11	91.49
	3	9	133.81

We tested the optimal rotation age when timber price increases every year at 1% and 10% (Tables 20 and 21). For *E. urophylla,* compared to the carbon rotation age with a constant price, the rotation age when timber price is non-constant and increasing every year is longer at every discount rate, increasing from 8-10 years to 13-14 years and to 14-18 years at 1% and 10% price increase per year, respectively. With the 1% timber price increase per year, the rotation age decreases as the discount rate increases. However, with a 10% annual price increase, this rule seems to be no longer valid. In particular, at the timber price of VND 2 million per cubic meter, the rotation age is 13-14-13 years as the discount rate increases. This unusual relationship of the discount rate and the rotation age happens not only with this carbon sequestration function but also with the other carbon sequestration function[16], and for *A. mangium* as well. Interestingly, at a 10% increase, the optimal rotation of *A. mangium* is no longer sensitive to the timber price. At a 1% discount rate, it is optimal to keep trees until the end of the planning horizon.

[16] (3) $Qct(x_{st}) = (e^{(4.1343-4.6438/x_{st})})/1000$

Table 20. Sensitivity analysis of Faustmann carbon rotation age where timber price is non-constant and increasing every year for *E. urophylla*

Timber price (m. VND/m^3)	Discount rate (%)	1% price increase/year		10% price increase/year	
		T (year)	NPV (m. VND/ha)	T	NPV
0.2	1	15	218	18	6501
	5	15	69	15	1257
	8	14	33	15	447
	10	14	21	15	242
0.37	1	14	258	18	7608
	5	14	83	14	1487
	8	14	41	14	526
	10	13	27	14	285
0.5	1	14	290	18	8454
	5	14	94	14	1669
	8	14	47	14	591
	10	13	31	14	321
2	1	13	671	13	18438
	5	10	239	14	3766
	8	9	135	14	1340
	10	9	99	13	735
3	1	10	940	13	25534
	5	9	348	13	5191
	8	9	202	13	1855
	10	8	150	10	1032

Table 21. Sensitivity analysis of Faustmann carbon rotation age where timber price is non-constant and increasing every year for *A. mangium*

Timber price (m. VND/m^3)	Discount rate (%)	1% price increase/year		10% price increase/year	
		T (year)	NPV (m. VND/ha)	T	NPV
0.2	1	17	322	50	14027
	5	15	103	25	2107
	8	15	52	26	654
	10	15	34	17	346
0.33	1	17	364	50	15850
	5	15	117	25	2381
	8	15	59	26	740
	10	15	39	17	392
0.5	1	17	419	50	18235
	5	15	136	25	2740
	8	15	69	26	853
	10	15	46	17	451
2	1	17	904	50	39274
	5	15	300	25	5909
	8	14	157	26	1843
	10	11	110	17	980
3	1	17	1227	50	53300
	5	14	410	25	8021
	8	13	219	26	2504
	10	10	159	17	1332

3.4.5 Carbon sequestration function

As mentioned in Section 2.1.2, we analysed the impacts of three different carbon functions (equation 10 to 12) on the optimal rotation length for *E. urophylla*. At the stand-level, results show that the rotation age for households (see equation 10) is lengthened to 50 years when carbon sequestration has value, except at a 10% discount (Table 22). At the forest-level, 4 out of 10 cases (from Table 8) have a rotation age of 12 years at 1% and 2% discount rates (Table 23). At a 6% discount rate, only case five has a longer rotation age. For other cases and at other discount rates, the rotation ages remain the same. Both the initial ages equal to and greater than zero can have longer rotation ages. So, when the amount of carbon sequestered is significantly large as trees grow, carbon rotation age may lengthen up to the end of planning horizon (i.e., 50 years). This result is in line with the literature on slow-growing trees.

For equation (11), adding carbon value does not change the Faustmann optimal rotation age. The reason is that the patterns of sequestering carbon in this equation and timber growth are nearly similar. For equation (12), carbon sequestration makes the rotation age slightly shorter. In this equation, the amount of carbon uptake increases perpetually with age (similar to equation 10); however, it sequesters significantly more at its early life (in contrast to equation 10). That explains why the optimal rotation age is shorter.

