Forest Policy and Economics 38 (2014) 56–64

Contents lists available at ScienceDirect

Forest Policy and Economics

journal homepage: www.elsevier.com/locate/forpol

Optimal rotation age for carbon sequestration and biodiversity conservation in Vietnam

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ARTICLE INFO

Article history:
Received 18 June 2012
Received in revised form 30 March 2013
Accepted 8 April 2013
Available online 3 May 2013

Keywords:
Biodiversity conservation
Birds
Carbon sequestration
Multiple-stand forests
Optimal rotation age
Net present value

ABSTRACT

Biodiversity loss is a major problem in terms of loss of genetic and ecosystem services and more specifically via impacts on the livelihoods, food security and health of the poor. This study modeled forest management strategies that balance economic gains and biodiversity conservation benefits in planted tropical forests. A forest-level model was developed that maximized the net present value (NPV) from selling timber and carbon sequestration while maintaining a given level of biodiversity (as per the population density of birds). The model was applied to *Eucalyptus urophylla* planted forests in Yen Bai Province, Vietnam. It was found that the inclusion of biodiversity conservation in the model induces a longer optimal rotation age compared to the period that maximizes the joint value from timber and carbon sequestration (from 8 to 10.9 years). The average NPV when considering timber values plus carbon sequestration was 13 million Vietnamese Dong (VND) ha^{-1} (765 USD ha^{-1}), and timber, carbon sequestration and biodiversity values were 11 million VND (676 USD) ha^{-1}. Given this differential, governments in such tropical countries may need to consider additional incentives to forest owners if they are to encourage maximizing biodiversity and its associated benefits. The results also have some implications for implementing the climate control measure of "Reducing Emissions from Deforestation and Forest Degradation-plus (REDD+)" in developing countries, i.e., payment for carbon sequestration and biodiversity benefits in planted forests.

1. Introduction

According to the Copenhagen Accord, climate change is one of the greatest challenges of our time and a deep cut in global greenhouse gas emissions is required to deal with this problem (UNFCCC, 2009b). The Copenhagen Accord also recognizes the crucial role of reducing emissions from deforestation and the need to enhance the carbon uptake of forests. Furthermore, it commits to provide funding for implementing such actions in developing countries. Meanwhile, climate change may contribute to biodiversity loss, which poses a particularly real threat to the livelihoods, food security and health of the poor.

Forests (natural but also human-made or modified) are home to more than half of the known terrestrial plant and animal species (Hassan et al., 2005). Beside supplying wood production, plantation forests provide additional ecosystem services such as recreation and ecotourism (Evans, 2009), erosion control from land-slides (Dymond et al., 2006) and wind (Evans, 2009), flood protection and benefits to water quality, and climate regulation through carbon sequestration (Carnus et al., 2003; Rudel et al., 2005). Moreover, there is abundant evidence that plantation forests can provide habitat for a wide range of native forest plants, animals and fungi (some of which are used by people for food or traditional medicines). Since the annual global rate of natural forest loss is 0.3% (FAO, 2007), and is difficult to reverse (Brockerhoff et al., 2008), planted forests may be a "lesser evil" (compared to having agricultural land) as a means to protect indigenous vegetation remnants (Brockerhoff et al., 2008).

Lindenmayer and Franklin (2002) stated that "the use of long rotations can have direct and significant consequences for biodiversity conservation at both landscape and stand levels". Longer rotations reduce the rate of timber harvest over a given planning horizon, and hence help to decrease some of the negative impacts of short rotations while still continuing to allow forest products to be obtained (Curtis, 1997; Moning and Muller, 2008). In addition, longer rotations result in fewer clear-cut areas per decade (Carey et al., 1999), and thus contribute to the succession of species which is sensitive to the proportion of recently disturbed landscapes (Økland, 1996). Furthermore, increasing the rotation age allows more time for organisms to become re-established after clear-cutting and provides a habitat for species that depend on old-growth forests, such as large-diameter trees, large-snags and logs (Brockerhoff et al., 2005; Curtis, 1997).

In contrast to achieving biodiversity conservation, long rotations are not always positively related to carbon sequestration. Trees sequester carbon as they grow, so the rate of tree growth is critical for carbon sequestration (van Kooten et al., 1995). For fast-growing trees,

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http://dx.doi.org/10.1016/j.forpol.2013.04.001

which grow faster in the first several years of their life, carbon is sequestered more in these early years. For slow-growing trees, carbon sequestration may reach a peak after many years, depending on growth rate patterns.

Forests and changes in forest management practices can help to conserve biodiversity while contributing to carbon sequestration. "Reduce Emissions from Deforestation and Forest Degradation" (REDD) is a mechanism to encourage carbon sequestration after the period of 2008–2012 via payment for forest owners in developing countries to keep their forests growing (UNFCCC, 2011). Going beyond deforestation and forest degradation, "REDD+" considers the role of conservation, sustainable management of forests and enhancement of forest carbon stocks. The REDD+ mechanism has been suggested both to be an effective tool for climate change mitigation (via carbon sequestration) and to offer the important co-benefit of biodiversity conservation (Busch et al., 2011). The biodiversity co-benefit (i.e., reducing deforestation and forest degradation is better for both climate change control and biodiversity conservation) exists for natural forests, but might not be true for planted forests in some cases. Biodiversity conservation in planted forests might be achieved with some trade-offs in productivity gains (and hence carbon sequestration) (Bullock et al., 2011; Cannell, 1999; Lindenmayer and Hobbs, 2004), and therefore there may need to be a policy option for foresters to be compensated for that to ensure the optimal society-level outcomes.

