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Optimizing thinnings for timber production and carbon sequestration in planted teak (*Tectona grandis* L.f.) stands

María-Alejandra Quintero-Méndez (Quintero-Méndez, M.A.), Mauricio Jerez-Rico (Jerez-Rico, M.)*

Universidad de Los Andes. Facultad de Ciencias Forestales y Ambientales, Av. Principal Chorros de Milla, Conjunto Forestal, edificio principal, Mérida, Venezuela.

Abstract

Aim of study: We developed an optimization model for determining thinning schedules in planted teak (*Tectona grandis* L.f.) stands that maximize the financial output in terms of soil expectation value (*SEV*) and net present value (*NPV*) considering a) the simultaneous optimization of timber production and carbon (C) sequestration and b) only for C sequestration.

Area of study: Planted teak forests in the western alluvial plains of Venezuela.

Material and methods: We integrated a stand growth and yield model with a constrained optimization model based on genetic algorithms (*GA*) for determining optimal thinning schedules (number, age, and removal intensity) that maximize *SEV* when simultaneously managing for timber production and C sequestration. The data came from permanent plots established in planted teak stands with remeasurements from 2 to 32 yr.-old. Plots differ in site quality, initial spacing, and thinning schedules. We obtained optimal thinning schedules for several scenarios combining site quality, initial spacing, interest rates, harvest and transport costs, as well as timber and C prices. The stand growth and yield model estimates timber products and C flows (storage and emissions) until most stored C is reemitted to the atmosphere.

Main results: When considering simultaneously both, timber production and C sequestration, the scenario with the maximum *SEV* consisted of initial stand densities = 1,111 trees ha^{-1}, site quality (*SQ*) I, harvest age 20 years, and four thinnings (ages 6, 10, 14, 17 with removal intensities 26 %, 28 %, 39 %, and 25 % of stand basal area respectively). For maximizing C sequestration only, the best schedule consisted of 1,600 trees ha^{-1}, *SQ* I, harvest age 25 years, with no-thinning. A sensitivity analysis showed that optimal schedules and *SEV* were highly sensitive to changes in interest rates, growth rates, and timber prices.

Research highlights:

• The management schedules favoring merchantable timber production are not the same that favor C sequestration.

• For planted teak, the objectives of maximizing timber production and carbon sequestration are in conflict because the thinning schedules that maximize financial gains from C sequestration reduce economic gains from timber and vice versa.

• With actual timber teak and market C prices, optimal NPV^W is much larger than optimal NPV^C.

• For C prices under 40 $US MgC optimizing simultaneously for timber production and C sequestration is the best option, as additional although sub-optimal revenues can be obtained from C payments.

• Lengthening the rotation, avoiding thinnings, or reducing their intensity increase carbon storage in planted teak, although, under the analyzed scenarios, after 120 yr. almost all carbon has been re-emitted to the atmosphere.

Additional keywords: heuristics, genetic algorithms, operations research, forest management planning, stand level model, carbon stocks.

Abbreviations used: C (Carbon); *GA* (genetic algorithm); NPV^W, NPV^C, NPV^T (net present value from the cash flows of timber (wood), carbon, and total); *SEV* (Soil (land) expectation value); *dbh* (diameter at 1.3 m from the ground); *G* (stand basal area); G_p (potential site carrying capacity in terms of *G*); *SQ* (site quality); *R* (rotation, harvest age); *A* (age); *I* (thinning intensity); V_{ob}, V_{ub} (overbark, underbark volume); g_r (basal area growth rate); *r* (interest rate); harvest and transport costs (*Hc*); *Pc* (C price).

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Correspondence should be addressed to Mauricio Jerez-Rico: jerezorama@gmail.com

Introduction

Given its high value as a precious tropical timber and its decline in natural forests, teak (*Tectona grandis* L.f.) is being planted at increasing rates in tropical regions of Asia, Africa, and America. So far, this species represents a small proportion of the total market of tropical timbers; however, it is the only precious wood tropical species that is becoming a commodity.

Commercial teak forest plantations must be managed intensively to obtain maximum profitability, however, an increasing awareness of society in environmental issues implies the need of reaching a trade-off between economic and environmental benefits. Today, many countries and private companies are investing in commercial teak plantations; however, there is a strong concern on global climate change, especially after the Paris 2015 Climate Change Conference, which raised the interest in planted forests as providers of environmental services, e.g., carbon sequestration. Planted forest for producing durable solid timber products can play an important role in carbon sequestration, as a large proportion of fixed C remains stored as solid, large size pieces of wood for long time after harvest. Thus, it should be appealing for planted teak forest managers to consider the additional potential benefits of producing timber and simultaneously providing environmental services such as C storage.

Within the frame of the intensive management of planted teak, managing the stand´s carrying capacity and optimizing the planting density, thinning, and pruning schedules is crucial for producing high quality timber in large logs with a high proportion of heartwood, as these have much higher value for the international markets.

Most knowledge on the effect of initial spacing and thinning schedules in teak growth and yield come from field trials based on permanent plots subjected to several combinations of spacing and thinning schedules, and from growers' experience and judgement. The latter is difficult to generalize; whereas, the former is limited by the number of testable combinations and circumscribed to specific sites. Mathematical models can integrate information from these experiences allowing generalization of growth responses and financial results to a large number of combinations including those for which no experimental studies exist. Moreover, models allow the assessment of the weight of intervening variables in the magnitude of observed changes in the biological, financial, and environmental outputs. Mathematical models for analyzing responses to thinning schedules include stand density diagrams (e.g., Kumar *et al.*, 1995; Jerez *et al.*, 2003) and simulation models (e.g., Jayaraman & Rugmini, 2008; Tewari *et al.*, 2014; Nölte *et al.*, 2018). Less explored approaches for teak are optimization models, including classic optimization techniques (Mathematical Programming); meta-heuristics (e.g., genetic algorithms, simulated annealing), and multicriteria-decision-making techniques (e.g., goal programming) (Belavenutti *et al.*, 2018, Pukkala & Kurttila, 2005). Thinning schedules can favor carbon sequestration in planted forests (Hoen & Solberg, 1994; Karjalainen, 1996; Pohjola & Valsta, 2007). Several works analyzed the carbon sequestration capacity of teak (Kraenzel *et al.*, 2003; Gera *et al.*, 2011; Takahashi *et al.*, 2012; Sreejesh *et al.*, 2013; Olayode *et al.*, 2015; Nölte *et al.*, 2018); however, for teak, optimization models incorporating a trade-off between commercial (timber production) and environmental goals (carbon sequestration) considering biological and financial variables through meta-heuristics are rare. Quintero-Méndez & Jerez-Rico (2017) used a metaheuristics approach to develop a forest level (multiple stands) optimization model to determine alternative thinning schedules for a forest teak project. Optimize simultaneously for different objectives when managing planted forests can be a very complex task due to a large number of decision variables, constraints, and potential non-linear relationships among them. In this case, heuristic techniques can be applied as they can handle the model complexity more efficiently, although usually produce near optimal solutions rather than exact solutions.