Table 22. Sensitivity to carbon sequestration function at stand-level for *E. urophylla*

Discount rate (%)	Timber only		With carbon	
	T	NPV	T	NPV
1	10	52	50	860
2	10	38	50	528
3	10	28	50	325
4	10	21	50	200
5	10	16	50	122
6	10	12	50	74
7	9	9	50	44
8	9	7	50	26
9	9	5	50	14
10	9	4	9	6

Table 23. Sensitivity to carbon sequestration function at forest-level for *E. urophylla*

Discount rate (%)	Case No.	Timber only		With carbon	
		T	NPV	T	NPV
1	2	9	52.83	12	66.05
	6	9	52.61	12	65.87
	7	10	53.86	12	68.32
	10	9	52.22	12	65.57
2	2	9	39.40	12	48.85
	6	9	39.21	12	48.70
	7	10	40.65	12	51.01
	10	9	38.89	12	48.44
6	5	9	14.68	10	19.02

3.4.6 The level of economies to planting scale λ

At the forest-level, we did a sensitivity analysis to the level of economies to planting scale by varying λ of the timber planting cost function (see equation 13). When only timber is marketable, we found that lower values of λ shorten the rotation age and increase the NPV in all 10 cases (from Table 8), with an exception of case 3, where they make the rotation longer and the NPV smaller (Table 24). It means that the more the planting cost decreases to scale, the shorter the rotation age and the higher the NPV. As λ decreases from 0.98 to 0.05, the gaps among the rotation age and the NPV in comparison to the base case (i.e., λ =0.98) reaches two years and VND 18 milion per hectare, respectively, across cases, discount rates, and λ. When carbon value is included, similar to the stand-level, it induces forest owners to cut their trees sooner by up to two years with different values of λ and *r*, and for all 10 cases (Table 25).

Table 24. Sensitivity of the optimal rotation to λ at forest-level when only timber has value for *E. urophylla*

Discount rate (%)	Case No.	T				NPV			
		λ = 0.05	0.3	0.6	0.98	λ = 0.05	0.3	0.6	0.98
1	**1**	10	10	10	10	75.2	73.2	68.9	57.4
	2	9	9	9	9	70.6	68.6	64.3	52.8
	3	10	10	10	10	54.9	55.7	56.4	56.8
	4	9	9	9	9	59.6	57.9	55.6	52.1
	5	10	10	10	12	68.9	66.6	62.4	53.1
	6	9	9	9	9	68.7	66.4	62.1	52.6
	7	10	10	10	10	63.8	61.8	58.9	53.9
	8	9	9	9	9	66.8	64.4	60.4	52.5
	9	10	10	10	10	58.9	58.4	57.6	56.5
	10	9	9	9	9	62.3	60.2	57.1	52.2
5	**1**	8	8	8	10	33.3	32.0	29.0	21.4
	2	8	9	9	9	28.0	26.8	24.4	17.8
	3	10	10	10	10	21.5	21.6	21.5	21.3
	4	9	9	9	9	21.7	20.7	19.4	17.4
	5	8	8	8	10	28.5	27.1	24.3	18.5
	6	9	9	9	9	26.9	25.6	23.1	17.7
	7	8	8	10	10	25.8	24.4	22.4	19.1
	8	9	9	9	9	25.8	24.4	22.1	17.6
	9	10	10	10	10	23.4	22.9	22.2	21.0
	10	9	9	9	9	23.2	22.0	20.3	17.5
8	**1**	7	8	8	8	21.7	20.6	18.3	12.2
	2	7	8	8	9	17.0	16.0	13.9	8.6
	3	9	9	8	8	12.6	12.6	12.4	12.1
	4	8	8	9	9	11.7	10.9	9.9	8.3
	5	8	8	8	8	17.5	16.3	14.2	9.5
	6	8	8	8	9	16.0	14.9	12.9	8.5
	7	8	8	8	8	15.8	14.8	13.1	10.1
	8	8	8	8	9	15.1	14.0	12.1	8.5
	9	8	8	8	8	14.2	13.7	13.0	11.8
	10	8	8	9	9	13.0	12.0	10.5	8.4

Table 25. Sensitivity of the optimal rotation to λ at forest-level when carbon has value for *E. urophylla*