Traditionally, planted forests are usually managed by determining rotation lengths to optimize timber values only. Optimal forest rotation has been scientifically investigated for over 150 years and the optimal management strategy for a single stand forest was developed by Faustmann (1849). The optimal rotation length is positively related to changes in planting costs and inversely related to the changes in timber prices and discount rates. Going beyond timber values, other benefits from forests have been taken into account in optimizing forest rotation length. 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 the stand age. Subsequently, Englin and Callaway (1993) considered the value of carbon and reported that the optimal rotation age differed from the standard Faustmann model. The effect of carbon taxes and subsidies on the optimal forest rotation age was then studied by van Kooten et al. (1995) who concluded that the "carbon optimal rotation age" was slightly longer than the Faustmann rotation age.

While the above analyses (Englin and Callaway, 1993; Faustmann, 1849; Hartman, 1976; van Kooten et al., 1995) dealt with a single forest stand, forests usually consist 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) and this definition can vary by country. The optimal management strategy for a multiple stand forest (i.e., management at the forest-level) was introduced by Mitra and Wan (1985, 1986). They applied a dynamic programming approach and found that: (i) if the utility function is linear, the Faustmann periodic solution is optimal, and (ii) if the utility function is increasing and strictly concave, an optimal solution converges to the maximum sustained yield solution (that is maximizing the mean annual increment (Hyytiainen and Tahvonen, 2003)). Tahvonen (2004) included old-growth values into his forest level model and found that the optimal rotation age was longer than the Faustmann rotation. However, there is no study at a forest level that collectively includes timber values, carbon sequestration benefits, and biodiversity conservation to determine the optimal rotation length. Therefore the study presented here aimed to determine the optimal management strategy at a forest level for multi-stand planted forests while considering all these three issues (timber values, carbon sequestration and biodiversity conservation). Furthermore, it conducted this in a tropical developing country context which is relevant since tropical planted forests contribute to 28% of the total world forest area (FAO & JRC, 2012), and carbon sequestration via forests and biodiversity conservation need to be enhanced in this area (Convention on Biological Diversity, 2002; UNFCCC, 2009b).

The setting for this study was Vietnam which belongs to the Indo-Burma hotspot, one of 25 global biodiversity hotspots (Myers et al., 2000). The total forest area in Vietnam is 31% (13 million ha) of the total land area in 2010 (FAO, 2010). Vietnam has implemented a Clean Development Mechanism (CDM) project so there is scope for revenue generation for foresters from carbon sequestration via this Mechanism (DOF/MARD, 2008; UNFCCC, 2009a). Furthermore, Vietnam is a pilot country to develop the REDD+ mechanism (Government of Vietnam, 2008, 2010; UN-REDD Programme, 2013).

In Vietnam, all forest land is under state ownership and forest land allocated to individual households does not exceed 30 ha in size and is limited to a 50 year-land-use right (Government of Vietnam, 1999). These features of household ownerships make this type of forest ownership different from other types of ownerships in other nations which have been studied previously (Englin and Callaway, 1993; Tahvonen, 1999; van Kooten et al., 1995) (e.g., individual private owners, which are more focused on a commercial purpose; non-industrial forest owners, which are more focused on obtaining forest services such as biodiversity conservation and recreation; and private-owned enterprises). The 50 year-land-use right is also different to the infinitive investment period for forestry in the optimal rotation literature. This relatively short investment period could limit Vietnamese foresters in applying long rotations, and hence has impacts on carbon sequestration services and biodiversity conservation.

In Vietnam, most of the fast-growing tree species such as *Eucalyptus urophylla* in plantation forests are cut at the average age of five years (Nguyen et al., 2006). Moreover, the majority of forest farmers apply a clear-cut practice (Bui and Hong, 2006) that destroys habitat and causes serious loss of biodiversity (Pawson et al., 2006). Short rotation periods and clear-cutting are common forestry practices in plantation forests nation-wide in Vietnam. Another aspect of Vietnam is the tropical nature of the forests. Most of the studies on optimal forest rotation lengths focus on slow-growing trees in developed countries and temperate forests, which account for 10% of the total world forest area (FAO & JRC, 2012). However, optimal rotation lengths for the same tree species may still be different by both country and climate zone because of the differences in input parameters such as timber growth rates, planting costs, annual management costs and harvesting costs (Diaz-Balteiro and Rodriguez, 2006).

2. Method

2.1. The selection of taxa for a biodiversity indicator

The biodiversity of even a small area is far too complicated to be comprehensively measured (Duelli and Obrist, 2003). Measuring biodiversity requires not only identification of the explanatorily salient dimensions of diversity (i.e., to define variety or differentiation among systems in order to determine which system is more diverse) but also a measurement of biological systems (i.e., the biodiversity level) and given the constraints on time, resources, and information available (Maclaurin and Sterelny, 2008), this task is neither practical or feasible. Thus, suitable indicators have to be found to measure biodiversity instead (Duelli and Obrist, 2003).

Among biodiversity indicators, species diversity (species richness and species abundance) is the most commonly accepted indicator in terms of measurement and valuation (Pearce et al., 2002) and is widely applied to measure biodiversity by economists (Eppink and van den Bergh, 2007; Juutinen and Mönkkönen, 2004; Smith et al., 2008). This indicator is relatively simple (Begon et al., 1996; Magurran, 1988), has a good discriminant ability (Magurran, 1988), and is the most available in terms of data (Begon et al., 1996; Mayer, 2006). As comprehensive biological inventories of sites are unlikely to be present (Harper and Hawksworth, 1996), it is necessary to look for some taxa that are particularly good indicators of overall biodiversity.

The ideal characteristics of biodiversity indicators are that they are immediately affected by a change in harvest practices, easily monitored, taxonomically tractable, and representative of overall diversity. In this regard, animals are preferred to plants as biodiversity indicators, since the latter are not immediately affected by changes in harvest practices as a result of seed bank effects (i.e., seeds remaining in the soil can subsequently propagate). Among animals, a taxon that is often employed is birds (Aves) since this group is well-documented and easy to monitor in the field (Lawton et al., 1998). Species diversity in this taxon has a strong linear correlation with the overall biodiversity of a community (Pearman and Weber, 2007).

