



Economic potential and management of tropical mixed-species plantations in Central America

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Abstract

Tropical forest plantations play an important role in meeting global wood demand. While research has highlighted the ecological potential of mixed-species plantations, studies on the economic viability and management of such plantations are largely missing in the context of tropical plantation forestry. In this study, we estimated the economic potential and optimized the management of commercial mixed-species plantations of four tree species native to Central America (*Dalbergia retusa*, *Dipteryx oleifera*, *Hieronyma alchorneoides*, and *Vochysia guatemalensis*) and Teak (*Tectona grandis*). We combined the forest growth model *3-PGmix* and detailed economic data for two plantation sites in Costa Rica to optimize the management of 11 different mixtures using a genetic optimization algorithm. We found that several of the modeled mixed-species stands can be highly profitable with net present values (NPV) up to 4821.2 USD/ha at an 8% discount rate, and internal rates of return up to 17% (under excellent site conditions). This indicates that the most profitable mixtures (e.g. of *V. guatemalensis*-*D. oleifera* or *T. grandis*-*D. oleifera* on excellent sites) could compete economically with conventional monoculture plantations such as Teak monocultures. Further, mixed stands can be managed based on the same simple even-aged management approaches currently applied in monoculture plantations if the specific management parameters are adapted. The optimized management parameters also lead to improved NPV of the modeled stands under alternative valuation assumptions but are site-specific. In the present study, we only considered financial benefits from timber production. However, establishing mixed-species plantations in the tropics could provide a wide range of ecosystem services including climate change mitigation and biodiversity protection.

Keywords Reforestation · Close-to-nature forestry · Native species · Forest management · Forest economics · 3-PG

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Introduction

Tropical forest plantations play a disproportionately important role in supplying the world with wood products. In the tropics, forest plantations cover only 3% (131 million ha) of the total forested area but recently produced 46.3% of the total global and 63.7% of the tropical supply of industrial roundwood (FAO 2020; Jürgensen et al. 2014; Payn et al. 2015).

Tropical forest plantations are dominated by a handful of tree species grown in monocultures, including species of *Eucalyptus spp.*, *Acacia spp.*, *Pinus spp.*, and *Tectona grandis*, while mixed-species plantations are restricted almost exclusively to forest plantations planted for ecological restoration or protective purposes (Gunter et al. 2013; Pancel and Köhl 2016). This is despite the fact, that researchers have repeatedly highlighted the possible silvicultural benefits of mixed-species plantations, such as increased productivity and reduced overall risk (Kelty 2006; Knoke et al. 2008; Liu et al. 2018; Messier et al. 2021). Several studies have shown that some tropical mixed-species plantations can potentially achieve higher stand productivity than their monoculture peers, if species are carefully selected (Ewel et al. 2015; Le et al. 2020; Mayoral et al. 2017; Piotto 2008; Schnabel et al. 2019). Some rare economic studies for tropical mixed-species plantations concluded that mixed-species plantations could achieve IRR between 7.37 and 15.64% in Costa Rica (Piotto et al. 2010; Streed et al. 2006). Most recently, Sinacore et al. (2022) estimated mixed-species reforestation with (partly) native tree species to yield IRR between 4 and 8% in Panama, with mixed-species stands partly outperforming their monoculture peers. Meanwhile, Trujillo-Miranda et al. (2021) found that mixed-species reforestations in Mexico would not be economically viable at any interest rate without receiving subsidies, while monocultures were viable at low interest rates (< 4%).

Despite the apparent silvicultural and economic potential of mixed-species forest plantations, the uptake by forest plantation practitioners has been limited. The present preference towards monoculture forest plantations might be driven by the simplicity of managing monoculture systems, a lack of management recommendations for mixed-species plantations, perceived higher costs of mixed-species plantations, the hesitance of giving up monoculture plantation systems with a long-proven track record of attractive financial returns, and the use of simplified economic models that are favorably biased towards monoculture plantations (Knoke et al. 2008; Nichols et al. 2006). So far, the aforementioned economic studies offer little insight and guidance into how tropical mixed-species forest plantations should be managed.

In this study, we aim to address several of these barriers to mixed-species plantations by (1) *determining the economic potential of tropical mixed-species plantations*, (2) *optimizing plantation management regimes of mixed-species plantations*, (3) *determining whether forest management practices currently applied in monoculture plantations can be applied to mixed-species plantations*, and (4) *exploring the sensitivity of optimized management regimes and their associated economic potential to valuation assumptions, and other management constraints*. To meet these research objectives, we will pursue a simulation–optimization approach. Simulation–optimization approaches are widely used to solve forest modeling problems in plantation forestry related to, for example, stand establishment, thinning, and harvesting (e.g. Jayaraman and Rugmini (2008); Jin et al. (2017); Mabvurira and Pukkala (2002); Seppänen and Mäkinen (2020)). A central part of this approach is the prediction of the effects of different silvicultural treatments through simulation, and evaluation according to the management objectives.

Just recently, Nölte et al. (2022) published a forest growth model for 5 tropical tree species in Central America. The model allows for full-rotation growth predictions of single- and mixed-species stands under varying site and climatic conditions and hence allows for the management optimization of complex mixed-species plantation systems.

Methods

To apply the simulation–optimization approach we constructed a forest economic model that can simulate the economic performance of tropical mixed-species plantations under different silvicultural treatments. We then used this model to optimize stand management. Our study was based on two plantation sites in Costa Rica and five tree species grown in mixed-species stands. This study was performed using R (R Core Team 2019).

Case study: Mixed-species plantations in Costa Rica

In the twentieth century, Costa Rica experienced a sharp decrease in forest cover from above 60% before 1960 to below 30% by the 1980s (Kleinn et al. 2002). Since then the forest cover has rebounded (FAO 2020). While only 1–2% of the land is covered by forest plantations, 75% of the harvested wood (407,046 m³ in 2014) was derived from forest plantations of mainly *T. grandis* and *Gmelina arborea* monocultures (Barrantes Rodríguez and Ugalde Alfaro 2019; REDD/CCAD-GIZ-SINAC 2015; SIREFOR 2016).