Discount rate (%)	Case No.	T				NPV			
		$\lambda = 0.05$	0.3	0.6	0.98	$\lambda = 0.05$	0.3	0.6	0.98
1	**1**	8	8	10	10	88.0	85.6	81.1	69.6
	2	9	9	9	9	82.1	80.2	75.8	64.4
	3	10	10	10	10	67.2	68.0	68.7	69.1
	4	9	9	9	9	71.2	69.5	67.2	63.7
	5	9	10	10	10	80.7	78.3	74.1	64.7
	6	9	9	9	9	80.3	78.0	73.7	64.2
	7	10	10	10	10	75.7	73.7	70.7	65.7
	8	9	9	9	9	78.4	76.0	71.9	64.0
	9	10	10	10	10	71.1	70.6	69.9	68.7
	10	9	9	9	9	73.8	71.7	68.7	63.8
5	**1**	8	8	8	8	39.1	37.7	34.7	26.8
	2	8	8	9	9	33.0	31.7	29.0	22.5
	3	10	10	10	8	26.8	26.9	26.8	26.6
	4	9	9	9	9	26.4	25.4	24.1	22.1
	5	8	8	8	9	33.7	32.2	29.4	23.3
	6	8	8	9	9	31.8	30.3	27.8	22.4
	7	8	8	8	8	31.1	29.7	27.6	24.0
	8	8	9	9	9	30.6	29.1	26.8	22.3
	9	8	8	8	8	28.7	28.2	27.5	26.3
	10	9	9	9	9	27.9	26.7	24.9	22.1
8	**1**	7	7	8	8	25.7	24.6	22.1	15.9
	2	7	7	8	8	20.2	19.1	16.9	11.5
	3	8	8	8	8	16.4	16.4	16.3	15.9
	4	8	8	8	8	14.7	13.9	12.8	11.1
	5	7	7	8	8	20.8	19.6	17.4	12.7
	6	7	7	8	8	19.2	18.0	15.9	11.4
	7	8	8	8	8	19.2	18.1	16.4	13.4
	8	7	8	8	8	18.2	17.0	15.1	11.3
	9	8	8	8	8	18.0	17.5	16.8	15.6
	10	8	8	8	8	16.0	15.0	13.5	11.2

4.0 CONCLUSIONS AND POLICY IMPLICATIONS

This research studied optimal forest management strategies when carbon sequestration is included, for *E. urophylla* and *A. mangium* in Yen Bai province, Vietnam. We applied the Faustmann formula to find the optimal rotation age and the NPV for planted forest at stand-level. We also extended the Faustmann model to include multi-stands and spatial arrangement among forest stand in order to analyse the optimal strategy at the forest level.

Survey results suggested that the actual tree cutting age is five years. However, we found that, at the stand-level, the optimal rotation age of *E. urophylla* when only timber has market value is 10 and 9 years for households and forest enterprises, respectively, at a 5% discount rate. For *A. mangium,* the optimal rotation age is 13 years for both households and forest enterprises. The NPV is VND 16 million per hectare for households of both *E. urophylla* and *A. mangium.* For forest enterprises, the NPV is VND 57 million and VND 62 million per hectare for *E. urophylla* and *A. mangium*, respectively.

Adding carbon values make the optimal rotation age slightly shorter and the NPV higher. Similarly, taking into account the spatial arrangement of forest stands shortens the rotation age and improves the NPV. Nevertheless, the rotation age including carbon or forest level (i.e., eight to nine years) is still well above the actual one. The optimal rotation age decreases with an increasing carbon price, planting subsidy level, constant timber price, and discount rate. The optimal rotation age increases with a rise in the level of increasing timber price, the level of economies to planting scale, and stochastic carbon price. The optimal rotation age is sensitive to the particular carbon payment scheme.

The government can use a lump-sum payment of carbon benefits at the beginning of the rotation to encourage forest owners to lengthen the rotation age. Survey results suggested that households equally prefer two payment schemes, either payment at the beginning, or annually. Moreover, households agree to lengthen rotation age with a subsidy of VND 7 million per hectare per year or VND 21 million per hectare per rotation and with a commitment to keep their forest until it is 11 years old. These figures show that the optimal management strategy can be achieved, for example at a carbon price of USD 3 (VND 0.051 million) per metric tonne with a 5% discount rate. Almost all households agree to engage in a carbon pooling project and one-fourth of them believe there would be no obstacles in implementing the project.

Given that the majority of households cut their trees sooner based on their family's financial status, a planting cost subsidy would help to narrow the actual and the optimal rotation age. Intuitively, instead of investing money to plant trees, households can use it for their living cost and hence, can delay their harvest. At a 5% discount rate, full subsidy can reduce rotation age from 10 down to 6 years.