This study therefore used bird population density as a proxy for biodiversity. The population size of birds must be at least equal to a minimum viable population. Shaffer (1981, p. 132) defined that "a minimum viable population (MVP) for any given species in any given habitat is the smallest isolated population having a 99% chance of remaining extant for 1000 years despite the foreseeable effects of demographic, environmental, and genetic stochasticity, and natural catastrophes". Shaffer suggested that the critical level for survival probabilities might be set at any level, and the planning horizon can be lengthened to 10,000 or shortened to 100 years. Franklin (1980) and Bulte and van Kooten (2001) recommended that the MVP in the short or medium term is about 50–100 individuals. Since the setting of this research was in Vietnam with a time horizon of 50 years, the MVP of 50 individuals (that is a desired population density if biodiversity conservation to be considered) was employed. This population size was also close to the bird density ha^{-1} in natural forests in Vietnam identified by Hill et al. (2001) and in plantation forests in New Zealand by Seaton et al. (2010).

2.2. The optimization model structure

The optimal forest management model is maximizing the net present value (NPV) from selling timber and providing carbon sequestration services while maintaining a given population density of birds. The model included multiple forest stands, and arrangements of forest stands. Bird density (as per total bird abundance of all species since planted forests at different ages accommodate different species of birds) was used as a biodiversity indicator and their population was linked to different timber cutting regimes, forest ages, and forest sizes. Carbon sequestration was included in the baseline scenario since the Government of Vietnam has agreed to pay for forest environmental services (Government of Vietnam, 2007, 2008, 2010), and also the Kyoto Protocol (UNFCCC, 1997, 2012) and the REDD+ (UNFCCC, 2011) mechanism have set up a framework for carbon payment via CDM projects or international carbon trading schemes.

The model assumed a planted forest consists of n stands ($n > 1$). To include arrangements among forest stands, it was assumed that forest stands were arranged into strips, i.e., stands are connected if they are next to each other. For example, stand 1 is adjacent to stand 2, and stand 3 is adjacent to stand 2 and stand 4 and so on. Interactions among forest stands were captured by economies of planting scale. If adjacent stands are harvested at the same time, they form a larger planting area in the following year. A larger planting area requires a lower unit of planting cost which is captured in the model (Eq. (11)). The objective of the model was to maximize the NPV from harvesting timber and sequestering carbon. The model was subject to a constraint which is the density of birds (i.e., MVP ha^{-1}). The planning horizon, as well as the maximum length of the rotation interval for the simulations, were 50 years, since in Vietnam, both household forest owners can use their forest lands for 50 years at most. At the end of the lease, forest owners were supposed to harvest the whole forests.

Let

$v(.)$ be the discounted sum of timber value (V_t) and carbon sequestration value (A_t);
a_s the area of stand s (ha);
x_{st} the age of stand s in period t.

The model objective was to maximize the discounted revenue from timber and carbon sequestration:

$$v(a_1, \ldots, a_n; x_{10}, \ldots, x_{n0}) = max\sum_{t=1}^{50}(1+r)^{-t}(V_t + A_t). \quad (1)$$

Subject to:

$$d_{st} = 0 \text{ or } 1, \ s = 1, ..n, \quad \text{binary decision variables} \quad (2)$$

$$x_{s,t+1} = (x_{st} + 1).(1-d_{st}), \ s = 1, ..n, \quad \text{age of stand } s \text{ at period } t+1 \quad (3)$$

$$x_{st} \geq 0, \ s = 1, ..n, \quad \text{non-negative age constraint} \quad (4)$$

$$\bar{S}_{BT} \geq \text{MVP} \quad \text{minimum viable population for birds ha}^{-1} \text{ year}^{-1}. \quad (5)$$

Where:

$$r \quad \text{discount rate} \quad (6)$$

$$V_t = \sum_{s=1}^{n}(q(x_{st}).a_s.d_{st}.P(x_{st}))-G(h_t) \quad \text{timber value at the period } t \quad (7)$$

$$q(x_{st}) \quad \text{timber volume ha}^{-1} \text{ of stand } s \text{ in period } t \quad (8)$$

$$d_{st} \quad \text{the binary decision variable,} \quad (9)$$

$d_{st} = 1$ stand s is clear-cut in period t
$d_{st} = 0$ stand s is kept in period t.

$$P \quad \text{price of timber volume unit}^{-1} \quad (10)$$

$$G(h_t) \quad \text{planting cost of timber at period } t, \text{ which varies with planting size,} \quad G(h_t) = \beta h_t^{\lambda} \quad (11)$$

$$h_t = \sum_{s=1}^{n} d_{st}.a_s \quad \text{planting size (ha) in period } t \quad (12)$$

$$A_t = \left(\sum_{s=1}^{n} Q_c(x_{st}).a_s.d_{st}\right).P_c \quad \text{value of carbon sequestered at period } t \quad (13)$$

$$Q_c \quad \text{amount of carbon sequestered, tonne ha}^{-1} \quad (14)$$

$$P_c \quad \text{carbon price tonne}^{-1} \quad (15)$$

$$\bar{S}_{Bt} = \frac{\sum_{t=1}^{50} S_{Bt}}{50} \quad \text{the average number of birds ha}^{-1} \text{ over a 50-year period} \quad (16)$$

$$S_{Bt} = \frac{\sum_{s=1}^{n} f(x_{st}, a_{st})}{\sum_{s=1}^{n} a_{st}} \quad \text{the number of birds ha}^{-1} \text{ at period } t \quad (17)$$

Eq. (17) implies that the bird density depends on stand age itself and on the age structure of the whole forest.