Study sites and tree species

We conducted our analysis for two sites in northern Costa Rica. The first site, “Las Delicias” is characterized by tropical moist forest conditions according to the Holdridge Life Zone System (Kohlmann et al. 2007) with an average of 2221 mm/m² precipitation yearly, mean temperatures ranging between 21 and 35 °C and a pronounced dry period (Fig. 1). The second site, “La Virgen”, is characterized by tropical wet forest conditions with a yearly precipitation of 3549 mm/m², mean temperatures between 20 and 32 °C, and no pronounced dry period. Both sites have previously been used as cattle pastures and partly

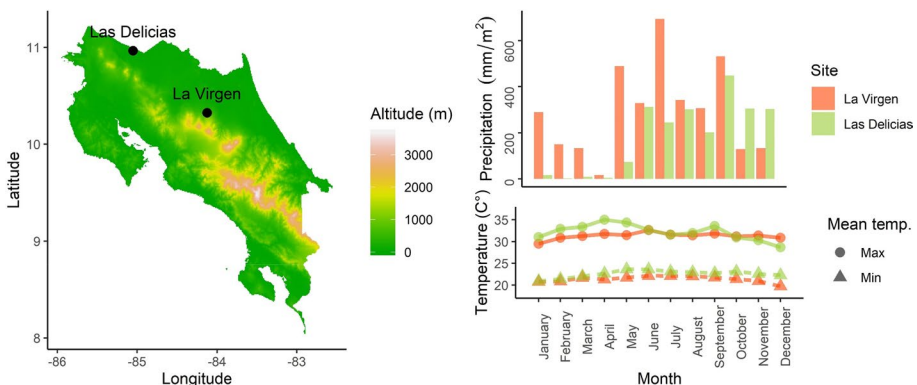


Fig. 1 Study sites and climate in Costa Rica

reforested with mixed-species stands of two or three species. In the mixtures, fast-growing pioneer species are mixed tree-by-tree with intermediate and/or slow-growing species, or intermediate species are mixed with slow-growing species. We selected *V. guatemalensis*, *H. alchorneoides*, *D. oleifera*, *Dalbergia retusa*, and *T. grandis* as our study species. *V. guatemalensis*, *H. alchorneoides*, *D. oleifera*, and *D. retusa* are native species that are currently important timber species in the region or have been so in the past, and have been considered promising species for commercial native species plantation forestry (Cordero 2003a, 2003b, 2003c; Murillo 2018; González J 2018; SIREFOR 2021). We included *T. grandis* as it is the most common plantation-grown species in the region (SIREFOR 2021).

Forest economic model

The forest economic model roughly consists of four parts: forest growth modeling, timber valuation, cost and subsidies estimation, and economic performance evaluation. Figure 2 shows an overview of the model components and data flows. A detailed description of our forest economic model can be found in Supplementary Information (SI) 1.

Forest growth model

For our forest growth model, we used 3-PGmix. 3-PGmix is an extension of the 3-PG model (Physiological Principles Predicting Growth) developed by Waring and Landsberg (1997). While the original 3-PG model allows for growth predictions of single-species stands, the 3-PGmix model by Forrester and Tang (2016) was modified to allow for growth predictions of mixed-species stands through vertical and horizontal differentiation in the canopy. 3-PG calculates the total carbon fixed from absorbed photosynthetically active radiation, corrected for mediating effects from soil and climatic conditions, and stand age. To predict the growth of our species of interest we used the 3-PGmix parameters published by Nölte et al. (2022).

By default, the 3-PGmix model can make predictions for one rotation (i.e. planting to harvesting), and management options are limited to pre-determined age-based thinning and harvesting. We extended the management options to include basal area-based thinning, and target mean dbh (diameter at breast height) harvesting. Furthermore, we allowed for the replanting of trees after harvesting to model multiple rotations.

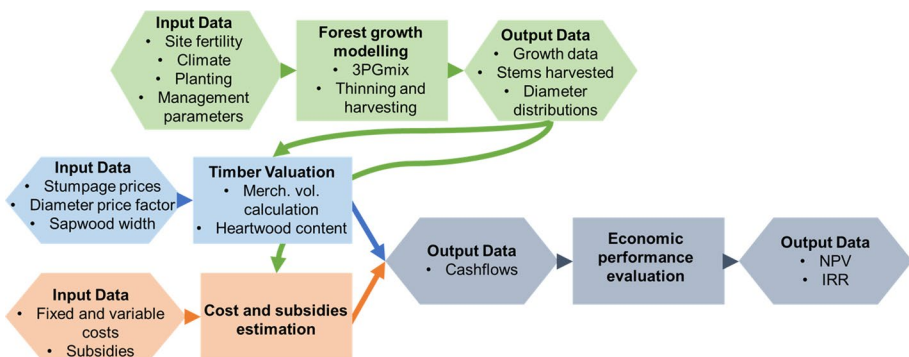


Fig. 2 Overview of the modelling components, data, and data flows in the forest economic model. Bullet points give examples of the most important modelling steps and data in the different model components

Basal area-based thinning is initiated when the modeled stand basal area (BA) exceeds a specified BA thinning threshold. The modeled stand is then thinned to a target BA. In modeled mixed-species stands, the species with the largest species-level BA is targeted for thinning. Target mean dbh harvesting is initiated when the species-level modeled mean dbh exceeds a set target dbh.

We included the option to replant harvested trees either after the modeled stand is clear-cut or underplanting trees under the remaining stand. Underplanting of harvested species was integrated by applying a stand density threshold for underplanting based on the relative spacing of the remaining stand. When the remaining modeled stand's relative spacing after the harvest of a tree species is higher than the applied underplanting threshold (i.e. the stand density is lower) the species is replanted. Otherwise, the replanting is postponed and reevaluated at the next management intervention. We assume that the trees are pruned to a stem height of 2.5 m, 5 m, and 8 m when the tree heights exceed 5 m, 10 m, and 12 m (Pérez et al. 2003).

