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Original Article



# Close-to-nature management of tropical timber plantations is economically viable and provides biodiversity benefits

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## Abstract

Reforestation of tropical forests is crucial to mitigate the climate crisis and restore ecosystems. However, past efforts have been criticized for establishing monoculture timber plantations with exotic tree species. Close-to-nature (CTN) practices aim to minimize negative forest management impacts on forests ecosystems by mimicking natural dynamics. So far, CTN management practices are rarely applied in tropical plantation forestry. This study evaluates the economic, carbon sequestration, and biodiversity potential of CTN management in tropical mixed-species plantations in Central America using a simulation-optimization approach. To our knowledge, this study is the first to assess the potential of tropical CTN-managed plantations on the basis of detailed process-based forest growth simulations. CTN practices such as *selective harvesting*, *retention forestry*, and *shelterwood cutting* of mixed-species stands were compared to even-aged mixtures and conventional monoculture practices. Results showed that CTN management was economically viable for certain species mixtures and management practices at an 8 % discount rate and had the potential to increase carbon storage and biodiversity in the modeled plantations. At current carbon prices, CTN-managed plantations may only become financially competitive with monocultures, if monocultures are excluded from carbon certification schemes that increasingly aim at co-producing non-carbon benefits like biodiversity conservation. If carbon prices increase, the sale of carbon credits could finance the transformation of monocultures to CTN-managed mixed-species stands. The competitiveness of CTN management could also be improved through performance-based biodiversity payments, such as the sale of biodiversity credits.

*Keywords:* climate-smart; reforestation; forest economics; native species; VCM; REDD+

## Introduction

Recent climate change and biodiversity reports have concluded that following current trajectories the world will not be able to meet its climate or biodiversity sustainability goals (IPCC 2018; IPBES 2019). Large-scale reforestation and restoration of tropical forest landscapes have emerged as one important strategy to mitigate the global climate crisis through the sequestration of carbon while also restoring important habitats and other ecosystem functions (Griscom et al. 2017; Bastin et al. 2019; IPBES 2019). Past reforestation efforts have been criticized for the widespread establishment of exotic-species monoculture timber plantations with a limited long-term carbon sequestration potential and limited biodiversity value (Lewis et al. 2019). Nonetheless, the area of tropical timber plantations is expected to increase further (FAO 2020). Studies have repeatedly highlighted that the carbon sequestration potential of tropical timber plantations could be increased substantially through management adaptations, such as extended rotation times and maintaining higher stand densities (Olschewski and Benítez 2010; Quintero-Méndez and Jerez-Rico 2017; Nölte et al. 2018; Pinnschmidt et al. 2023a). The establishment of mixed-species plantations could also increase carbon sequestration potential of plantations by achieving overyielding through complementary species interaction effects and risk reduction (Hulvey et al. 2013; Pretzsch et al. 2015; Mayoral et al. 2017; Di Sacco et al. 2021; Messier et al. 2021; Mori et al. 2021; Schnabel et al. 2021; del Río et al. 2022; Feng et al. 2022). From a biodiversity perspective, plantation forests can offer more suitable habitats for native forest species than competing agricultural land uses (Barlow et al. 2007; Stephens and Wagner 2007; Brockerhoff et al. 2008). A wide variety of measures can be taken to enhance biodiversity in plantation forests, such as using multiple (native) tree species, establishing mixed-species stands, preventing large-scale clearcutting, and leaving patches of trees or individual mature trees unharvested (Carnus et al. 2006; Brockerhoff et al. 2008; Gustafsson et al. 2012; Di Sacco et al. 2021).

The consideration of multiple forest management objectives has led to the development of many different ‘Close-to-nature’ (CTN) forest management strategies, especially for managed temperate forests (Pommerening and Murphy 2004; Pukkala and von Gadow 2012). CTN management practices seek to mimic the

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ecological dynamics of natural forests and minimize negative impacts of forest management activities, while fulfilling key management objectives, such as timber production (O'Hara 2016; Maennicke and Griess 2019). Accordingly, CTN forest management spans a wide range of management strategies but for this study *we define CTN forest management practices to be characterized by the absence of large-scale clearcutting events, the use of multiple (native) tree species, and/or the maintenance of an uneven-aged stand structure.* Clearly, even with all these management measures implemented simultaneously, the resulting forest might still not closely resemble a natural forest in terms of, e.g., structural and species diversity. Some authors instead refer to CTN management as 'Closer-to-Nature' (Larsen et al. 2022; Krumm et al. 2023; Rosa et al. 2023).