With regard to the biodiversity constraint, Eq. (5), using the average of bird density per ha over a 50-year period $\overline{S}_{Bt} \geq MVP$ is problematic. Since requiring the average bird density (over 50 years) to be greater than the MVP ha^{-1} means that in some years, the bird density may be below the MVP ha^{-1}. In those cases, when the population goes below the MVP, it may never recover. Thus, preferably bird density per ha per year (S_{Bt}) should be used. However, using that as a constraint leads to unfeasible solutions (i.e., no optimal solution is found mathematically, see (Nghiem, 2011) for further details). Moreover, since the context in this study was small forests (3.95 ha on average (Nghiem, 2011)), and most tropical birds are good fliers, it was assumed that birds can migrate and return in the subsequent rotations.

In this study, the CDM Project provided carbon sequestration funds on the assumption that the timber production resulted in a long-term carbon store (i.e., timber used for building materials and furniture). Also the model did not consider the release of carbon into the atmosphere at the time of harvest (i.e., via milling equipment and transport to sawmills). The reason was that household forest owners in Vietnam are relatively poor, and the Government does not impose carbon emission taxes on them. Thus, as the forest owners are not penalized for the release of such harvest-associated carbon emissions, it would be inappropriate to include such costs in the model. The payment for carbon sequestration services to the foresters was assumed to be made annually and thus contract or time commitment was not required.

2.3. The optimization method

The model described in the above section was solved by a direct search algorithm (Fig. 1). To find the optimal strategy, all scenarios with different rotation ages were compared in terms of the objective variables and constraint, and the scenario that had the highest NPV was chosen as the optimal strategy. The model was coded in GAMS—General Algebraic Modeling System (codes are available from the author upon request).

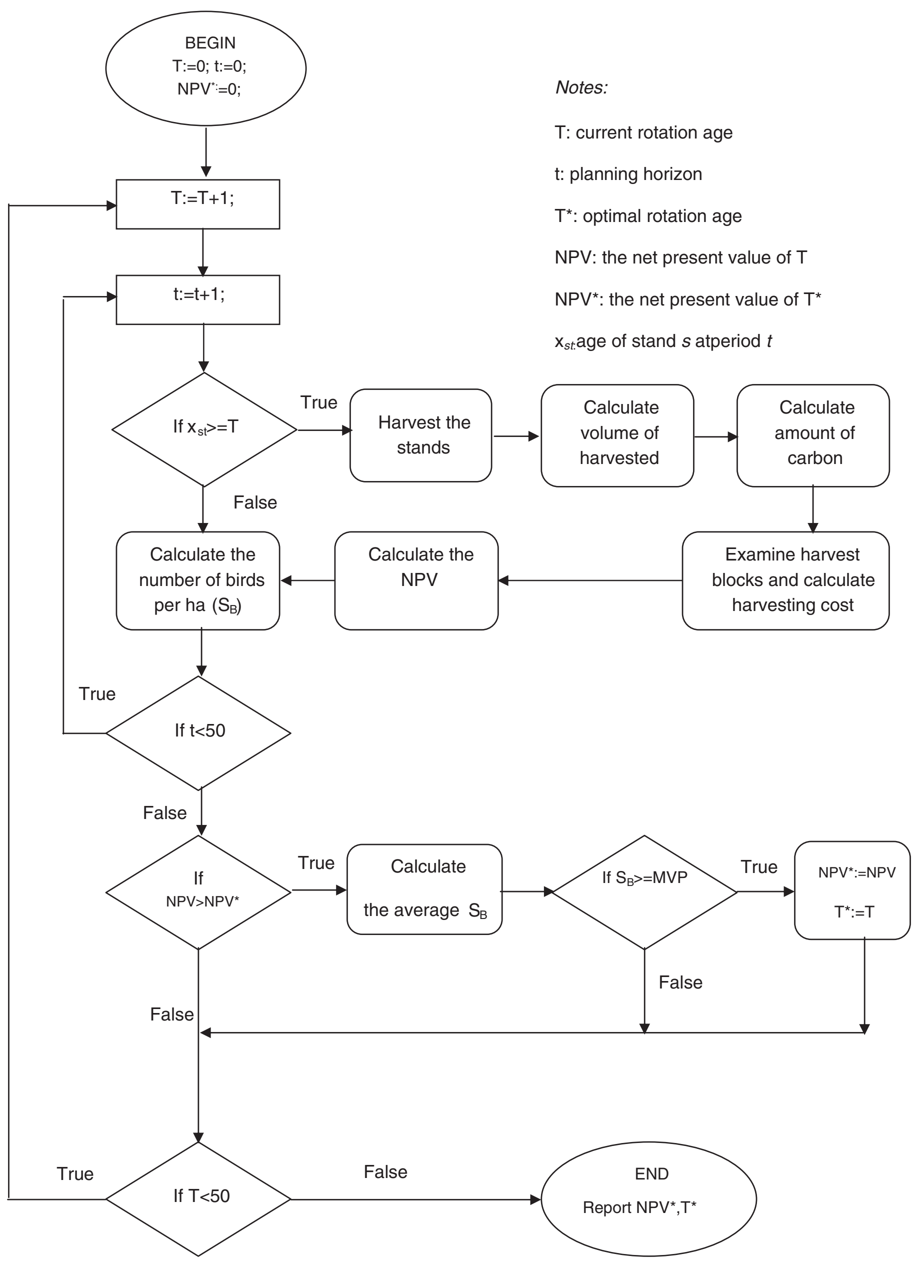

Fig. 1. Graphical representation of the direct search algorithm for the optimal net present value and optimal rotation age in planted forests in Yen Bai Province, Vietnam.