Timber valuation

For the timber valuation, we first calculated the merchantable volume based on the modeled volume of the harvested trees. In Costa Rica, the commercial stem height of plantation trees is usually 7 m and stems are usually sold in two sections of 3.5 m, each with a minimum diameter of 10 cm. We assumed a bark thickness of 1 cm (Berrocal et al. 2018). We applied a Weibull distribution to convert the mean dbh from the 3-PGmix output into a diameter distribution (see SI 2). For each diameter class, we calculated merchantable volume up to a stem height of 7 m. If the lower diameter of the stem pieces was below 10 cm, or if the stem pieces were not pruned we did not consider them to be merchantable.

We used the most recent timber prices reported by the Costa Rican Oficina Nacional Forestal (ONF) and local price reports (Banco Central de Costa Rica 2021; Barrantes Rodríguez and Ugalde Alfaro 2020; Dario Extra 2014; Forda.com 2016; Robbins 2012; Vega and Chaves 2011; World Bank 2021a).

A majority of wood harvested Costa Rica is used for pallets (47%), construction (21%), or exported as roundwood or pallets (22%) (Barrantes Rodríguez and Ugalde Alfaro 2019). In the official price reports, timber is graded by stem diameter (for roundwood), and – in some instances – by origin (plantation or natural forest) (Barrantes Rodríguez and Ugalde Alfaro 2020). Timber prices are mainly influenced by two important quality characteristics: (1) stem diameter, and (2) stem heartwood content (Barrantes Rodríguez and Ugalde Alfaro 2020; Pérez and Kanninen 2005, 2003). For each modeled stem piece, we incorporated price corrections to address these quality characteristics. A detailed description of the timber valuation process and price corrections can be found in SI 1.

Costs and subsidies

We retrieved establishment and management costs from Vallejos (2019). The detailed cost data originate from 12 mid-size to large Costa Rican plantation forest enterprises and were collected from 2008 until today (Guevara-Bonilla 2011; Guevara-Bonilla and Murillo 2021). We applied fertilization and weeding costs in the first 5 years after planting. Costs for tilling and fertilization during stand establishment were only applied during the first rotation. As the modeled stems are sold standing, we only applied costs for tree selection and marking during harvesting. Finally, we assumed that the value of the modeled wood

harvested must exceed 1000 USD/ha at stumpage for the operation to be profitable for the harvesting company. If this minimum threshold was not met, the difference was added as a harvesting cost.

Finally, we applied species-dependent reforestation subsidies offered by the state during the first 5 years of the forest establishment between a total sum of 1239.2–2096 USD/ha (MINAE 2020). A detailed overview of all costs and subsidies can be found in SI 1.

Economic performance

Based on the cashflows of the modeled stands, we calculated the net present value (NPV) for one planning period of 80 years (i.e. 2020–2100). We used a discount rate of 8% (Cubbage et al. 2020, 2007). NPV is the sum of the discounted cash flows of an asset with a definite planning horizon. We also calculated the IRR. IRR is the discount rate at which the NPV is 0 and is commonly used to communicate the economic performance of forest assets. We calculated NPV using Eq. 1. IRR was determined using the R package “*jrvFinance*” (Varma, 2021).

$$NPV = \sum_{t=0}^T \frac{R_t - C_t}{(1 + r)^t} \quad (1)$$

where T is the total number of simulation periods (in years), R_t and C_t are all revenues and costs USD/ha) occurring in each simulation period t , and r is the discount rate.

Baseline scenarios for optimization

Planting schemes

We simulated the study species grown in mixed-species stands. The modeled stands were planted at 800 stems/ha, where up to three species of different growth characteristics are mixed within a single modeled stand. An overview of the planting schemes modeled on each site can be found in Table 1. *T. grandis* and *D. retusa* need a seasonal dry period to thrive and were hence not planted in La Virgen.

Site fertility

In 3-PG, site quality is represented in terms of the Fertility Rating (FR) parameter. FR is a relative measure of a site’s species-specific productivity adjusted for soil water and climatic growth influences. For our selected species, site preferences are still partly poorly understood, and sensible generalized site fertility scenarios challenging to formulate. Therefore, we used the species-specific FR model-fitted for our study sites by Nölte et al. (2022) (Table 2). Nölte et al. (2022) included FR as a parameter to be determined during the model calibration, i.e. FR was determined such, that the modeled growth data best fitted the observed data on the study sites. Similar approaches were applied in e.g. Forrester and Tang (2016) and Gonzalez-Benecke et al. (2014). It should be noted, that 3-PG growth predictions are highly sensitive to the chosen FR. We will address this issue further in the discussion.

Table 1 Planting schemes for the mixed-species stands. Stands modelled are marked with X

Species combination ^a	Initial planting density <i>Trees/ha</i>	Study sites	
		Las Delicias	La Virgen
<i>T. grandis</i> - <i>D. retusa</i>	400–400	X	
<i>T. grandis</i> - <i>D. oleifera</i>	400–400	X	
<i>V. guatemalensis</i> - <i>D. oleifera</i>	400–400	X	X
<i>V. guatemalensis</i> - <i>H. alchorneoides</i>	400–400	X	X
<i>V. guatemalensis</i> - <i>D. retusa</i>	400–400	X	
<i>V. guatemalensis</i> - <i>D. oleifera</i> - <i>D. retusa</i>	400–200-200	X	
<i>V. guatemalensis</i> - <i>H. alchorneoides</i> - <i>D. retusa</i>	400–200-200	X	
<i>V. guatemalensis</i> - <i>H. alchorneoides</i> - <i>D. oleifera</i>	400–200-200	X	X
<i>H. alchorneoides</i> - <i>D. oleifera</i>	400–400	X	X
<i>H. alchorneoides</i> - <i>D. retusa</i>	400–400	X	
<i>D. oleifera</i> - <i>D. retusa</i>	400–400	X	

^a*V. guatemalensis* is here considered a fast-growing pioneer species, *H. alchorneoides* and *T. grandis* are considered intermediate species, while *D. oleifera* and *D. retusa* are considered slow-growing and partly shade tolerant species

Table 2 Model-fitted fertility ratings from Nölte et al. (2022)

Study site	Fertility rating				
	<i>V. guatemalensis</i>	<i>D. oleifera</i>	<i>D. retusa</i>	<i>T. grandis</i>	<i>H. alchorneoides</i>
Las Delicias	0.402	1.338	0.567	1	0.478
La Virgen	0.376	1.149			0.379

Baseline management scenarios

To assess whether our optimization leads to improved performance we formulated 4 baseline management scenarios (Table 3) by reviewing recent literature on the management of tropical timber plantations (Griess and Knoke 2011; Ladrach 2004; Nölte et al. 2018; Onyekwelu et al. 2011; Pérez and Kanninen 2005). In two of the management scenarios, we applied age-based thinning and harvesting, while we applied basal area-based thinning in the other two.