Our objective was to develop and implement an optimization model integrating a growth and yield model with a heuristic optimization technique (genetic algorithms, *GA*) for determining thinning schedules that maximize the financial outputs (i.e., *SEV, NPV*) in teak plantations considering simultaneously merchantable timber production and C sequestration, and carbon sequestration only. In addition, the annual dynamics of C storage and emissions during and after the rotation is simulated for standing trees, solid products, and debris generated from thinning and harvest operations until the total re-emission of the stored carbon to the atmosphere. The model produces "optimal thinning" schedules under management scenarios varying in site quality (*SQ*), initial stand density at planting, variable rotation age (*R*), and financial variables: interest rates (*r*), harvest and transport costs (*Hc*), and timber and C prices. A comparative example shows technical and financial results for scenarios that combine rotation ages 20 and 25 yr., site index of 27 and 24 at base age 16 years, and initial spacings of 816, 1,111, and 1,600 trees ha^{-1} that are common for teak management in Venezuela, and other countries in Latin America and Africa.

Materials and methods

Model description

The system represents planted, even aged teak stands managed with the primary purpose of producing solid merchantable timber and, in addition, storing carbon. Stands may differ in site quality, initial spacing, and rotation age (20 or 25 yr.). We developed a model that looks for combinations of thinning schedules (number, age, and intensity) that maximize the stand´s financial benefits. The model comprises three modules: 1) a stand growth and yield model (Jerez *et al.*, 2015); 2) a module for computing carbon storage and emissions, and 3) an heuristic optimization module based on a Genetic Algorithm that looks for maximizing the financial benefits (*NPV*) for the goals of maximizing NPV^W, NPV^C, or both simultaneously (Fig. 1).

Growth and yield module

The growth and yield module consists of a whole-stand model based on a system of differential equations describing the dynamics of the main state variables; e.g. top height (*H*, m), basal area (*G*, m^2 ha^{-1}), and stand density (*N*, trees ha^{-1}). The model projects growth in basal area, height, *dbh*, stand merchantable volume, total biomass, and stored carbon for various combinations of site quality, initial spacing, and thinning schedules. The basal area growth submodel follows the Pienaar & Turnbull (1973) approach to project the growth of thinned and unthinned plantations with a Richards´s growth equation (Jerez *et al.* 2015). The carrying capacity in terms of basal area (G_p) of the best sites for teak average 37.5 m^2 ha^{-1} (Zambrano *et al.*, 1995, Bermejo *et al.*, 2004). Dominant height growth was modeled as an anamorphic family of site index curves (base age = 16 yr.) that follows a Richards´s function fitted with the algebraic difference method (Clutter *et al.*, 1983, Quintero *et al.*, 2012). Site index classes were I = 24, II= 21, and III = 18 m. Stands with lower site index have corresponding lower G_p. For *SQ*s I, II, and III, G_p is 37.5, 34, and 30 m^2 ha^{-1}, respectively. Quadratic diameter (*dbh*, cm) growth is computed from *G* and *N*. Stand average height is a function of dominant height and the ratio *dbh* of removed trees to *dbh* of remaining trees.

The mortality submodel has three components: a) density-independent mortality due to factors other than tree competition (e.g. drought, pests, and weeds); b) density-dependent mortality due to intraspecific competition; and c) removal of trees by thinning and final harvest. Density-independent mortality oc-

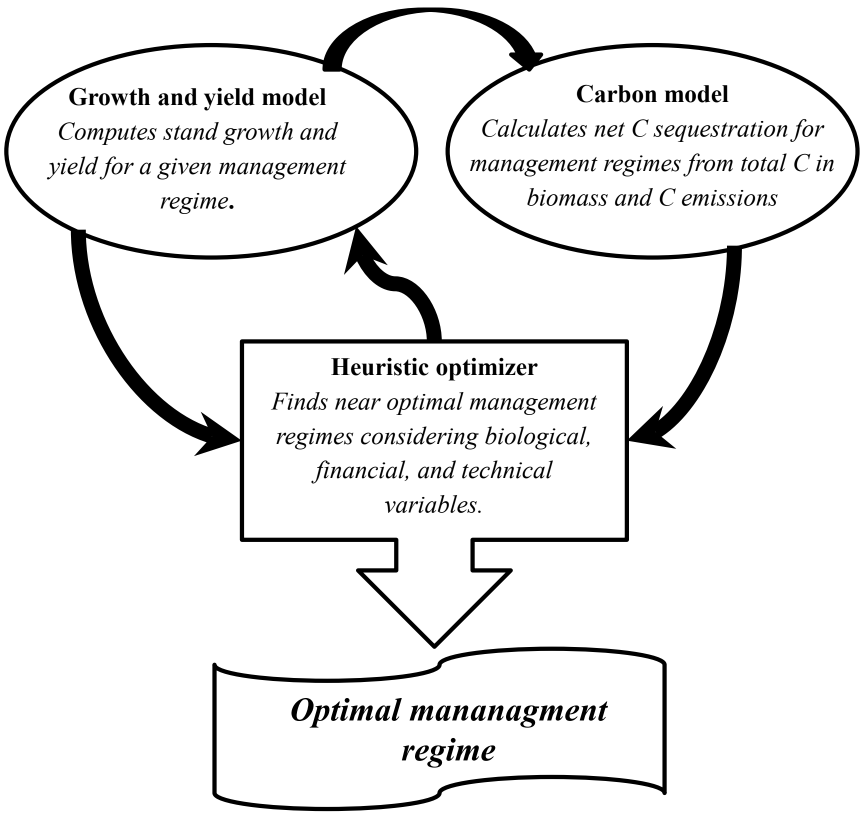

Figure 1. Model components and their relationships.

curs only for trees between 0 and 3 yr.-old with decreasing probability. Density-dependent mortality is a decreasing exponential function of stand density. Estimates of equations´ coefficients came from permanent plots remeasured from 2 to 32 yr.-old established in the western plains of Venezuela.

The model predicts the instantaneous change in stand quadratic diameter and the proportion of harvested trees with respect to removed basal area depending on a thinning selectivity coefficient th_s, where $th_s = 1$ for systematic thinning, $th_s < 1$ for thinning from below, and $th_s > 1$ for thinning from above (Jerez *et al.*, 2015). Merchantable volume was calculated as overbark (V_{ob}) and underbark (V_{ub}) volumes in m^3 from stem base up to 5-cm diameter at tree top (Moret *et al.*, 1998).