2.4. Model data

The optimization model described above was applied to determine optimal forest harvest strategies for case studies in Yen Bai Province, Vietnam. This area was selected since it is a major timber producing province in Vietnam and has *E. urophylla* as a favored species grown by household foresters. The case studies comprised 10 household-managed forests that were randomly selected from a pool of 271 household-managed forests in Yen Bai Province in 2008 with different stand number, size and age (Nghiem, 2011).

Parameters and functions including timber growth, carbon sequestration, carbon price, timber price, planting costs, and discount rate (data source: (Nghiem, 2011) unless otherwise indicated) used in the model are presented in Table 1. The timber growth function of *E. urophylla*, which shows standing timber volume by timber age, was estimated from reliable and experimental data obtained from a Government source (Vietnam Ministry of Agriculture and Rural Development, 2003). The carbon sequestration function used in the model was estimated based on reliable experimental data for *E. urophylla* in planted forests by Vo et al. (2009). Carbon sequestered included carbon in standing timber, shrubs and ground cover vegetation, litterfall, and soil. The bird density was estimated using data about forest bird abundance in Vietnam by Hill et al. (2001). The carbon price used in this study was based on that of a CDM Project implemented in Hoa Binh, Vietnam (DOF/MARD, 2008). In Yen Bai Province, the majority of the foresters sold stumpage trees, thus standing timber volume (including tree tops and branches) and stumpage timber prices were used in the analysis. To analyze the optimal rotation age, the 8% interest rate on the Government Bonds with five year maturity (the same time horizon with the actual tree cutting age), was chosen as the discount rate for household farmers (Sirius Financial, 2007; State Securities Commision of Vietnam, 2007; Xuan, 2007). Sensitivity analyses were performed by varying discount rate, timber price, carbon price, and MVP (Table 1).

3. Results

The biodiversity optimization model was applied to each of the 10 selected household-managed forests in Yen Bai Province, Vietnam. The optimal rotation age considering biodiversity conservation ("biodiversity rotation age"), its associated NPV, and the bird density are presented in Table 2.

The results in Table 2 suggested that the inclusion of biodiversity conservation (when the MVP was set at 50 birds ha^{-1} year^{-1}) into the optimization model led to a longer optimal rotation age compared to the rotation age that considered only timber values, or timber values and carbon sequestration values. The inclusion of carbon sequestration values actually shortened the optimal rotation age compared to that of the management strategy with the timber values only. In particular, for all 10 cases, the timber rotation age was 8.5 years, and the "carbon rotation age" was 8 years, while the "biodiversity rotation age" (MVP = 50) was between 10 and 11 years, or 10.9 years on average. Satisfying the biodiversity conservation constraint also resulted in lower monetary benefits for household farmers. The average NPV when considering timber values only was 9.8 million VND ha^{-1} (576.51 USD ha^{-1}), timber values and carbon sequestration were 13.01 million VND ha^{-1} (765. USD ha^{-1}), timber values and biodiversity conservation were 8.71 million VND ha^{-1} (512.51 USD ha^{-1}) and timber values, carbon sequestration and biodiversity benefits were 11.46 VND (676.00 USD ha^{-1}).

The incorporation of a constraint on minimum bird density (MVP ha^{-1} = 50) led to an increase in optimal rotation length of 2.9 years (or 36%) on average, an increase in bird density from a minimum of 41 to a maximum of 54 individuals ha^{-1} year^{-1} (approximately by 32%), and a decrease in the NPV from a maximum of 15.93 million VND ha^{-1} (937.06 USD ha^{-1}) to a minimum of 9.68 million VND ha^{-1} (569.41 USD ha^{-1}) (by 39%). Lengthening the rotation age by 36%, would benefit biodiversity conservation with 28% higher in bird density, and an increased supply of large-sized timber, both for a relatively small decrease in the NPV of 12%.

Table 3 shows that the optimal rotation age and the bird density increased when MVP was set at a higher level (from 50 to 100). As the MVP increased, the NPV, as expected decreased. In particular, the rotation age increased from 10.9 years on average to 15.0, and 18.7 years as the MVP increased. The average NPV decreased from 11.65 million VND ha^{-1} (685.29 USD ha^{-1}) to 6.7 million VND ha^{-1} (394.12 USD ha^{-1}) and 2.67 million VND ha^{-1} (157.06 USD ha^{-1}), meaning that forest owners have to forgo revenue from selling timber and sequestering carbon to increase biodiversity in their forests. Nevertheless, the bird density increased from 53 to 77, and 103 individuals ha^{-1} year^{-1}.

Table 4 shows the results of a sensitivity analysis of the "biodiversity rotation age" to the discount rate. The optimal rotation age and the bird density slightly decreased with a rise in the discount rate from 1 to 5%, and remained constant as the discount rate increased from 5 to 10%. This was because the "biodiversity rotation age" depended on variables such as the bird density, which were not influenced by the discount rate. The NPV was reduced significantly by 65% and 67% as the discount rate increased from 1 to 5%, and from 5 to 10%, respectively. In conclusion, the selection of a discount rate did not have a substantial on the optimal rotation age and biodiversity, but did significantly affect the profitability of planted forests to forest owners.

The results of the sensitivity analysis of the biodiversity rotation age to changing timber prices (from 0.37 million VND cubic meter^{-1} (21.76 USD cubic meter^{-1}) to 2 million VND cubic meter^{-1}

Table 1
Functions and parameters used in the forest optimization models applied for *Eucalyptus urophylla* in planted forests in Yen Bai Province, Vietnam.