If the assumption of constant timber price is relaxed, the study finds that it is optimal to grow large-sized timber. This fits in with the fact that in Vietnam, the wood-processing industry is growing fast and most of large-sized timber is currently imported. Economies of scale in planting show that it is more profitable to produce at a large scale to reduce production costs. Finally, the survey data showed that households are financially unable and unwilling to delay their harvest till 13-15 years for trees to become large-sized timber. Therefore, cooperation or joint ventures among households, forest enterprises, and wood-processing companies may bring a win-win solution. In such an arrangement, households can receive technical and capital support, achieve benefits from a large production scale, and wood processing companies can take advantage of cheap timber supply from domestic sources.

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APPENDIX. Random values of the carbon price used in the first run (out of ten runs) for two species with three magnitudes of the carbon price

Planning horizon (year)	*E. urophylla*			*A. mangium*		
	Price A*	Price B*	Price C*	Price A*	Price B*	Price C*
1	0.81	0.13	0.08	0.46	0.11	0.15
2	0.44	0.41	0.00	1.05	0.43	0.04
3	0.06	0.25	0.29	0.20	0.05	0.09
4	0.61	0.46	0.01	0.92	0.40	0.22
5	0.27	0.36	0.18	0.88	0.16	0.19
6	0.65	0.22	0.01	0.44	0.14	0.27
7	0.65	0.10	0.22	0.43	0.09	0.01
8	0.65	0.06	0.13	1.19	0.34	0.06
9	0.67	0.25	0.06	0.14	0.17	0.13
10	0.31	0.24	0.22	0.02	0.49	0.24
11	0.97	0.10	0.05	0.81	0.43	0.03
12	0.84	0.49	0.17	0.92	0.44	0.05
13	0.81	0.29	0.11	0.24	0.29	0.18
14	0.58	0.02	0.03	0.48	0.26	0.24
15	0.75	0.23	0.07	0.61	0.11	0.09
16	1.10	0.16	0.13	0.11	0.37	0.29
17	0.60	0.34	0.17	0.12	0.33	0.12
18	0.97	0.41	0.28	0.50	0.20	0.04
19	1.02	0.02	0.29	1.12	0.43	0.22
20	0.11	0.20	0.01	0.83	0.06	0.18
21	0.81	0.34	0.27	0.29	0.04	0.01
22	0.18	0.35	0.23	1.17	0.36	0.09
23	1.07	0.24	0.23	0.68	0.13	0.28
24	0.42	0.02	0.24	0.57	0.30	0.20
25	0.78	0.05	0.24	0.74	0.45	0.25
26	0.24	0.40	0.24	0.28	0.28	0.20
27	0.20	0.23	0.11	0.31	0.15	0.29
28	0.96	0.29	0.00	0.35	0.24	0.13
29	0.73	0.30	0.11	1.14	0.37	0.02
30	0.49	0.02	0.01	0.48	0.16	0.22
31	1.14	0.02	0.13	0.31	0.06	0.26
32	0.62	0.12	0.18	0.32	0.15	0.20
33	0.23	0.50	0.01	0.83	0.39	0.13
34	0.43	0.36	0.18	1.17	0.11	0.03
35	1.12	0.08	0.13	0.65	0.37	0.06
36	0.92	0.34	0.05	0.94	0.29	0.11
37	0.28	0.20	0.08	0.76	0.17	0.22
38	0.68	0.15	0.20	0.05	0.27	0.05
39	1.19	0.31	0.05	0.11	0.28	0.04
40	0.43	0.32	0.29	0.83	0.04	0.02
41	0.09	0.11	0.24	0.21	0.22	0.20
42	0.73	0.26	0.20	0.20	0.31	0.28
43	1.14	0.34	0.14	0.36	0.13	0.22
44	0.82	0.10	0.13	0.10	0.49	0.06
45	0.04	0.29	0.30	0.31	0.48	0.10
46	1.13	0.46	0.13	0.44	0.35	0.10
47	0.44	0.31	0.03	0.70	0.30	0.01
48	0.35	0.36	0.17	0.56	0.44	0.01
49	0.34	0.01	0.25	0.69	0.07	0.28
50	0.39	0.12	0.07	0.88	0.23	0.06

Note: Carbon price A ranges from VND 0 to VND 1.2 million per metric tonne (equal to USD 0 to USD 70 per tonne), carbon price B from VND 0 to VND 0.5 million per tonne (equal to USD 0 to USD 29.5 per tonne), and carbon price C from VND 0 to VND 0.3 million per tonne (equal to USD 0 to USD 17.7 per tonne). This is one out of ten planning horizons with 50 years each that we simulated.

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