Carbon sequestration module

This module represents the yearly dynamics of stand carbon capture and emissions due to growth and death of above and belowground biomass. Carbon emissions come from the decomposition of branches, stumps, stems, and wood from dead or harvested trees throughout the stand rotation; plus decomposition of harvested forest products and wood losses from processing. Net carbon sequestration is the difference between carbon stored in biomass and carbon emitted to the atmosphere. Total above and belowground stored C was calculated from the total stand overbark volume using the conversion and expansion factors obtained by Kraenzel *et al.* (2003) for teak plantations. The model does not describe explicitly C stored or released from the soil, harvest operations, transport of products (i.e., carbon emitted by trucks and machinery), recycling, or effects of substituting fossil fuels by wood. Carbon emissions were estimated according to Hoen & Solberg (1994) who consider future C emissions as a function of the various decomposition and emission rates and organic lifetime (anthropogenic time) of the biomass components (categories). The carbon emission (E) in period $i + j$ from category q removed in period i is:

$$E_{ik,i+j} = RB_i \times e_k \times Q_{k,i+j} \quad [1]$$

where RB_i = removed biomass in period i, e_k = the fraction of removed total biomass from category k, and $Q_{k,i+j}$ = emission rate of category k in $i + j$ defined by:

$$Q_{k,i+j} = \begin{cases} 0 & if\ j \le A_{Tk} \\ & or \\ (1-q_k)^{j-A_{Tk}} \times q_k & if\ j > A_{Tk} \end{cases} \quad [2]$$

A_{Tk} = anthropogenic time for category k, q_k = annual decomposition fraction for category k:

$$q_k = 1 - 0.1^{1/D_{Tk}} \quad [3]$$

where D_{Tk} = decomposition time of category k.

For each use category, emission and decomposition stop when a very tiny fraction (< 0.01 MgC ha^{-1}) is emitted. Thus, a small fraction of biomass will remain without further decomposition, i.e., soil organic carbon (Hoen & Solberg, 1994). We assumed that carbon emission patterns are not appreciably affected by carbon mineralization processes.

Seven carbon compartments were considered: 1) roots, 2) deadwood, 3) branches and stumps, 4) bark and debris, 5) short-term duration products (small poles for fencing), 6) midterm duration products (struts and large poles), and 7) long term duration products (sawn wood). Information on decomposition and anthropogenic times are from Hoen & Solberg (1994). Fractions of wood products per category came from Quintero-Méndez & Jerez-Rico (2017).

Optimization module

This module determines the thinning schedule that maximizes *NPV* of cash flows related to stand timber production and carbon sequestration. Financial benefits of C sequestration come from the payment of environmental services made annually according to C prices following (Backéus *et al.*, 2005, Díaz-Balteiro & Rodríguez, 2006, Baskent *et al.*, 2008). The optimizer selects the best thinning schedule based on the outputs from the growth and yield model and from the C module (Fig. 1).

Mathematical model

We developed a constrained optimization model that maximizes an objective function *Z*, where Z is the total net present value (NPV^T) of the cash flows through the rotation for a stand whose objectives are producing timber and sequestering carbon simultaneously:

$$NPV^T = NPV^W + NPV^C \quad [4]$$

where NPV^W = the net present value of the cash flows of timber (wood) from thinning and final harvest occurred through the stand life:

$$NPV^W = -\sum_{i=1}^{t} \frac{Cm_i}{(1+r)^i} + \sum_{i=1}^{t} \frac{B_i}{(1+r)^i} \quad [5]$$

and NPV^C = the net present value of the cash flows due to positive net C storage through the stand life:

$$NPV^C = P_c \sum_{i=1}^{Td} \frac{F_i - E_i}{(1+r)^i} \times \text{In}_i \quad [6]$$

where t = rotation age (yr.), r = interest rate, Cm_i = establishment and maintenance costs in yr. i, B_i =

benefits in yr. i from timber harvested, P_c = carbon price (US\$ $Mg^{-1}C$), F_i = carbon fixed in yr. i (MgC), E_i = carbon emitted in yr. i (MgC), Td = time (yr.) in which 90% of C has decomposed, In_i = indicator variable ($In_i = 1$ if $F_i > E_i$, $In_i = 0$ otherwise). There are three maximization options for Z: maximizing NPV^W only, maximizing NPV^C only, or maximizing both values simultaneously:

$$Maximize\ Z = \begin{cases} NPV^W & or \\ NPV^C & or \\ NPV^W + NPV^C & \end{cases} \quad [7]$$

considering the following decision variables: A_j = number of yr. from planting (age = 0) to first thinning (j=1), or yr. between successive thinnings, where the subscript j is the j-th thinning, j = 2, 3, 4); I_j = intensity of thinning j (j = 1, 2, 3, 4) as a percent of current basal area G; subject to the following constraints:

$$Go_{i+1} = Gf_i + \Delta G_{i+1,i} \quad [8]$$

$$Gthin_i = I_j \times G_i \text{ (if thinning } j \text{ is carried out in yr. } i) \quad [9]$$

$$Gf_i = Go_i - Gthin_i \quad [10]$$

$$A_j \geq 3 \quad \forall j \quad [11]$$

$$I_j \geq 25 \quad \forall j \quad [12]$$

$$A_j \text{ is an integer } \forall j \quad [13]$$

Go_i and Gf_i are basal areas ($m^2\ ha^{-1}$) at the beginning and end of yr. i respectively subject to constraints (8-9-10); $\Delta G_{i+1,i}$ = current annual increment in yr. i and $Gthin_i$ = removed basal area by thinning in yr. i. Constraint (11) specifies age = 3 yr. after planting as the minimum for carrying out the first thinning, and also the minimum interval between successive thinnings. Constraint (12) indicates that at least 25% G must be removed by a given thinning. The incomes by C sequestration (payment at market price per MgC) occur only the year in which sequestered C is larger than emitted C (Báckeus *et al.*, 2005).

Optimization technique

We designed a heuristic procedure based on genetic algorithms (*GA*), a very robust optimization technique for solving efficiently many optimization problems (Dréo *et al.*, 2006). The *GA* consists of searching throughout the possible solutions space by a process analogous to species evolution (Holland, 1975). The *GA* uses a binary codification to represent the possible problem solutions by generating a random initial solution and then applying a set of genetic operators: selection, crossing, and mutation.

Data

The data for growth and yield came from a network of permanent and temporal plots established on teak plantations in the western plains of Venezuela remeasured two or more times between 1.8 and 32 yr.-old. Initial spacing varied from 2.0 × 2.0 to 4.0 × 4.0 m and thinning schedules comprised from 0 to 4 thinnings varying in intensity, age, and intervals of execution. Establishment, management, harvest, and operation costs are shown in Quintero-Méndez & Jerez-Rico (2017).

Model implementation

The model, implemented in Visual Basic 2015, comprises the growth & yield, carbon sequestration, and optimization modules. The program generates the best thinning schedules to optimize separately for timber production or carbon sequestration or for optimizing both objectives simultaneously. Inputs are site quality, initial spacing, rotation age, and desired number of thinnings, timber prices differentiated by diameter categories, carbon prices, establishment, maintenance and harvest operations costs, and interest rates. Outputs are optimal thinning schedules (age and intensity of thinnings), NPV^T, NPV^W, and NPV^C. Soil expectation value (*SEV*) was calculated according to Bettinger *et al.* (2009):

$$SEV = \frac{NPV(1+r)^t}{(1+r)^t - 1} \quad [14]$$

where NPV = net present value, t = rotation age, and r = interest rate.