So far, the application of CTN management practices to the context of tropical timber plantations has not been studied extensively (Maennicke and Griess 2019). Importantly, studies on the financial implications of CTN practices in tropical plantation forests are currently lacking. Such studies are a crucial first step in the development of tropical CTN plantations, as financial considerations—i.e. expected profitability of plantations—remain the most important drivers of investments into tropical plantation forests (Da Silva et al. 2017). Recent studies have suggested that monoculture and mixed-species plantations of native tree species might be an economically competitive alternative to exotic species monoculture plantations in Central America (Streed et al. 2006; Piotto et al. 2010; Griess and Knoke 2011; Sinacore et al. 2022; Pinnschmidt et al. 2023b). Following the definition applied in this study, establishing mixed-species plantations and using native tree species could be considered first steps toward CTN management of tropical plantations (Maennicke and Griess 2019). Pinnschmidt et al. (2023a 2023b) further suggested that mixed-species stands might outperform monocultures substantially if also payments for carbon credits were considered in the valuation. While these results are promising, the studies only considered native species monoculture and mixed-species plantations managed as even-aged stands with reoccurring clearcutting activities but do not consider alternative silvicultural management approaches. In the existing studies, the transformation of existing tropical monoculture plantations into CTN plantations forests has also not been considered yet, nor have potential impacts of such management changes on the carbon sequestration potential and biodiversity.

The economic potential of uneven-aged management practices without clearcutting has been studied more extensively for temperate and boreal forests (Hanewinkel 2002; Knoke 2012). Here, studies have shown that uneven-aged management practices *can* be economically advantageous under a wide variety of conditions, and due to many different factors. For example, applying selective harvesting practices (i.e. periodically harvesting individual trees instead of clearcutting) can ensure that individual trees are harvested closer to their economic optimum; more frequent harvesting events and the resulting temporal diversification of revenues might reduce risk from timber market fluctuations; the presence of fewer trees in the dominant canopy layer might increase growth rates for the largest (and accordingly most valuable) trees in an uneven-aged stand (Roessiger et al. 2011; Hanewinkel et al. 2014; Pukkala 2015).

In this study, we aim to determine the economic potential of CTN management practices in the context of commercial tropical plantation forestry. We further aim to estimate the potential of such management practices to increase the carbon sequestration and biodiversity potential of tropical plantation forests. We will do so by applying a simulation-optimization approach extending on a forest economic model previously published by Pinnschmidt et al. (2023a, 2023b). While the previous studies by Pinnschmidt et al. (2023a, 2023b) only explored the economic and carbon potential of even-aged managed monoculture and mixed-species plantations, the present study will focus on exploring the potential of applying CTN management practices such as shelterwood cutting, retention forestry, and selective harvesting to mixed-species plantations in Central America. Furthermore, the study explores the potential of transforming existing monoculture plantations into CTN-managed mixed-species plantations. The study considers both revenues from timber sales, as well as revenues from carbon payments and biodiversity payments in its economic evaluation. To our knowledge, this study is the first to assess the economic, carbon, and biodiversity potential of tropical CTN-managed plantations and the transformation of monoculture plantations on the basis of detailed process-based forest growth simulations.

Specifically, we will simulate and optimize the application of CTN management practices including selective harvesting, retention forestry, and shelterwood cutting in tropical mixed-species plantations in Central America. We will then compare the economic, carbon sequestration, and biodiversity performance of these stands against conventionally managed even-aged monocultures.

## Methodology

In this study, we compared the economic, carbon sequestration, and biodiversity performance of optimized CTN-managed plantations against conventionally managed monoculture stands using a simulation-optimization approach. We do so based on a case study of CTN management of mixed-species plantations in Costa Rica. Specifically, we optimized the management of CTN-managed stands with regards to maximizing their profitability, considering both revenues from timber sales and carbon payments.

To apply the simulation-optimization approach, we extended the forest economic model of Pinnschmidt et al. (2023a, 2023b) by integrating CTN management options. The model is suitable to simulate both monoculture and mixed-species stands by combining a process-based forest growth model (*3PGmix*) with detailed economic and operational data. So far, the model only allowed for even-aged management options (i.e. clearcut harvesting). For the later comparisons between monoculture and CTN-managed stands, we also extended the model by adding a biodiversity module to estimate selected biodiversity indicators based on the model's growth outputs. Figure 1 gives an overview of the extended model.