Functions/parameters	Data sources	Baseline values	Values for sensitivity analyses
Discount rate	State Securities Commision of Vietnam (2007)	8%	1–10%
Timber function	Vietnam Ministry of Agriculture and Rural Development (2003)	$q(x_{st}) = -1.38x_{st}^2 + 40.33x_{st} - 94.07$ where x_{st} denotes timber age of stand s in period t, and $q(x_{st})$ represents timber volume at age x_{st}.	
Timber price (2007)	Nghiem (2011)	0.37 million Vietnamese Dong (VND) cubic meter^{-1}	0.37–2 m. VND (21.76–117.65 USD)
Carbon price (2007)	DOF/MARD (2008)	0.051 million VND cubic meter^{-1}	0.051–0.7 m. VND (3–41.18 USD)
Carbon sequestration function	Vo et al. (2009)	$Q_c(x_{st}) = -0.071x_{st}^2 + 6.0155x_{st} + 11.567$ where x_{st} denotes timber age of stand s in period t, and $Q_c(x_{st})$ represents the carbon amount (tonne ha^{-1}) sequestered up to age x_{st}.	
Bird abundance function (bird population density)	Hill et al. (2001)	$S_{Bt} = (22.21e^{0.1421x_{st}})a_{st}$ where S_{Bt} is the total bird abundance (all species), x_{st} is the age of forest stand, and a_{st} is the size of forest stand.	50–100 bird individuals (year^{-1} ha^{-1})
Planting cost function (2007)	Nghiem (2011)	$G(h) = 5.16h^{0.98}$ where h is planting size (ha).	

Table 2
Optimal rotation ages for alternative management strategies for 10 randomly selected household-managed forests in Yen Bai Province, Vietnam.

Case of household forests	Initial age of stands (years)	No of stands	Total forest size	Timber values only			Timber values and carbon uptake			Timber values and biodiversity conservation			Timber values, carbon uptake and biodiversity conservation (MVP = 50)		
				T (years)	NPV[a]	Birds[b]	T (years)	NPV[a]	Birds[b]	T (years)	NPV[a]	Birds[b]	T (years)	NPV[a]	Birds[b]
1	15	5	8.6	8	12.16	42	8	15.93	42	11	10.85	54	11	13.97	54
2	0	5	8.6	9	8.64	46	8	11.47	41	11	7.49	53	11	9.95	53
3	10	4	1.6	8	12.08	43	8	15.93	43	10	11.75	50	10	15.14	50
4	0	4	1.6	9	8.34	46	8	11.14	41	11	7.21	53	11	9.68	53
5	3	3	5.0	8	9.52	41	8	12.75	41	11	8.39	54	11	11.06	54
6	0	3	5.0	9	8.55	46	8	11.37	41	11	7.40	53	11	9.87	53
7	4	3	3.5	8	10.07	41	8	13.44	41	11	8.89	54	11	11.69	54
8	0	3	3.5	9	8.48	46	8	11.30	41	11	7.34	53	11	9.81	53
9	6	2	2.0	8	11.79	42	8	15.57	42	11	10.57	54	11	13.70	54
10	0	2	2.0	9	8.38	46	8	11.19	41	11	7.25	53	11	9.71	53
Mean values	3.8	3.4	4.14	8.5	9.80 (576.51)	43.8	8	13.01 (765.24)	41.4	10.9	8.71 (512.51)	53.2	10.9	11.46 (674)	53.1

Note: The discount rate used was 8% and the carbon price was 0.051 million VND (3 USD) tonne^{-1}.
[a] Average million VND ha^{-1} (USD ha^{-1}).
[b] Average number of individuals year^{-1} ha^{-1}.

(117.65 USD cubic meter^{-1})) are presented in Table 5. The change in the rotation age to a rise in the timber price was similar to the one with an increase in the carbon price. At an 8% discount rate, the rotation age (from 10 to 11 years, Table 2) and the bird density (from 50 to 54 individuals ha^{-1}, Table 2) remained constant with a rise in the timber price. The rotation age and the bird density were again determined by the MVP constraint. The relative increase in the NPV was substantially larger (52%) than the rise in the timber price.

The results of a sensitivity analysis of the "biodiversity rotation age" to the carbon price showed that the "biodiversity rotation age" and the bird density remained constant as the carbon price went up, but the NPV increased. The results suggested that the increase in the carbon price had no effect on the biodiversity rotation age (since MVP was binding), but led to a higher economic return to forest owners. On the contrary, a higher carbon price made the "carbon rotation age" shorter (Table 6). As the carbon price increased from 0.051 to 0.7 million VND tonne^{-1} (3 to 41.18 USD tonne^{-1}), the optimal rotation age decreased from eight to five years. As a result, the bird density went down from 41 to 33 individuals ha^{-1}. However, the NPV increased from 13.01 to 59.12 million VND ha^{-1} (765.25 to 3477.74 USD ha^{-1}).

4. Discussion and conclusions

This research has suggested that the inclusion of the biodiversity component (MVP ha^{-1} of birds) into the optimization model induced a longer rotation age compared to the carbon rotation age for *E. urophylla*. The optimal biodiversity rotation age (when the MVP ha^{-1} was 50) was between 10 and 11 years. The average NPV was 11.46 million VND ha^{-1} (674.12 USD ha^{-1}). This result for the incorporation of biodiversity preservation resulting in lengthening of the optimal rotation age, was similar to the findings by Koskela et al. (2007).

The finding that the optimal carbon rotation was shorter than the timber-only rotation was in contrast to the results of van Kooten et al. (1995) and Gutrich and Howarth (2007). The main reason was probably because the forest owners in this study did not have to pay a carbon tax when the timber was harvested (or similarly no carbon release at harvesting was assumed) as in the research by van Kooten et al. The results of van Kooten et al. suggested that if all sequestered carbon in timber is released at harvest, it is optimal never to harvest trees; yet if only a portion of sequestered carbon was released, it is optimal to harvest trees. That said, as the portion of carbon released from harvesting becomes smaller, the optimal rotation length will become shorter, *ceteris paribus*; and if stored carbon is never assumed to be released as in this Vietnam-based model, it is possible that optimal overall rotation age is shorter than optimal rotation age when just considering timber value. A minor additional reason for the apparent differences in optimal rotation length between this and other studies could be the inclusion of soil carbon, which accounted for a large proportion (44 to 87%) in the total carbon uptake in the first several years (Vo et al., 2009), in this Vietnam-based model.