Optimal schedules are accompanied by the corresponding stand information on density, average tree diameter, basal area, dominant/average height, and merchantable volume on an annual basis. Outputs from carbon dynamics include storage, emissions, and annual C flows from stand initial conditions till 120 yr. after harvest considering standing trees, short, medium, and long term forest products, and wood debris from thinnings and final harvest.

Model runs

We determined thinning schedules for two optimization criteria: A) maximizing the NPV of timber production and carbon sequestration simultaneously (maximize $NPV^W + NPV^C$); and B) maximizing the financial benefits associated with C sequestration only (maximize NPV^C). For each criteria 60 scenarios were defined combining *SQ* (I and II), initial planting density (816, 1,111, and 1,600 trees ha^{-1}), thinning schedules (0 to 4 thinnings from below; *i.e.,* the average *dbh* of removed trees was lower than that of the remaining trees for a given thinning (th_s = 0.9), and harvest age (*R* = 20 and 25 yr.). Stand growth and yield was simulated by integrating the differential equations with the Runge-Kutta method, initial time was t_0 = 0 yr. at planting, initial *G* was calculated by multiplying the initial density times the root collar average diameter (1 cm). Initial stand height = 0.5 m.

The model was set to execute 50 runs for *r* = 10 %, harvest and transport costs (*Hc*) = 14.24 US\$ m^{-3} and C price = 10 US\$ Mg^{-1}C (equivalent to 2.72 US\$ $MgCO_2$ where 1 MgC = 3.67 $MgCO_2$), commonly used in financial analysis including C sequestration (Álvarez, 2009). Merchantable timber prices according to diameter category (Table 1) correspond to 2013 international market prices (De Camino & Morales, 2013).

Sensitivity analysis

We carried out a sensitivity analysis to determine the effects on the optimal solution (thinning schedule and maximum for the objective function) when assumed inputs (independent variables) were changed. Each input was changed within a given range and the other parameters kept fixed. The following parameters were varied: a) growth rate (g_r) at intervals of ±1%, (e.g., increases attributable to favorable climate conditions); b) thinning and harvest costs between ±10 and ±50% (base value =14.24 US\$ m^{-3}) at 10% intervals; c) *r* = 5, 8, 12, 14 %, base 10%); d) C prices (0, 20, 30, 40, 50, 100, 150, and 200 US\$ Mg^{-1}C, base US\$ 10); and e) ratios of timber prices per cubic meter among diameter classes. Teak timber prices depend largely on log size and age, as large logs with a high proportion of heartwood are preferred by the market (e.g. furniture, plywood). For young teak plantations, log dimension is a valid surrogate of wood quality. Four situations were considered: 1) all diameter classes have the same price in US\$ m^{-3} (i.e., no premium for large diameter logs); 2) logs with diameter ≥ 25 cm are worth twice the price of logs 10 ≤ d ≤ 25 cm; 3) logs with diameter ≥ 25 cm are worth three times the value of 10 ≤ d ≤ 25 cm logs; and 4) logs with size d ≤ 10 cm have no value (Table 1).

Table 1. Timber log prices according to diameter classes used in model runs and sensitivity analysis.

Diameter class (cm)	Timber prices (US\$ m^{-3})			
	Base	Cases: 1	2	3
< 10	0	100	0	0
[10 - 15)	53	100	100	100
[15 - 20)	77	100	100	100
[20 -24)	155	100	100	100
[25 - 29)	232	100	200	300
[30 - 39)	310	100	200	300
>= 40	400	100	200	300

Results

Best thinning schedules

For the optimization criterion A (simultaneous maximization of NPV^W and NPV^C), the largest *SEV* was reached for the scenario in *SQ* I, rotation (*R*) = 20 yr., and 1,111 trees ha^{-1} (US\$ 14,542) and the NPV^W is US\$ 12,380, being the contribution of NPV^C less than 3.5% (Table 2). The *SEV* for scenario (*SQ* I, *R*= 20, 1,600 trees ha^{-1}) was only slightly lower (US\$ 14,318), but with a small increase in NPV^C (4.2% of NPV^T). The scenario (*SQ* I, *R* = 20, 816 trees ha^{-1}) had a considerably lower *SEV* (US\$ 11,364). Thus, scenarios with 1,111 trees ha^{-1} always had the largest *SEV* as compared to the other stand densities. Also, stands in *SQ* I had always larger *SEV* than stands in *SQ* II; and scenarios with *R* = 20 had always larger *SEV* than *R* = 25. For optimization criteria B, i.e., only NPV^C is optimized; the highest NPV^C = US\$ 763 is for scenario *SQ* I, 1600 trees ha^{-1}, and *R* =25; however, if we look for the largest *SEV,* then the best scenario is *SQ* I, 816 trees ha^{-1}, *R* = 20, despite that the NPV^C is under the optimal. This is because the weight of the non-optimized NPV^W, at base conditions, is very large when compared to the optimized NPV^C (Table 2). Although longer rotations and higher densities increase the optimal NPV^C, the *SEV* is strongly reduced, being as low as for scenario *SQ* II, *R* = 25, 1600 trees ha^{-1}. In this case, NPV^C is even larger than NPV^W.

The thinning schedule with the best *SEV*, i.e., maximizing simultaneously NPV^W and NPV^C for *SQ* I, 1,111 trees ha^{-1}, *R* = 20, included four thinnings at ages 6, 10, 14, 17 with intensities 26, 28, 39, and 25% *G* (Table 3). However, for *SQ* II, the best schedule was for 1,111 trees ha^{-1}, *R* = 20, but only two thinnings (5 and 11 yr.-old) and removal intensities of 30.5 and 46.2% *G*).

The optimal number of thinnings in *SQ* II was always lower or equal than in *SQ* I scenarios given the same initial stand density and harvest age. On the other hand, the number of thinnings is always lower for *R* = 20 as compared with *R* = 25 yr. In the former case, 50% of scenarios showed a higher *SEV* when only two thinnings were executed. Conversely, for *R* =25, four thinnings

Table 2. Net Present Values and Soil Expectation Value for the best thinning schedules at base values (Interest rate =10%, C price = 10 US$ Mg^{-1} C, base timber prices). A) Optimal combination of $NPV^W + NPV^C$ and, B) Optimal NPV^C only (No thinning). Best schedules highlighted in grey.