Management optimization

We aimed to determine the thinning and harvesting regimes that offer the highest NPV. We optimized the modeled stand NPV based on two different thinning and harvesting approaches: (1) an age-based approach, and (2) an approach based on stand growth performance. In the age-based approach, we optimized thinning ages and stem numbers, and optimal harvesting ages. We allowed for 3 thinnings in mixed-species stands of two species, and 4 thinnings in mixed-species stands of three species (Eq. 2). In the second approach, we optimized the upper BA threshold for thinning, the target BA after thinning, and the

Table 3 Overview of the 4 alternative baseline management scenarios

Management scenario	Thinning	3-species mixtures	Harvesting
(1) Age-based thinning, moderate	Fast-growing species thinned to 300 and 200 stems/ha age 3 and 5. Intermediate species thinned to 300 and 200 stems/ha age 12 and 20	Fast-growing species thinned to 300 and 200 stems/ha age 3 and 5. Intermediate species and slow-growing species thinned to 150 stems/ha at age 12 and 20 respectively	<i>V. guatemalensis</i> is harvested at age 12, <i>H. alchorneoides</i> and <i>T. grandis</i> at age 20, and <i>D. oleifera</i> and <i>D. retusa</i> at age 40
(2) Age-based thinning, intensive	Fast-growing, intermediate, and slow-growing species thinned to 250 and 150 stems/ha at age 3 and 5, 5 and 12, and 12 and 20 respectively	Fast-growing species thinned to 250 and 150 stems/ha age 3 and 5. Intermediate species and slow-growing species thinned to 150 stems/ha at age 12 and 20 respectively	<i>V. guatemalensis</i> is harvested at age 8, <i>H. alchorneoides</i> and <i>T. grandis</i> at age 16, and <i>D. oleifera</i> and <i>D. retusa</i> at age 35
(3) BA-based thinning, moderate	When the stand-level BA exceeds 25 m ² /ha the stand is thinned to 15 m ² /ha		As management scenario 1
(4) BA-based thinning, intensive	When the stand-level BA exceeds 15 m ² /ha the stand is thinned to 9 m ² /ha		As management scenario 2

target mean dbh for harvesting (Eq. 3). We further included the stand density threshold for underplanting as a parameter for optimization.

$$\max z = NPV_{TA,TS,HA,RS} \quad (2)$$

where TA is the applied thinning ages, TS is the applied number of stems remaining after thinning, HA is the applied harvesting ages, and RS is the applied relative spacing threshold for underplanting.

$$\max z = NPV_{BA1,BA2,TD,RS} \quad (3)$$

where $BA1$ is the applied upper basal area threshold to initiate thinning, $BA2$ is the applied target basal area after thinning, TD is the applied target mean dbh.

We relied on a genetic optimization algorithm using Differential Evolution (Mullen et al. 2011). A detailed description of the optimization and the applied parameter bounds can be found in SI 1. We ran the optimization for each scenario with 100 iterations.

Sensitivity analysis

To assess whether the optimized management parameters lead to improvements compared to the baseline management scenarios under alternative valuation and site assumptions we applied 7 alternative sensitivity scenarios (Table 4).

Further, to maintain the mixed-species character of the modeled stands we introduced a revenue share constraint. The constraint prescribes that each species must contribute a certain minimum percentage of the modeled stand-level discounted revenues from timber sales. We applied the three different constraint scenarios so that each species in a mixture contributes at least 5%, 10%, and 20% of the discounted revenue from timber sales. The constraint ensures that at least some trees of all species reach merchantable sizes. We reran the optimization under the application of the revenue share constraints.

Results

We ran optimizations to find management parameters for thinning and harvesting that would maximize the economic performance of the studied planting schemes. We applied both an age-based management approach and a management approach based on growth performance (i.e. BA and dbh).

Economic performance and productivity

First, we found that all mixtures except *H. alchorneoides*-*D. retusa* were economically viable under optimized management on our two study sites at a discount rate of 8%. The most profitable mixtures could support required rates of return above 15%.

Figure 3 shows (A) the discounted cash flows and NPV for the studied mixed-species plantations when applying the optimized growth performance-based management parameters (see also Tables 5 and 6), (B) the mean annual increments (MAI) of stem biomass, and (C) merchantable stem volume. The performance outcomes under optimized age-based management were largely similar (but slightly lower in pairwise comparison) and can be found in SI 3.

Table 4 overview of the varying valuation and site key assumptions applied in the robustness scenarios

Sensitivity analysis scenarios	Key assumptions	
	Valuation	Site
<i>MAIN</i> ^a	<ul style="list-style-type: none"> • Discount rate 8% • Sapwood width 8 cm • Lower 7 m of stem utilized only • Costs for Costa Rica 	<ul style="list-style-type: none"> • Model tuned site fertilities
<i>V.LIST</i>	<i>As MAIN except:</i> <ul style="list-style-type: none"> • No heartwood correction 	<i>As MAIN</i>
<i>V.OPTI</i>	<i>As MAIN except:</i> <ul style="list-style-type: none"> • Sapwood width 4 cm • Whole stem utilized • Costs for Central America exempt Costa Rica^b 	<i>As MAIN</i>
<i>V.PESS</i>	<i>As MAIN except:</i> <ul style="list-style-type: none"> • Sapwood width 12 cm 	<i>As MAIN</i>
<i>DISC6</i>	<i>As MAIN except:</i> <ul style="list-style-type: none"> • Discount rate 6% 	<i>As MAIN</i>
<i>DISC15</i>	<i>As MAIN except:</i> <ul style="list-style-type: none"> • Discount rate 15% 	<i>As MAIN</i>
<i>FR.MED</i>	<i>As MAIN</i>	<ul style="list-style-type: none"> • Generic median site fertilities (Fertility Rating of 0.5)
<i>FR.HIGH</i>	<i>As MAIN</i>	<ul style="list-style-type: none"> • Generic high site fertilities (Fertility Rating of 0.9)

^aThe robustness scenario “MAIN” reflects the valuation and site assumptions applied in the main text and management optimization

^bCosts corrected correcting for purchasing power parity of other Central American countries (World Bank, 2021b)

On average an NPV of 2640.1 USD/ha was achieved across all mixtures. The mixture of *V. guatemalensis*-*D. oleifera* (4821.2 USD/ha and 3433.4 USD/ha) shows the highest NPV of all mixtures in La Virgen and Las Delicias respectively. IRR varied between 4.7 and 16.7%.