### Site and species selection

We conducted our analysis based on a plantation site in northern Costa Rica (10.96551, −85.05070). The site is characterized by tropical moist forest conditions with an average yearly precipitation of 2221 mm/m$^2$ and average temperatures ranging between 21 and 35°C. The site was previously used as a cattle pasture but was reforested with both monoculture and mixed-species timber plantations. For our study, we selected five tree species as the basis for our analysis: *Tectona grandis*, *Vochysia guatemalensis*, *Hieronyma alchorneoides*, *Dipteryx oleifera*, and *Dalbergia retusa*. *Vochysia guatemalensis*, *H. alchorneoides*, *D. oleifera*, and *D. retusa* are native to the area and have been suggested as promising native species for timber plantations (Gamboa et al. 2015; González 2018). Teak (*T. grandis*) was included as it is currently the most important plantation-grown species in Costa Rica.

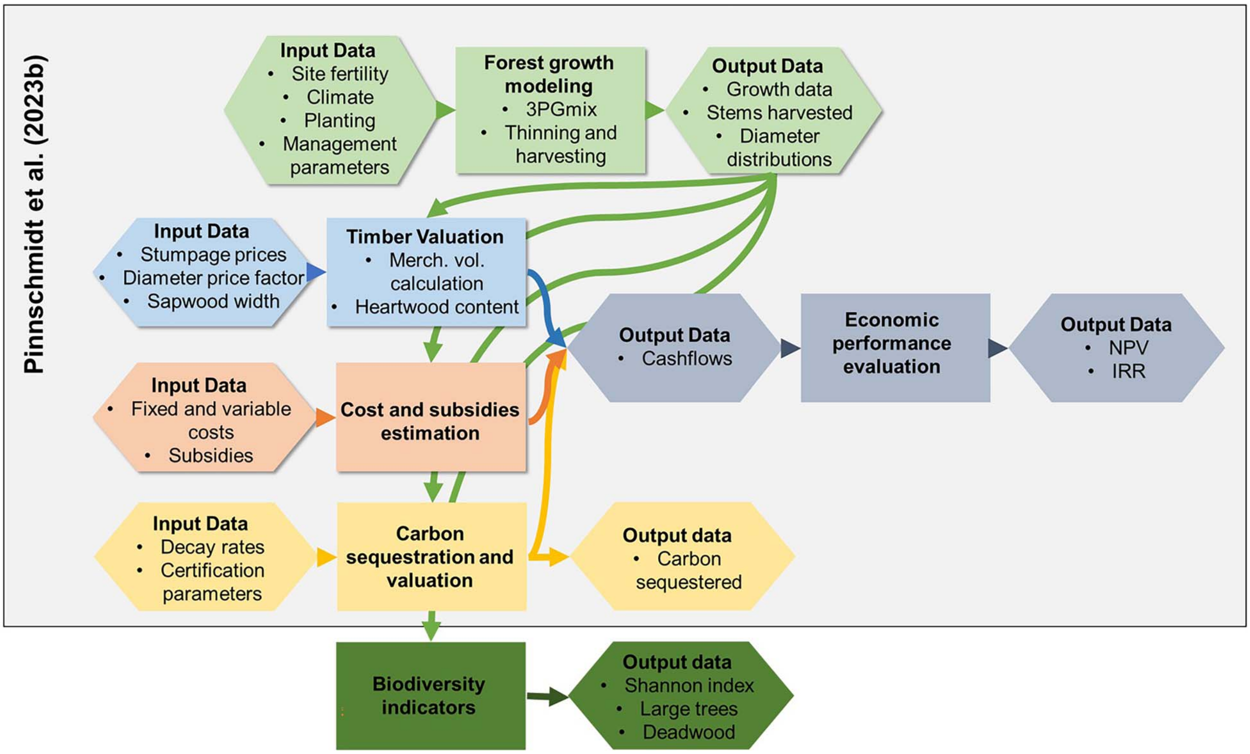


**Figure 1.** Overview of modeling components, data, and data flows of the forest economic model used in this study. Bullet points give examples of important modeling steps and data in the different model components.