		A) Optimal $NPV^W + NPV^C$ (US$)											
SQ	***R***	**816 trees ha^{-1}**				**1,111 trees ha^{-1}**				**1,600 trees ha^{-3}**			
	(yr,)	***NPV^W***	***NPV^C***	***NPV***	***SEV***	***NPV^W***	***NPV^C***	***NPV***	***SEV***	***NPV^W***	***NPV^C***	***NPV***	***SEV***
I	**20**	9,319	356	9,675	**11,364**	11,951	429	12,380	**14,542**	11,684	507	12,190	**14,318**
	25	8,381	378	8,759	**9,650**	10,306	448	10,754	**11,848**	10,035	511	10,547	**11,619**
II	**20**	6,920	284	7,204	**8,462**	8,710	374	9,085	**10,670**	8,627	383	9,009	**10,582**
	25	5,877	355	6,232	**6,866**	7,856	381	8,237	**9,075**	7,747	435	8,182	**9,014**
		B) Optimal NPV^C (US$)											
		816 trees ha^{-1}				**1,111 trees ha^{-1}**				**1,600 trees ha^{-3}**			
		NPV^W	***NPV^C***	***NPV***	***SEV***	***NPV^W***	***NPV^C***	***NPV***	***SEV***	***NPV^W***	***NPV^C***	***NPV***	***SEV***
I	**20**	6,228	426	6,654	**7,816**	4,174	532	4,706	**5,528**	3,933	594	4,527	**5,317**
	25	3,951	468	4,419	**4,868**	4,217	594	4,811	**5,300**	1,993	644	2,637	**2,905**
II	**20**	2,931	342	3,273	**3,845**	3,292	442	3,734	**4,386**	553	486	1,039	**1,220**
	25	3,154	391	3,545	**3,906**	1,758	485	2,243	**2,471**	163	530	693	**763**

SQ: Site quality, *R*: Rotation age (yr.), *NPV*: Net present value (US$ ha^{-1}). *NPV^W*: Net present value from timber (US$ ha^{-1}), *NPV^C* : Net present value from carbon sequestration (US$ ha^{-1}), *SEV*: Soil expectation value (US$ ha^{-1}).

produce an optimal *SEV* 50 % of times. Furthermore, for the lower initial spacing (816 trees ha^{-1}), in 50% of scenarios the best schedule is two thinnings. In contrast, with 1,111 trees ha^{-1}, in 50% of scenarios, the model indicated that the best schedule includes four thinnings. For 1,600 trees ha^{-1}, 75% of prescribed scenarios consisted of three intensive thinnings (33, 31, 52% *G*) and *R* =20.

Overall, larger final diameters were reached for *R* = 25 years. The largest diameter was 42.1 cm for *SQ* I, 1,111 trees ha^{-1}, and four thinnings; whereas, the lowest diameter (30.3 cm) was reached for *SQ* =II, 816 trees ha^{-1}, harvest age = 20 yr. and two thinnings.

When only C storage was optimized, all scenarios showed no thinning schedules (Table 3). As occurred when maximizing simultaneously for C and timber, when optimizing only for C, scenarios with longer rotation age reached larger diameters, although these were comparatively low due to lack of thinnings. Thus, the highest *dbh* (27.6 cm) occurs for *SQ* I, 816 trees ha^{-1}, R = 25, and the lowest *dbh* (18.9 cm) occurs for *SQ* I, 1600 trees ha^{-1}, *R* = 20.

The curves for simulated *G*, stand density, *dbh*, and *h* for the scenario with the highest *SEV* (maximize $NPV^W + NPV^C$) show a high contrast respect to the curves with the best *SEV* scenario that maximizes only C storage (Fig. 2).

Carbon sequestration and emissions

In addition to determining optimal *SEV, NPV*, and thinning schedules, the model generates information about annually stored and emitted C in standing trees and by type of product from initial planting to the time in which 99.99 % of all stored C has been released to the atmosphere for the scenarios that maximize NPV^C and $NPV^W + NPV^C$ (Fig. 3, A and B respectively).

Until harvest ages, most C remain stored in standing trees for both scenarios until harvest age. When maximizing only for NPV^C, at age 25, just before harvest, C stored in standing trees peak at approximately 143 MgC ha^{-1} with only a small amount as debris from natural mortality (Fig. 3A). On the other hand for the scenario that maximizes $NPV^W + NPV^C$, the maximum stored C peaks around 13 years (94.1 MgC ha^{-1}) with 73.4 MgC ha^{-1} in standing trees, and the rest in various products (Fig. 3B). By harvest age at year 20 only 103.5 MgC ha^{-1} remain stored, from which 55.6 is C in standing trees, and the rest in various products and debris. After peaking, in both cases C is emitted to the atmosphere till about 120 yr. when most C has been released (Fig. 3). In the period following thinnings or final harvest, the C stored in removed woody biomass is released according to the assumed emission rates. For this reason, when the objective is maximizing $NPV^W + NPV^C$ (Fig. 3B), after the first and second thinning (ages 6 and 10) stored C in standing trees shows no or only a slight decrease in stored C because fast growing rates. After the third and fourth thinnings (ages 14 and 17); however, stored C showed relatively large reductions for standing trees due to the larger size of cut trees (Fig. 3B). For both optimization criteria, after the final cut,

Table 3. Stand values for the best thinning schedules for A) Optimal combination of $NPV^W + NPV^C$ and B) Optimal NPV^C only (Interest rate =10%, timber prices (base) , carbon price = 10 US$ Mg^{-1} C). The best schedules are highlighted in grey.

A) *Optimal* $NPV^W + NPV^C$

SQ	*R*	816 trees ha^{-1}					1,111 trees ha^{-1}					1,600 trees ha^{-1}				
	(yr.)	*A*	*I*	*G*	*dbh*	*V*	*A*	*I*	*G*	*dbh*	*V*	*A*	*I*	*G*	*dbh*	*V*
I	**20**	**12**	42	9.2	18.2	86	**6**	26	4.2	13.0	34	**4**	33	3.9	9.3	25
		16	40	6.0	23.0	69	**10**	28	5.7	18.1	53	**11**	31	8.1	18.2	75
		20	100	13.4	31.7	141	**14**	40	8.0	22.7	80	**16**	52	12.8	23.2	127
							17	25	3.8	27.0	39	**20**	100	15.3	32.1	153
							20	100	13.5	35.0	143					
I	**25**	**4**	35	2.0	9.1	13	**5**	41	5.1	11.7	39	**5**	40	6.6	11.1	49
		15	33	6.6	22.8	66	**9**	31	4.8	18.4	45	**11**	35	8.1	18.7	76
		19	31	5.3	27.4	54	**18**	40	8.1	27.1	83	**15**	48	9.6	23.3	96
		22	30	4.0	30.8	41	**21**	35	5.0	31.9	53	**25**	100	17.4	36.8	185
		25	100	10.7	40.1	115	**25**	100	11.6	42.1	124					
II	**20**	**5**	28	2.0	10.2	50	**5**	31	3.3	10.7	24	**5**	47	6.5	10.4	46
		11	44	6.3	18.2	58	**11**	46	8.6	18.3	81	**11**	46	8.5	18.2	80
		20	100	15.2	30.3	159	**20**	100	18.0	30.5	188	**15**	28	3.9	23.2	39
												20	100	13.2	31.6	138
II	**25**	**15**	49	10.9	18.3	10	**3**	32	1.2	6.3	5	**5**	41	5.7	10.3	41
		19	27	3.8	22.6	38	**11**	27	5.2	18.3	48	**12**	35	7.4	18.0	69
		25	100	14.0	30.9	146	**17**	40	10.0	23.9	100	**17**	48	9.0	22.8	89
							21	43	5.1	30	53	**25**	100	14.3	34.2	152
							25	100	9.3	39.7	100					