Most mixtures accumulated stem biomass and merchantable volume at a rate of 10–15 tons/ha/year and 4–22 m³/ha/year respectively. In Figs. 2B and C it is evident that under (unconstrained) optimized management a single species could dominate the mixed stands in terms of biomass and volume, effectively transforming the modeled stands into single-species stands.

Optimized management parameters

Secondly, we found that the optimized management parameters varied strongly between the different mixtures. Generally, under optimized management, the mixed stands were managed in conventional rotations of even-aged trees (i.e. no underplanting takes place). The modeled stands were kept below a BA of 16–31 m²/ha, with higher stand densities in stands where *V. guatemalensis* is dominant, and lower stand densities in mixtures with *D. oleifera* and *T. grandis* (Tables 5 and 6). Between 150–300 trees/ha of each species are

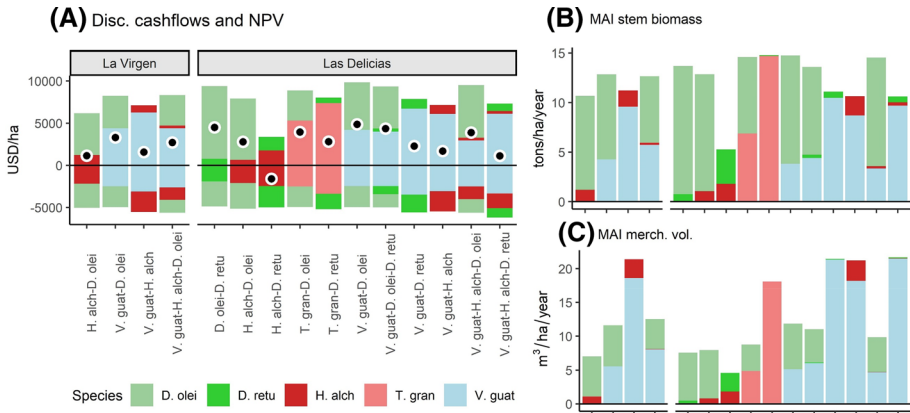


Fig. 3 Economic and productivity performance of the modeled mixed-species stands when the optimized BA thinning thresholds and target diameters are applied. A) shows the total discounted cash flows where bars above the zero-line show total discounted revenues and bars below the zero-line show total discounted costs for each species. The values for the individual species are stacked to show stand-level performance. The dots on A) indicate the stand-level NPV achieved under optimized management. Figures B) and C) show the MAI for stem biomass and merchantable timber volume. The x-axis on all three figures are identical. The first 4 stands from the left are modeled for the site “La Virgen” while the remainder are modeled for “Las Delicias”. *D. olei*, *D. retu*, *H. alch*, *T. gran*, and *V. guat* refers to the species *D. oleifera*, *D. retusa*, *H. alchorneoides*, *T. grandis*, and *V. guatemalensis* respectively

maintained until the end harvest is reached. Due to space constraints, we report the optimized age-based parameters for age-based thinning and harvesting in SI 3.

Thinning

When examining the BA thinning thresholds roughly 5 distinguishable thinning schemes emerged: (1) in mixtures where *D. oleifera* was dominant (i.e. when mixed with *D. retusa* or *H. alchorneoides*) thinning was initiated when the modeled stand-level BA exceeded 16.1–18.8 m²/ha and the modeled stand was thinned to 14–16.5 m²/ha (i.e. BA of the dominant species was lowered by 1.8–2.3 m²/ha during thinning); (2) in mixtures where *V. guatemalensis* was dominant (i.e. when mixed with *D. retusa* and/or *H. alchorneoides*) thinning was initiated when stand-level BA exceeded 28.1–30.6 m²/ha and the stand was thinned to 23.3–27.1 m²/ha (i.e. BA of the dominant species was lowered by 3.5–5.3 m²/ha); (3) when *V. guatemalensis* occurred in a mixture with *D. oleifera* the stand was thinned from 19.9–23.9 to 13.4–19 m²/ha (4.8–6.5 m²/ha of the dominant species were removed); (4) when *T. grandis* was mixed with *D. oleifera* the stand was thinned from 18.6 m²/ha to 13.2 m²/ha, and (5) when *T. grandis* was mixed with *D. retusa* the stand was thinned from 22.9 to 17.1 m²/ha.

Harvesting

Target mean dbh varied between 13.1 and 54.8 cm for *D. retusa*, 25.7–35.1 cm for *D. oleifera*, 10.1–23 cm for *H. alchorneoides*, 34.6–36.9 cm for *T. grandis*, and 36.2–43.8 cm for *V. guatemalensis*. However, it should be noted, that the large target mean dbh around 50 cm or higher for *D. retusa* was the result of high competition-related mortality (in 3-PG small

Table 5 Optimized BA thinning thresholds, target mean dbh, stand density thresholds for underplanting at Las Delicias