## Forest economic model

To optimize CTN management, we used the forest economic model published by Pinnschmidt et al. (2023a, 2023b). The model predicts forest growth using the process-based forest growth model 3PGmix *(Physiological Processes Predicting Growth)* and uses the model's growth outputs as the basis for its valuation modules for timber sales and the sale of carbon credits, and the cost module. 3PGmix estimates forest growth on a stand-level by estimating the total amount of carbon fixed through photosynthesis under consideration of soil conditions, climate, and tree age. It is an extension of the 3PG model originally developed by Waring and Landsberg (1997). While 3PG only allowed for the simulation of monoculture stands, 3PGmix allows for vertical differentiation in the stand canopy, thereby allowing for the simulation of multilayered stands—i.e. mixed-species and uneven-aged stands (Forrester and Tang 2016). 3PGmix accounts for the different microclimates and shading that species (or cohorts) with different canopy heights might experience by considering the vertical gradients in light availability, aerodynamic conductance, vapor pressure deficit, and net radiation that occur in multilayered stands. Hereby, 3PGmix can represent aboveground species interaction effects and complementarity. However, possible interaction effects related to soil nutrients are not represented. 3PGmix has been used to model mixed-species and multilayered forest stands under a wide variety of conditions (Forrester and Tang 2016; Nölte et al. 2020; Trotsiuk et al. 2020; Bouwman et al. 2021; Forrester et al. 2021; Xu et al. 2022).

To run 3PGmix growth simulations, the model needs input information of species composition, species-specific site fertility ratings, and soil and climatic site characteristics. Fertility ratings are 3PG-specific relative measures for species-specific site productivity, corrected for climatic and soil water growth influences. The model delivers typical forest growth outputs on a cohort-level (i.e. species- or age-cohort-level) in monthly intervals, such as mean diameter at breast height (dbh), total height, stem volume, and different biomass pools. Based on the outputs of the 3PGmix model, the forest economic model calculates the revenues that can be generated through the sale of timber, taking into account key quality characteristics such as heartwood content and log diameter. Details on the applied valuation approach, timber prices, and establishment and management costs can be found in Pinnschmidt et al. (2023b) and in Supplementary 1.

Furthermore, through the extension of Pinnschmidt et al. (2023a), the revenues that could be generated through the sale of carbon credits are calculated. Here, the amount of carbon credits that could be issued is estimated based on established carbon accounting and crediting methodologies applied in the Voluntary Carbon Market (such as carbon credits issued on the basis of Gold Standard, Verified Carbon Standard, or American Carbon Registry methodologies (Gold Standard 2017; Winrock International 2020; VERRA 2021)). The model allows for the application of either Afforestation/Reforestation (A/R) or improved forest management (IFM) carbon credit accounting methodologies.

A/R carbon crediting methodologies are applied for new forest stands established on former unforested land (e.g. abandoned pastures). Under this crediting scheme, credits are issued for additional carbon stored in a forest or reforestation within a given verification period. Typically, a project's carbon stocks are assessed (i.e. 'verified') at least every 5 years. The total amount of credits that can be issued for a plantation is limited by its long-term CO2 storage capacity. In plantations where clearcutting occurs, this long-term storage capacity is estimated based on the mean carbon stored in the stand during the whole project duration. If the stand is not clearcut during the project duration, then the long-term storage capacity is estimated based on the carbon stock achieved by the end of the project duration.

IFM carbon credits can be issued for existing forest stands if management changes are implemented that increase the long-term CO2 stored in the stand (Winrock International 2020; VERRA 2023a). '*Improved*' in IFM only refers to the increased long-term carbon storage and not to other potential forest management objectives, such as timber production. Typical IFM management changes in plantation forests include extended rotation times or maintaining higher stand densities but in principle all management changes that increase the long-term carbon storage qualify for IFM carbon credits (Kaarakka et al. 2021; Haya et al. 2023b). Accordingly, also management changes such as switching from an even-aged monoculture plantation system to a CTN-management mixed-species plantation system could qualify for IFM credits *if* these management changes increase the long-term carbon storage capacity. The amount of credits issued is calculated based on the difference between the carbon stored under IFM management and the carbon that would have been stored in the stand under 'business-as-usual' management. In the context of this study, the number of credits would hence be calculated based on the carbon stored in a modeled stand under CTN management (here considered 'IFM') compared to the carbon stored in a monoculture plantation managed for maximize financial returns from timber production (here considered 'business-as-usual').

A detailed overview of registered voluntary carbon credit projects, including A/R and IFM projects, can be found in Haya et al. (2023a). This includes monoculture timber plantations and mixed-species reforestation projects, as well as IFM projects for extending rotation times of even-aged and selectively harvested managed forests, logged-to-conservation forest projects, and enrichment plantings in tropical managed forests. So far, no IFM projects for the transformation from even-aged monoculture plantations to CTN-managed plantations have been registered.

We assumed a total project duration of 30 years with verification intervals of 5 years. For details on the applied carbon credits methodologies, equations, and associated costs see Pinnschmidt et al. (2023a) or Supplementary 1.

Based on the generated timber and/or carbon revenues, as well as the associated costs, economic performance indicators can be calculated such as net present value (NPV).