The setting for this study was Vietnam, which meant that the model's planning horizon as well as the maximum length of the

Table 3
Results from sensitivity analyses of the "biodiversity rotation age" to the minimum viable population (MVP) of birds for 10 randomly selected household-managed forests in Yen Bai Province, Vietnam.

Case of household forests	Optimal rotation age (years)			Optimal net present value (million VND ha^{-1} (USD ha^{-1}))			Birds density (all species) (individuals ha^{-1} year^{-1})		
	MVP = 50	70	100	MVP = 50	70	100	MVP = 50	70	100
1	11	15	18	13.97	8.62	4.70	54	78	101
2	11	15	19	9.95	5.71	1.75	53	77	103
3	10	15	18	15.14	8.64	4.64	50	78	102
4	11	15	19	9.68	5.47	1.54	53	77	103
5	11	15	19	11.06	6.49	2.22	54	77	105
6	11	15	19	9.87	5.63	1.68	53	77	103
7	11	15	19	11.69	6.93	2.48	54	77	105
8	11	15	19	9.81	5.58	1.64	53	77	103
9	11	15	18	13.70	8.40	4.49	54	78	101
10	11	15	19	9.71	5.50	1.57	53	77	103
Mean values	10.9	15	18.7	11.46 (674)	6.70 (393.94)	2.67 (157.12)	53.1	77.3	102.9

Note: The discount rate is 8% and the carbon price is 0.051 million VND (3 USD) tonne^{-1}.

Table 4
Results from sensitivity analyses of the biodiversity rotation age to the discount rate (r) for 10 randomly selected household-managed forests in Yen Bai Province, Vietnam (bird minimum viable population = 50).

Case of household forests	Optimal rotation age (years)			Optimal net present value (million VND ha^{-1}/USD ha^{-1})			Bird density (individuals ha^{-1} year^{-1})		
	r = 0.01	0.05	0.1	r = 0.01	0.05	0.1	r = 0.01	0.05	0.1
1	13	11	11	65.59	25.16	9.71	65	54	54
2	12	11	11	62.79	20.56	6.02	58	53	53
3	10	10	10	69.15	26.58	10.83	50	50	50
4	12	11	11	62.23	20.20	5.78	58	53	53
5	12	11	11	64.14	21.74	7.04	59	54	54
6	12	11	11	62.61	20.45	5.94	58	53	53
7	12	11	11	64.61	22.36	7.64	60	54	54
8	12	11	11	62.49	20.37	5.89	58	53	53
9	13	11	11	64.83	24.75	9.50	65	54	54
10	12	11	11	62.30	20.25	5.81	58	53	53
Mean values	12.0	10.9	10.9	64.07/3769.06	22.24/1308.35	7.42/436.24	58.9	53.1	53.1

rotation interval for the simulations was 50 years, since household forest owners can use their forest lands for 50 years at most (Government of Vietnam, 1999). Yet in Vietnam, there can also be an opportunity for households to extend their ownership of forestry land if the government has no prior plan to use the land. This means that at plantation establishment, if the forest owners know that their ownership could be extended (e.g., by 20 years); then the planning horizon of the model will be longer (i.e., up to 70 years instead of 50 years). In turn this means that the optimal rotation age can possibly be longer. However, if forest owners can only confirm such an extension at the end of their current contract (i.e., at the 50 year time point), then it is unlikely that the optimal rotation age for the whole planning horizon will be longer.

Since the Government of Vietnam desires to enhance biodiversity in planted forests, government policy is required to achieve this since private decision-making to optimize NPV at the household level will not lead to the desired outcome at the societal level. This research has shown how private owners may be affected financially when biodiversity conservation is included. In addition, when carbon sequestration services had market values, the optimal rotation age was shorter compared to that when they had no values, reducing the bird density. A higher carbon price did not support biodiversity conservation since it shortened the optimal rotation age and decreased the bird density in the forests. These results could help the Government of Vietnam to formulate appropriate policies to achieve national biodiversity objectives in planted forests. This could be done via the provision of financial incentives to foresters to extend the rotation length. Imposing a carbon tax at the time of harvesting could also help to lengthen rotation age, however, a downside of this could be the additional financial hardship on low-income Vietnamese foresters (see Nghiem (2013) for further discussion with regard to forest policy tools for promoting biodiversity in planted forests in Vietnam). These results have implications for implementing the REDD+ mechanism in Vietnam and in other developing countries that have similar tree species, such as Thailand, and Indonesia (Su-See, 1999), Costa Rica (Miranda et al., 2003), and Uruguay (Vihervaara et al., 2012).

Table 5
Results from sensitivity analyses of the biodiversity rotation age to timber price for 10 randomly selected household-managed forests in Yen Bai Province, Vietnam (8% discount rate and bird minimum viable population = 50).

Case of selected household forests	Optimal net present value (million VND ha^{-1}/USD ha^{-1})		
	P[a] = 0.37 / 21.76	0.5/29.41	2/117.65
1	13.97	20.93	101.22
2	9.95	15.44	78.77
3	15.14	22.77	110.81
4	9.68	15.16	78.49
5	11.06	16.99	85.38
6	9.87	15.35	78.68
7	11.69	17.89	89.41
8	9.81	15.30	78.62
9	13.70	20.67	101.19
10	9.71	15.20	78.53
Mean values	11.46/674	17.57/1033.53	88.11/5182.94

[a] Price of *E. urophylla* (million VND per m^3/USD per m^3) in Yen Bai Province, Vietnam in 2007.