Mixture ^a	BA thinning thresholds		Target mean dbh ^b			Min. RS to underplant ^c	NPV (IRR) USD/ha (%)
	Upper threshold m ² /ha	Target BA	Sp.1				
			Sp.1 cm (age)	Sp.2	Sp.3		
Sp.1-Sp.2-Sp.3							
<i>D. olei-D. retu</i>	18.8	16.5	34.1 (21–26)	14.5 (51)		0.15	4405.3 (14.3%)
<i>H. alch-D. olei</i>	17.9	16.1	13.9 (5)	35.1 (24–25)			2802.7 (11.8%)
<i>H. alch-D. retu</i>	16.1	8.6	23 (12–14)	20.6 (38–41)			-1632.9 (4.7%)
<i>T. gran-D. olei</i>	18.6	13.2	36.9 (13)	28.9 (29–30)			4081.8 (15.7%)
<i>T. gran-D. retu</i>	22.3	17.1	34.6 (15–16)	15.2 (15–16)		3.96	2984.2 (13.1%)
<i>V. guat-D. olei</i>	20.7	15.2	40.2 (10–11)	30.5 (25–26)			4821.2 (16.7%)
<i>V. guat-D. retu</i>	30.6	27.1	36.2 (11–15)	54.8 (16–20)		2.12	2268.3 (12.9%)
<i>V. guat-H. alch</i>	28.4	23.3	43.5 (13–17)	16.1 (15–17)		0.26	1717.5 (12.3%)
<i>V. guat-D. olei-D. retu</i>	19.9	13.4	38.7 (10–11)	32.7 (22–24)	13.1 (53–53)	0.59	4331.5 (15.7%)
<i>V. guat-H. alch-D. olei</i>	20	13.3	36 (11–12)	10.1 (3)	33.7 (20–21)		3868.3 (13.5%)
<i>V. guat-H. alch-D. retu</i>	29.5	24.2	36.7 (12–16)	10.1 (3–4)	46.1 (18–22)	1.93	1147.2 (10.3%)

^a*D. olei*, *D. retu*, *H. alch*, *T. gran*, and *V. guat* refers to the species *D. oleifera*, *D. retusa*, *H. alchomeoides*, *T. grandis*, and *V. guatemalensis* respectively.

^bThe age range at which the target mean dbh is reached is given in brackets

^cStand density thresholds for underplanting are based on relative spacing. If the stand relative spacing is below the threshold (i.e. stand density is higher) underplanting is not performed. Missing values indicate no underplanting occurred under optimized management

Table 6 Optimized BA thinning thresholds, target mean dbh, stand density threshold for underplanting at La Virgen

Mixture ^a	BA thinning thresholds		Target mean dbh ^b			Min. RS to underplant ^c	NPV (IRR)
	Upper threshold	Target BA	Sp.1	Sp.2	Sp.3		
Sp.1-Sp.2-Sp.3	<i>m</i> ² / <i>ha</i>		<i>cm (age)</i>				<i>USD/ha (%)</i>
<i>H. alch-D. olei</i>	16.1	14	16.1 (7–8)	32.3 (26–27)			1104.3 (9.9%)
<i>V. guat-D. olei</i>	21.4	16.3	42 (11–12)	25.7 (25–26)			3433.4 (15.3%)
<i>V. guat-H. alch</i>	28.1	23.8	39.3 (12–14)	14.7 (14–15)		0.25	1579.5 (12%)
<i>V. guat-H. alch-D. olei</i>	24.6	20	39 (12–13)	10 (4)	27.5 (21–23)		2688.7 (12.7%)

^a*D. olei*, *D. retu*, *H. alch*, *T. gran*, and *V. guat* refers to the species *D. oleifera*, *D. retusa*, *H. alchormeooides*, *T. grandis*, and *V. guatemalensis* respectively

^bThe age range at which the target mean dbh is reached is given in brackets

^cStand density thresholds for underplanting are based on relative spacing. If the stand relative spacing is below the threshold (i.e. stand density is higher) underplanting is not performed. Missing values indicate no underplanting occurred under optimized management

trees die first). As competition-related mortality removed individuals from the lower part of the diameter distribution, the mean dbh was shifted upwards.

Underplanting

Underplanting occurred in 7 of the 15 optimized mixtures. The minimum relative spacing threshold for underplanting varies between 0.15 and 3.96. For reference, with a minimum relative spacing threshold of 1, the mean tree height of the remaining stand cannot exceed 7 m if the stocking is above 200 tree/ha, or 14 m if the stocking is above 50 tree/ha. Accordingly, underplanting was likely to occur when only *D. retusa* remains in a stand (*D. retusa* generally showed a slow height growth and low maximum height), or in mixtures of *V. guatemalensis*-*H. alchorneoides*. Otherwise, replanting only occurred after clear-cut events.

Improvements and sensitivity analysis

Finally, we found that applying the optimized management parameters lead to improvements in the economic performance of all mixtures compared to the best-performing baseline management scenarios (under sensitivity scenario “*MAIN*”) (Fig. 4). The optimized management parameters also lead to improvements in NPV in all valuation scenarios except *H. alchorneoides*-*D. retusa* under “*V.LIST*”. However, when alternative site fertility ratings were applied the optimized management parameters did not consistently improve the economic performance.

Maintaining the mixed-species character of stands

When enforcing a minimum revenue share of each admixed species, the economic performance decreased consistently for all mixtures (Fig. 5). On average, increasing a species' minimum revenue share by 1 percentage point decreased the stand-level NPV 119 USD/ha.

Discussion

In this study, we aimed to determine the economic potential and optimized management of mixed-species plantations in the tropics based on a case study in Costa Rica. To our knowledge, we are the first to combine detailed economic and operational data with a process-based forest growth model that can integrate species-interaction effects in the context of tropical mixed-species plantation management.