B) *Optimal* NPV^C ***only***

SQ	*R*	816 trees ha^{-1}					1,111 trees ha^{-1}					1,600 trees ha^{-1}				
	(yr.)	*A*	*I*	*G*	*dbh*	*V*	*A*	*I*	*G*	*dbh*	*V*	*A*	*I*	*G*	*dbh*	*V*
I	**20**	-	-	28.4	25.7	289	-	-	33.1	23.8	332	-	-	35.2	20.4	339
	25	-	-	30.7	27.6	315	-	-	34.3	25.1	348	-	-	35.7	21.3	348
II	**20**	-	-	24.2	23.7	242	-	-	28.3	22.0	278	-	-	30.0	18.9	283
	25	-	-	26.2	25.5	265	-	-	29.3	23.2	291	-	-	30.4	19.7	219

SQ: Site quality, *R*: Rotation age in yr., *A*: Thinning age (yr.), *G*: removed basal area (m^2 ha^{-1}), *I*: thinning intensity (%G), *dbh*: quadratic diameter at breast height of harvested trees (cm), V_{ob}: harvested over-bark volume (m^3 ha^{-1}).

C stored at a given moment begins to decrease due to C emissions from degradation of wastes remaining in the forest, wastes generated during the various stages of wood processing, and by the slower degradation rates of harvested products. By year 40 for both scenarios the amount of C is approximately equal to 40 MgCha^{-1}. This volume is comprised mainly by short and medium duration products (*dbh* = 21.3 cm) for scenario that maximizes C storage; whereas, for the other scenario, C remain stored in larger durability products (*dbh* = 35.0 cm). At age 60 from planting, most medium duration products have decomposed in both scenarios, thus, the scenario that maximizes C + wood, has a higher amount (20 MgCha^{-1}) of C stored in long duration products. Afterwards, the remaining C is slowly released until 120 yr. when most of it has been reemitted in both scenarios, remaining only a small fraction that never decomposes or it is incorporated into the soil as organic C (Hoen & Solberg, 1994).

Sensitivity analysis

The sensitivity analysis for the model using as base the scenario with the maximum *SEV* (*SQ* I, 1,111 trees ha^{-1}, *R*= 20 yr., and four thinnings: ages 6, 10, 14, 17 and intensities 26, 28, 39, and 25% *G*) showed that *SEV,*

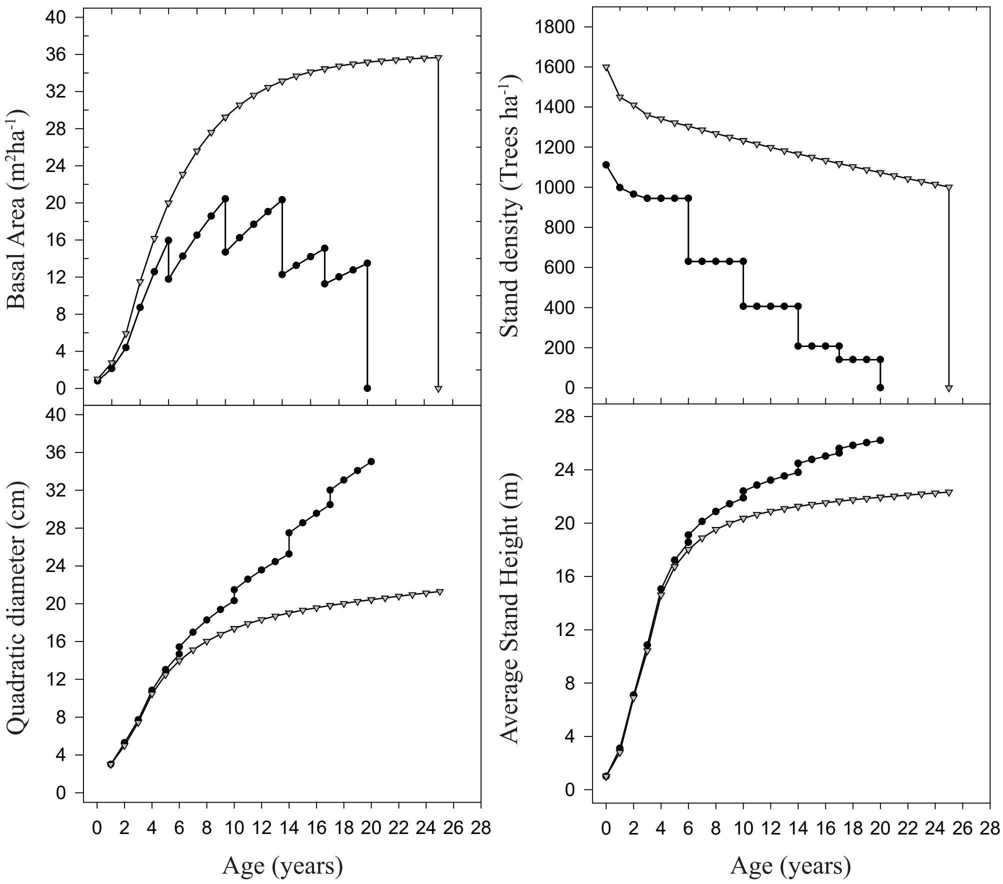

Figure 2. Stand basal area, density, quadratic diameter, and average height for the best management scenarios: Dotted line corresponds to the optimization criteria: Max $NPV^W + NPV^C$ (initial stand density = 1,111 trees ha^{-1}, *SQ* I, $R = 20$ yr., four thinnings ages 6, 10, 14 and 17 and thinning intensities 26 %, 28 %, 39 % and 25 % of stand basal area); triangles line corresponds to the optimization criteria Max NPV^C (initial stand density = 1,600 trees ha^{-1}, *SQ* I, $R = 25$ yr., No thinnings).