The biodiversity optimization model presented here has several limitations regarding the biodiversity function. As described in Eq. (17), the bird density depends only on the age of forest stands — the older the stands the higher the density. This function does not allow for the possibility that the bird density may also be affected by other biological variables, such as forest plant density and diversity, types of dominant tree species, and disturbance intensity. But the inclusion of other biological parameters makes the models more complicated. In addition, this function implies that, as the age of forest stand increases, the bird density will increase indefinitely. Under this circumstance, incorporating other biological variables will keep the bird density within a given range. However, as the model's constraint was to achieve a minimum bird population density, a maximum number does not affect the performance of the model.

Another weakness of the biodiversity optimization model in this study is that it did not consider corridors in fragmented areas in planted forests so that birds can move across forest stands. Landscape fragmentation – gaps created by clear cutting forest stands – could affect the movement of vertebrate species across forest stands. However, as most bird species are good fliers and the sizes of their home ranges vary from 4 to 40 ha, their traveling ability will not usually be affected if the clear-cut sizes are relatively small. The optimization model was applied to private planted forests in Yen Bai, Vietnam, which were only 3.95 ha on average (Nghiem, 2011) so gaps created by clear-cut areas which were not included in the model will not affect bird traveling and the model's results. But note that even so, the gaps may affect the habitat of other animals such as insects, and thus affect the overall biodiversity of plantation forests.

Finally, this study has not yet addressed additional benefits to those of carbon sequestration and biodiversity preservation. These environmental and social benefits from forests include protection of water quality, benefits for humans from forest products, and work safety. Longer rotational periods would benefit both water quality and flood protection since there is more forest biomass to hold water and release it slowly. Also water quality in local streams may temporarily deteriorate due to soil erosion with each harvesting event. More mature forests could provide disproportionately more wild food sources (e.g., wild animals that people hunt). Longer rotations could also reduce the risk of forest worker injury (which increases with each harvesting event). This study also did not consider other forest

Table 6
Results from sensitivity analyses of the biodiversity rotation age to the discount rate (r) for 10 randomly selected household-managed forests in Yen Bai Province, Vietnam (bird minimum viable population = 50).

Case of household forests	Optimal rotation age (years)				Optimal net present value (million VND/USD ha^{-1})				Bird density (individuals ha^{-1} year^{-1})			
	Carbon price (million VND/USD tonne^{-1})				Carbon price (million VND/USD tonne^{-1})				Carbon price (million VND/USD tonne^{-1})			
	0.051/3	0.17/10	0.34/20	0.7/41.18	0.051/3	0.17/10	0.34/20	0.7/41.18	0.051/3	0.17/10	0.34/20	0.7/41.18
1	8	8	7	5	15.93	24.72	38.10	68.83	42	42	38	33
2	8	8	7	5	11.47	18.44	29.04	53.36	41	41	38	32
3	8	8	7	5	15.93	24.92	38.56	69.82	43	43	38	33
4	8	8	7	5	11.14	18.11	28.68	52.91	41	41	38	32
5	8	8	7	5	12.75	20.28	31.68	57.94	41	41	38	32
6	8	8	7	5	11.37	18.33	28.93	53.21	41	41	38	32
7	8	8	7	5	13.44	21.32	33.20	60.62	41	41	38	33
8	8	8	7	5	11.30	18.26	28.85	53.12	41	41	38	32
9	8	8	7	5	15.57	24.39	37.76	68.44	42	42	38	33
10	8	8	7	5	11.19	18.15	28.73	52.97	41	41	38	32
Mean values	8	8	7	5	13.01/765.25	20.69/1217.3	32.35/1903.09	59.12/3477.74	41.4	41.4	38.1	32.5

management practices, such as uneven-aged stands and thinning. Thinning helps households to get regular income even well before final harvesting, and that may increase the optimal rotation age since it reduces the risk of acute household financial hardship. Other uncertainties have also not been incorporated in the study. For example, the risk of timber loss from fire may change with forest age, lower timber productivity due to severe weather events, and carbon release into atmosphere because of forest fires. Considerations of these additional issues in a forest level model could be included in future research.

In summary, this study found that the inclusion of biodiversity conservation into the optimization model for planted forests in Vietnam induced a longer optimal rotation age compared to the period that maximizes the joint value from timber and carbon sequestration. But this longer rotation period resulted in slightly lower NPV for forest owners. Given this differential, governments in such tropical countries may need to consider additional monetary incentives to forest owners if they are to encourage longer rotation ages and therefore maximize biodiversity and its associated benefits.

Acknowledgments

The author would like to thank Prof. Anton Meister and Dr. Brendan Moyle for their excellent guidance and encouragement throughout this research. Thanks also to Associate Prof. Nick Wilson, Rachel Foster, and Prof. Tony Blakely (University of Otago, Wellington) for their support and/or comments on various drafts. Many thanks to Dr. Nguyen Nghia Bien (Vietnam Ministry of Agriculture and Rural Development), MSc. Kieu Tu Giang and his colleagues (Yen Bai Forestry Department), colleagues at Vietnam Forestry University for their advice and field assistance, and to this Journal's reviewers and editors for very helpful suggestions for revisions. Special thanks also go to people in Yen Bai Province who were very cooperative and enthusiastically attended interviews. Funding from the Economy and Environmental Program for South East Asia and Ministry of Education was much appreciated. Any remaining limitations with the final draft are solely the responsibility of the author. The findings, opinions, and conclusions in this paper are those of the author alone and are not necessarily shared by the author's affiliated organizations and the funding bodies.

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