Economic potential and management of tropical mixed-species plantations

We found, that most of the modeled planting schemes were profitable at a discount rate of 8%, with IRR ranging between 9.9 and 16.7%. Only the mixture *H. alchorneoides*-*D. retusa* was not economically viable, presumably due to poor site suitability. Earlier studies had found that mixed-species plantations in Central America could yield internal rates of return 4–15.6% (Piotto et al. 2010; Sinacore et al. 2022; Streed et al. 2006). For monocultures of selected native species and *T. grandis* in Panama, Griess and Knoke (2011) and

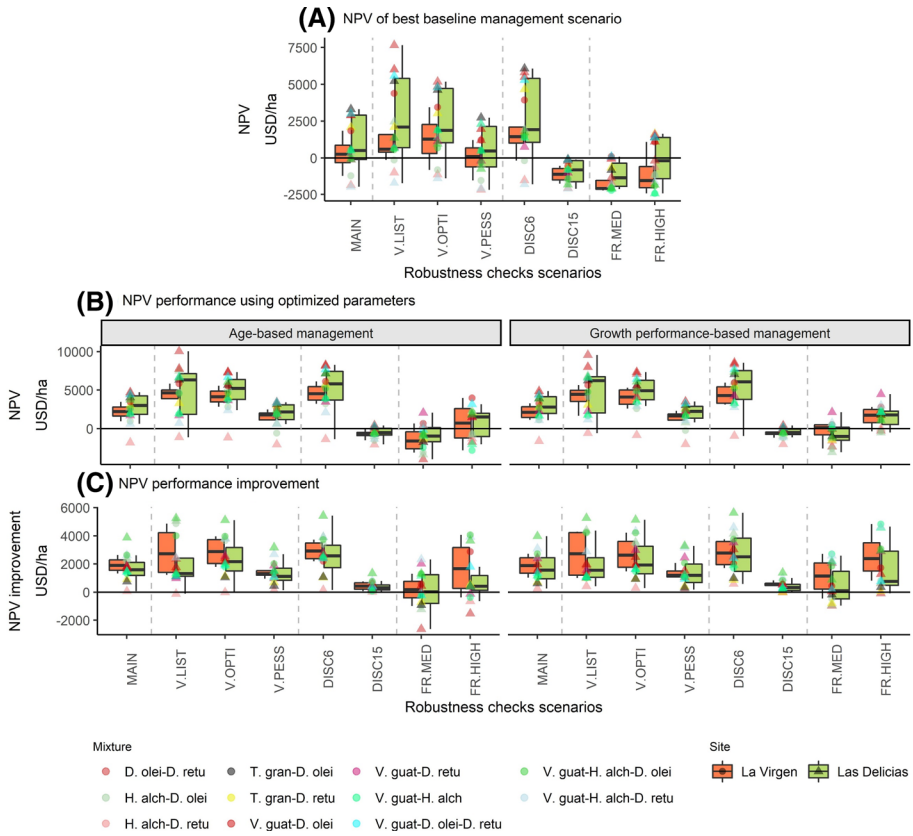


Fig. 4 Baseline management and sensitivity analysis results. A) shows the economic performance of the best-performing baseline management scenarios, B) shows the economic performance when the optimized management parameters are applied under varying valuation and site fertility assumptions, and C) shows the change in NPV achieved when the optimized management parameters are applied compared to best performing baseline management scenarios. Sensitivity analysis scenarios refer to the scenarios described in Sect. 2.5 and Table 4. *D. olei*, *D. retu*, *H. alch*, *T. gran*, and *V. guat* refers to the species *D. oleifera*, *D. retusa*, *H. alchorneoides*, *T. grandis*, and *V. guatemalensis* respectively

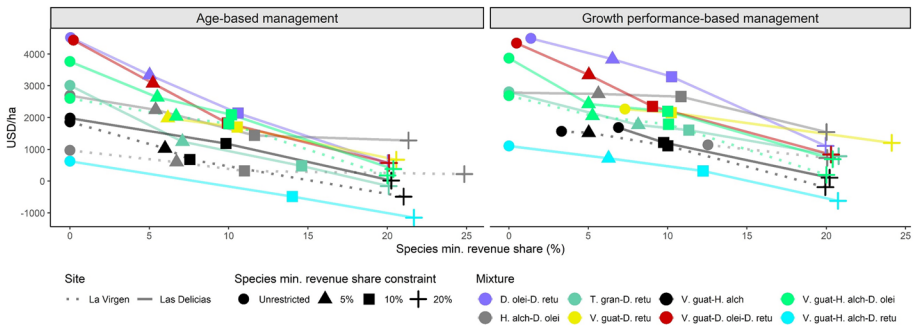


Fig. 5 Economic performance when the species minimum revenue share constraints are applied. Only mixtures that did not fulfill the 20% minimum revenue constraint under optimized unconstrained management are included in the figure. *D. olei*, *D. retu*, *H. alch*, *T. gran*, and *V. guat* refers to the species *D. oleifera*, *D. retusa*, *H. alchorneoides*, *T. grandis*, and *V. guatemalensis* respectively

Paul et al. (2015) estimated IRR of 10–15% and 2.8–12.6% respectively. Cabbage et al. (2020) in reviewing the economic performance of forest plantations across the globe IRR of tropical species in Central and South America between 8.1 and 21.8%, with plantations of *Gm. arborea* and *T. grandis* (the two most important plantations species in Costa Rica) reaching IRR up to 24.5% and 18.6% respectively. Our findings are within the range of previous economic performance estimates for tropical mixed-species plantations and indicate that mixed-species plantations can be economically competitive with conventional monocultures. However, our estimated IRR and NPV might be considered as upper boundaries for the economic performance of mixed-species plantations with the selected species, as applied fertility ratings for *D. oleifera* and *T. grandis* are exceptionally high and we assumed the mixtures are managed to achieve their optimal performance. On less fertile sites or under suboptimal management the economic performance could be considerably lower.

The second objective of our study was to determine how mixed-species plantations should be managed to achieve optimal economic outcomes. Our results indicate that both age-based and growth performance-based management approaches can achieve similar economic outcomes. Our optimized thinning parameters were highly variable from mixture to mixture with upper BA thinning thresholds ranging from 16.1 to 30.6 m²/ha, target BA after thinning between 8.6 and 27.1 m²/ha, and BA being lowered by 1.8–7.5 m²/ha per thinning. The optimized BA thinning parameters reflect the typical dichotomy between maximizing stand-level timber volume and maximizing individual tree stem volume. In our study, this dichotomy is partly driven by the integration of heartwood content into the valuation process. *D. oleifera*, *D. retusa*, *H. alchorneoides*, and *T. grandis* all produce distinguishable (and valuable) heartwood. As heartwood content increases with increasing stem diameter, optimized management for mixtures with only these four species will tend to favor individual tree growth by maintaining relatively low stand densities (upper BA threshold between 16.1 and 22.3 m²/ha with 1.8–7.5 m²/ha removed per thinning). *V. guatemalensis* does not produce distinguishable heartwood and optimized management favored maintaining higher stand densities in mixtures where *V. guatemalensis* was dominant (upper BA threshold between 28.4 and 30.6 m²/ha with 3.5–5.3 m²/ha removed per thinning). In mixtures where *V. guatemalensis* occurred with *D. oleifera* (both species have a high economic potential) a midway was found (upper BA threshold between 19.9 and 23.9 m²/ha with 4.8–6.5 m²/ha removed per thinning). Pérez and Kanninen (2005) in a comprehensive study for *T. grandis* applied BA thresholds for thinning 20–23 m²/ha to 12–17 m²/ha (the upper threshold for thinning and target BA after thinning respectively) when high individual tree growth is the management objective, and 22–25 m²/ha to 13–18 m²/ha when high stand growth is the main management objective.