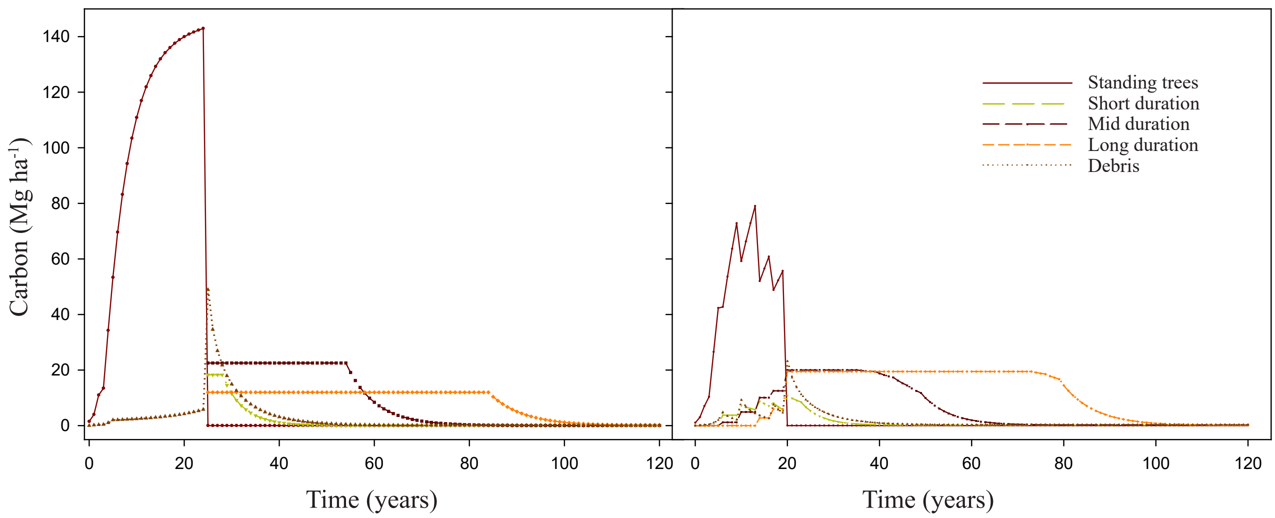

Figure 3. Carbon stored in standing trees, type of product and debris in a teak stand until 99.99 % has been released to the atmosphere. A) Carbon stored for the schedule that optimizes only the NPV^C (*SQ* I, initial stand density = 1,600 trees ha^{-1}, R= 25 yr., no-thinning). B) Schedule that optimizes NPV^W+NPV^C (*SQ* I, initial stand density = 1,111 trees ha^{-1}, R= 20 yr., four thinnings ages 6, 10, 14,17, and thinning intensities 26 %, 28 %, 39 %, and 25 % of stand basal area).

NPV, and thinning schedules were mainly affected by changes in the interest rate and the growth rate (Table 4).

Growth rate (g_r). The model was very sensible to variations in this parameter. In most scenarios, the optimal solution changes when g_r varies ±1%.

Harvest costs (Hc). Changes within the chosen range for this variable did not affect the thinning schedules; however, they caused changes in the *SEV* of about 100US\$ ha^{-1} for each change of ± 10% in harvest costs.

Interest rates (r). The optimal schedules were very sensitive to changes in *r*. For example, for r ≥ 12 %, the best schedule for *SQ* I, 1,111 trees ha^{-1}, *R* = 20 consisted of four thinnings. With r ≤ 8%, optimal solutions occur with only two thinnings, i.e., reduced interest rates favor lower number of thinnings. In addition the *SEV* increases sharply with lower *r*, e.g., from US\$ 14,452

Table 4. Sensitivity analysis from the simultaneous optimization of $NPV^W + NPV^C$ taking as basis the best scenario (*SQ* I, 1,111 trees ha^{-1}, *R* = 20 yr., and four thinnings: ages 6, 10, 14, 17 and intensities 26, 28, 39, and 25 % *G* (*r* =10%, C price = 10 US\$ Mg^{-1}C, timber prices vary with diameter class). The largest *SEV* for each variable are highlighted in grey.

Modified Variable	Value	Optimal Solution										
		Nt	*A1*	*I1*	*A2*	*I2*	*A3*	*I3*	*A4*	*I4*	*NPV*	*SEV*
r	5%	**2**	7	41	15	33	-	-	-		26,018	**41,755**
r	8%	2	7	35	16	44	-	-	-	-	15,340	19,530
r	12%	4	4	31	11	32	14	47	17	27	11,643	12,990
r	14%	4	4	46	10	25	13	33	16	50	6,641	7,162
g_r	0.1372 (-2%)	4	7	30	10	30	14	38	17	38	11,002	12,923
g_r	0.1386 (-1%)	3	7	27	12	33	15	45	-	-	11,812	13,874
g_r	0.1414 (+1%)	4	8	31	11	38	14	40	17	41	13,833	14,899
g_r	0.1428 (+2%)	4	3	31	9	29	13	30	16	50	14,523	**16,224**
Pt	Case 1 Table 1	4	4	38	9	27	13	28	17	42	5,331	6,262
Pt	Case 2 Table 1	3	5	30	9	26	14	50	-	-	8,872	10,421
Pt	Case 3 Table 1	**2**	7	34	16	55	-	-	-	-	13,169	**15,468**
C_{th}	7.12 (-50%)	4	6	26	10	28	14	40	17	25	12,875	**15,123**
C_{th}	8.54 (-40%)	4	6	26	10	28	14	40	17	25	12,793	15,026
C_{th}	9.97 (-30%)	4	6	26	10	28	14	40	17	25	12,709	14,928
C_{th}	11.39 (-20%)	4	6	26	10	28	14	40	17	25	12,627	14,831
C_{th}	12.82 (-10%)	4	6	26	10	28	14	40	17	25	12,543	14,628
C_{th}	15.66 (+10%)	4	6	26	10	28	14	40	17	25	12,378	14,539
C_{th}	17.01 (+20%)	4	6	26	10	28	14	40	17	25	12,299	14,447
C_{th}	18.51 (+30/%)	4	6	26	10	28	14	40	17	25	12,213	14,344
C_{th}	19.94 (+40%)	4	6	26	10	28	14	40	17	25	12,129	14,246
C_{th}	21.36 (+50%)	4	6	26	10	28	14	40	17	25	12,046	14,149
P_C	0	4	6	26	10	28	14	40	17	25	11,951	14,038
P_C	20	4	6	26	10	28	14	40	17	25	12,442	14,614
P_C	30	4	6	26	10	28	14	40	17	25	12,504	14,687
P_C	40	4	6	26	10	28	14	40	17	25	12,539	14,728
P_C	50	4	8	35	11	31	14	49	17	26	12,725	14,946
P_C	100	2	7	42	15	32	-	-	-	-	15,552	18,268
P_C	150	2	13	53	16	35	-	-	-	-	17,914	21,042
P_C	200	**2**	13	53	16	33	-	-	-	-	20,340	**23,892**

Base values: g_r: growth rate = 0.14, C_{th}: thinning and harvest cost = US\$ 14.24, *r*: interest rate = 10%, *Pc*: carbon price = US\$ 10, *Pt*: timber prices (Table 4), *Nt*: number of thinnings, A_i: Thinning age (yr.), I_i: Thinning intensity (% removed basal area), *NPV*: net present value (US\$ ha^{-1}), *SEV*: soil expectation value (US\$ ha^{-1}).

when r = 10 % to US$ 41,755 for *r* = 5%. Conversely, increments in *r*, decrease the *SEV,* but in a lower magnitude (Table 4).

Carbon prices (Cp). For C prices in the range 0 - 40 US$ MgC^{-1}, the optimal thinning schedules did not change and the *SEV* remained almost constant. Therefore, the timber prices determine the best thinning schedules, as they have the largest weight on the objective function. Above 40 $$MgC^{-1}$ the optimal solution changes by delaying the age and reducing the number or intensity of thinnings, and increasing the *SEV*.

Timber prices. Changing the relative prices among diameter categories changed the optimal solution by changing thinning number, ages, and intensities. When the difference in prices between the small and large diameter log was lower (Case 1 Table 1), the first thinning was done at earlier ages and greater intensity to produce monetary returns in the shortest time.