Target mean dbh for harvesting generally varied between 26 and 44 cm for *D. oleifera*, *T. grandis*, and *V. guatemalensis*. These values lay within the range of diameters at harvest for plantation-grown species reported in other studies (Griess and Knoke 2011; Pérez and Kanninen 2005). *D. retusa* had a target mean dbh between 15 and 20 cm (when correcting for mortality-induced shifts of the mean dbh). The species is mainly used for artisanal work or fine carpentry and even wood pieces of small dimensions might fetch considerable prices. Due to its slow growth, achieving a target dbh of 20 cm can take more than 30 years in a mixed-species plantation.

Underplanting of harvested tree species generally did not occur under optimized management. Instead, replanting occurred after clear-cutting.

Overall, it should be noted, that the optimization approach we applied in this study approximates the global optimum of the objective function (i.e. NPV). However, whether the global

optimum is reached at the end of the optimization is unknown. Often, (forest) economic optimization studies prefer to use models that can be optimized mathematically. This ensures both that the global optimum of the optimization problem is reached and allows for detailed static analyses but requires a substantial simplification of complex real-world biological and economic processes (Knoke et al. 2008).

Sensitivity and uncertainties

The results from our sensitivity analysis showed that using our optimized management parameters improved economic performance consistently also when alternative valuation assumptions are applied. However, under alternative fertility scenarios, the optimized parameters did not consistently lead to improvements in the modeled stands' economic performance, compared to the baseline management scenarios. This highlights that the optimized management parameters are site-specific, i.e. specific to the applied FR. On sites with diverging FR, the optimized management parameters from this study might not be applicable, and the economic potential of such sites might diverge substantially from the ones estimated in this study. This is demonstrated in the sensitivity analysis, where only 4 of 15 modeled stands are economically viable under generic median site fertility (all FR=0.5). This is especially important for the species *D. oleifera* and *T. grandis* which showed exceptionally high FR on the two study sites. On poorer sites, reaching the target mean dbh for harvesting might take much longer than suggested in this study (when applying a growth performance-based management strategy), or might not be reached within the planning period at all. Generally, poorer sites can be expected to have longer optimal rotation times (due to the lower opportunity costs for delaying cashflows from future rotations) and smaller target mean dbh for harvesting. For broader applications, the optimized management parameters need to be generalized in future research. The data underlying the calibration of the growth model used in this study included examples of commercial plantations with very poor FR (between 0 and 0.3) (Nölte et al. 2022), where stand growth stagnated with increasing stand age (e.g. *T. grandis* growth stagnated at a mean dbh around 20 cm). Such low FR can either indicate nutrient-poor soils or unsuitable species selection. While our model allows for the optimization of such stands, they are unlikely to be economically viable regardless of the applied management parameters. With improved knowledge of species-specific site requirements, more site-suitable species should be selected for the reforestation of such sites in the future.

Secondly, the applied timber prices in our study remain an important source of uncertainty. For *D. oleifera* and *D. retusa* plantation-grown wood is not yet available on the market and prices hence refer to wood from natural forests. While we corrected timber prices for two important quality characteristics of tropical high-value timber (heartwood and stem diameter), it remains to be seen whether these price estimates materialize once plantation-grown wood from *D. oleifera* and *D. retusa* enters the market.

Finally, changing interest rates pose a crucial uncertainty in our study due to the long planning horizon of 80 years. As indicated by the IRR, 4 of 15 mixtures would remain economically viable even if interest rates increased to 15%.

Potential beyond timber production

In the present study, we assessed mixed-species plantations exclusively based on their ability to generate revenues through timber sales. However, other ecosystem services are becoming increasingly important objectives of plantation establishment and management.

For example, reforestation in the tropics has been suggested as a powerful strategy for combating climate change through carbon sequestration (Bastin et al. 2019; Griscom et al. 2017). However, past reforestation efforts have been criticized for the excessive establishment of exotic species monocultures with a low long-term carbon sequestration potential (Lewis et al. 2019). Establishing mixed-species reforestations has been suggested as an alternative to such monocultures in carbon plantings (Hulvey et al. 2013). Further, mixing species in commercial plantations might also be used as a risk mitigation strategy against climate change uncertainties, such as shifts in tree species distributions and site suitability (Allen et al. 2010; Anadón et al. 2014; Baumbach et al. 2021; Messier et al. 2021).

In general, mixed-species plantations are expected to perform better than monocultures when multiple ecosystem services and biodiversity protection are taken into account as management objectives (Carnus et al. 2006; Di Sacco et al. 2021; Hulvey et al. 2013; Liang et al. 2016; Lindenmayer et al. 2003; Stephens and Wagner 2007).

Conclusion

Overall, this study found that mixed-species plantations in Costa Rica could be economically viable and even highly profitable if managed appropriately and planted on adequate sites. Even-aged management approaches currently applied in mono-specific plantations could be applied successfully to mixed-species plantations if management thresholds and target values are adapted to individual species combinations and site conditions. Interestingly, also tree species currently grown almost exclusively in monocultures, such as *T. grandis*, showed a high economic potential when grown in mixed stands. Taking a broader selection of management objectives into account—such as climate change and risk mitigation, and biodiversity protection—might highlight further advantages of establishing mixed-species plantations as an alternative to current monoculture practices in tropical plantation forestry.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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