Discussion

Optimal thinning schedules

As expected, plantations growing on *SQ* I, other conditions fixed, had the highest *SEV*; but also, more thinnings were needed that in lower site qualities. In this case, greater initial stand densities and longer rotations also required greater thinning intensities. The sensitivity analysis showed that growth rate, interest rate, and timber price were the most influencing input variables to determine the best thinning schedules for each objective. Thus, focusing on a more precise estimation of these variables will increase the reliability of results. Also, for C prices 0-40 US$ MgC^{-1}, the best thinning schedule is the same, no matter how much C is stored, indicating that C sequestration is not essential for optimizing the thinning schedules, because its weight in the objective function is not significant as compared to the timber prices (53–400 US$ m^{-3}). Thus, the optimal management schedules obtained for timber production and carbon sequestration (Table 2) can be compared with those reported in the literature for planted teak. Overall, our results agree with projected results of Pérez & Kanninen (2005) who propose three to four thinnings, each removing 25 to 50% of trees for 20-30 yr. rotations. Also, results agree with executing a first intensive thinning (40-60%) at ages 3-6 yr. (Chaves & Chinchilla, 1986, Jerez & Coutinho, 2017). The *SEV* values are in agreement with those reported for teak in other studies considering the range of interest rates (c.f., Restrepo & Orrego, 2015).

For teak plantations, the objectives of maximizing timber production and carbon sequestration are in conflict because the thinning schedules that maximize financial gains from C sequestration reduce economic gains from timber and *vice-versa*. Nepal *et al.* (2012) found a similar behavior when analyzing the financial relations between timber production and C sequestration in stands of *Pinus taeda* L. and *Quercus pagoda* Raf. Other authors (e.g., Báckeus *et al.*, 2005, Keles & Baskent, 2007, Baskent *et al.*, 2008, Raymer *et al.*, 2009) found that when implementing management practices that increase C sequestration, the economic benefits from timber harvest decrease. In scenarios with economic incentives such as payments for environmental services, the best option is to choose schedules maximizing the joint *NPV*. In this case, NPV^C will be lower than when maximizing only for C sequestration, but NPV^W will be much higher, generating larger economic benefits, but keeping the environmental benefits of C fixation. Nölte *et al.* (2018) found a trade-off between C storage and economic return in planted teak in Costa Rica suggesting the need of creating economic incentives for increasing C sequestration that compensate for losses in timber production. For teak, with the current C assumed prices, carbon credits schemes such as those suggested by Báckeus *et al.* (2005) or Derwish *et al.* (2009) are insufficient because they represent only a small percentage (4-5% in our work) of the plantation total benefits.

The management schedule affects the C storage capacity of planted teak. Increasing rotation length, higher initial spacings, and fewer thinnings with lower intensity or no thinning, stored more C and generated larger benefits independently of site quality. These results agree with those from Nölte *et al.* (2018) for teak, and for other species (Liski *et al.*, 2001; Pussinen *et al.*, 2002; Kaipanen *et al.*, 2004; Diaz-Balteiro & Rodríguez, 2006). For poor growing, non-profitable plantations, C storage could be attractive provided that it is paid as an environmental service. In this case, the best schedule would be no-thinning and delayed final harvest to reduce carbon emissions. Similar findings were reported by Lopera & Gutiérrez (2001) for *Pinus patula*, and Pohjola & Valsta (2007) in *Pinus sylvestris*.

In the analysis of C flows for a stand along the rotation under the model assumptions and scenarios, the average annual rate of C sequestration varied between 3.1 and 4.8 MgC $ha^{-1}yr.^{-1}$ depending on the management schedule. These values agree with those reported for teak by the IPCC (1996), i.e., a mean annual increment of dry matter accumulation in planted forest equivalent to 8 MgC $ha^{-1}yr.^{-1}$ representing a fixation rate of 4 MgC $ha^{-1}yr.^{-1}$. Also, they agree with those of Brown *et al.*

(1986), who estimated a potential C fixation between 2.7 and 9.6 MgC ha^{-1}yr.$^{-1}$for tropical plantations.

For a 20-yr. rotation, the model estimated between 55.7 and 77.0 MgC ha^{-1} of C stored in standing trees depending on the thinning schedule and site quality. For a 25-yr. rotation this value fluctuated between 67.2 and 87.1 MgC ha^{-1}. Nölte *et al.* (2018) estimated between 76.9 MgC ha^{-1} and 89.5 MgC ha^{-1} for stands harvested at ages 20-25 respectively. Observed differences with our results are due mainly to the thinning schedule chosen by these authors (4, 8, 12, 18, and 24 yr. with remaining trees of 556, 333, 200, 150, and 120 trees ha^{-1} and initial stocking of 1111 trees ha^{-1}) which differ from schedules generated by our model.

When the only objective was maximizing NPV^C (*SQ* I, 1,600 trees ha^{-1}, R = 25 yr., and no-thinning), the mean annual carbon storage increased at a rate of 5.7 MgC ha^{-1}yr^{-1}, and the amount of C stored in standing trees at final cut was 143 MgC ha^{-1}. This result agrees with those of Kraenzel *et al.* (2003) for unthinned planted teak in Panamá (100-141 MgC ha^{-1}). It is important to notice that for the scenario that optimized NPV^W +NPV^C a larger amount of C than for the scenario NPV^C remained stored until 80 years because it was contained in long duration products.

The sensitivity analysis showed that optimal schedules and *SEV* are very sensible to interest rates (Table 4). Lower r (5-8 %) increased sharply the *SEV* and reduced the number of thinnings from four moderate thinnings to two more intensive thinnings. On the other hand, increases of r to 12 -14%, decreased *SEV*, but maintained the schedule of four thinnings, although the first one changed from age 6 to age 4. Increased growth rate increased *SEV*, although its effect in thinning schedules appears to be erratic, e.g., increasing g_r by 2 % reduced the age of the first thinning to age 3; with an intensive thinning of 50 % intensity at age 16. On the other hand, reducing g_r by 1% reduced the number of thinnings to three. Changing the relative timber prices also affected optimal schedules and *SEV*. Paying a high price for larger logs in relation to smaller logs changed from four moderate thinnings to two intensive thinnings. Harvest and transport costs did not affect the original thinning schedules. Finally, C prices only began to affect the schedules when the prices were above US$ 40.

According to the above arguments, our model generates reasonable and consistent results under the imposed assumptions and constraints, making it useful for analyzing the potential of planted teak forest for storing C in biomass during and after the harvest as long duration forest products, as well as analyzing the effect of thinning schedules and rotation age for timber and C sequestration.

Additional economic benefits to timber production can be obtained by accounting for C sequestration in teak plantations without substantial changes in the optimal schedules that maximize NPV^W. In contrast, if the main objective was to maximize the benefits from C sequestration, moderate, infrequent, and late thinnings will be needed to reduce emissions. This leads to a much lower total *SEV* however, than that obtained by optimizing timber production. In scenarios with very low interest rates, long rotation (60-80 yr.) looking for very high quality veneer, and with an active market for carbon, this option could be attractive. If considering successive rotations on the same area for producing large duration solid timber products, teak plantations can become an efficient long-term system of C storage.

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