### *Integrating CTN management practices*

So far, the forest economic model by Pinnschmidt et al. (2023a, 2023b) only allowed for even-aged management by applying either age-based harvesting or harvesting based on reaching a species-specific target mean dbh. Replanting (or underplanting) only occurs when all trees of a species are removed from the simulated stand. To simulate CTN management practices we integrated alternative harvesting strategies, the possibility for continuous replanting/underplanting into the forest economic model, and the possibility of an uneven-aged stand structure.

As outlined in the introduction, CTN management can span a wide range of forest management practices that seek to mimic nature forest dynamics while minimizing negative ecological impacts for forest management interventions. For the purpose of this study, we consider *CTN forest management practices to be characterized by (i) the absence of large-scale clearcutting events, (ii) the use of multiple tree species, and/or (iii) the maintenance of an uneven-aged stand structure*. We selected four CTN management practices to be included in the study, namely even-aged management, retention forestry, shelterwood cutting, and selective harvesting. All four CTN management practices were applied to mixed-species stands and incorporate at least one of the CTN forest management characteristics defined above (see Table 1 for overview) (Maennicke and Griess 2019). Figure 2 illustrates key management interventions during the harvesting and regeneration phase of the CTN management practices included in this study. The CTN management practices were implemented into the simulation model based on simple harvesting parameters or thresholds shown in Table 2 that should be familiar most plantation managers (e.g. dbh and stand basal area (BA)). We applied thinning based on BA thresholds to all CTN management options.

First, we included even-aged management of the mixed-species stands as a CTN management practice in the study. While even-aged management is generally not considered to be a CTN management practice, the establishment of tropical mixed-species plantations (using native species) might itself be considered an important step toward CTN conditions compared to conventional exotic-species monoculture practices (Di Sacco et al. 2021). Even-aged management was implemented in the simulation model in the form of species-specific target mean dbh thresholds. Once a tree species in the simulated stand exceeds its target mean dbh threshold, all trees of the corresponding species are harvested.

Second, we included '*Retention Forestry*' as a CTN management practice. In retention forestry, parts of the forest stand (or individual trees) remain unmanaged or unharvested and are left to develop according to natural forest dynamics. Meanwhile, the managed parts of the stand can be managed according to conventional management practices. Accordingly, even-aged clearcut harvesting can take place on the managed stand sections while the retained forest patches offer important refuges for forest species during and after such management interventions. In the simulation model, retention forestry was implemented by setting aside an unharvested portion of the simulated stand, while the remaining stand was simulated using the even-aged management parameters described above. We assumed that 10% of the simulated stand would remain unharvested based on recommendations of Gustafsson et al. (2012).

Third, we included '*Shelterwood Cutting*' as a CTN management practice. Shelterwood cutting is a management practice in which a selected number of mature trees are left in the stand during final harvesting as a 'shelter' for the next generation of trees. Trees can be regenerated under this shelter either by natural regeneration or underplanting. The shelter trees are removed once the new stand has established itself. Shelterwood cutting practices hence avoid clearcutting and bare-land microclimatic conditions during the final harvesting and regeneration phase. While the stands are uneven-aged during the regeneration phase, the stands are managed as even-aged stands once the shelter trees are harvested. Shelterwood cutting was implemented in the simulation model on the basis of a target mean dbh harvest threshold (as with conventional even-aged management), a shelterwood BA parameter, and shelterwood duration. Under shelterwood cutting, the simulated stands are managed using the even-aged harvest thresholds until only one tree species remains in the stand. Once this tree species reaches its target mean dbh, the shelterwood sequence is initiated. In this sequence, the stand is first partially harvested and underplanted with the trees of the following rotation. The amount of shelterwood remaining is determined by the applied shelterwood BA. The shelterwood trees are left for a period of time (the shelterwood duration) and then harvested. Once the shelterwood has been harvested, only trees of the new rotation remain in the simulated stand.

**Table 1.** Overview of alignment of selected management practices with 'CTN' management characteristics.

| Management practice | CTN management characteristics[i] | | |
|---|---|---|---|
| | Uses multiple trees species | No clearcutting | Uneven-aged stand structure |
| Even-aged mixed-species | X | | |
| Retention forestry[ii] | X | (X) | (X) |
| Shelterwood cutting[iii] | X | X | (X) |
| Selective harvesting | X | X | X |

i) X indicates that the selected managed practices fulfill CTN characteristic, (X) indicates that characteristic are partly fulfilled. ii) In retention forestry, the stand is partly clearcut. The harvested section of the stand is even-aged. iii) In shelterwood cutting, the stand is only uneven-aged during the harvest and regeneration phase.

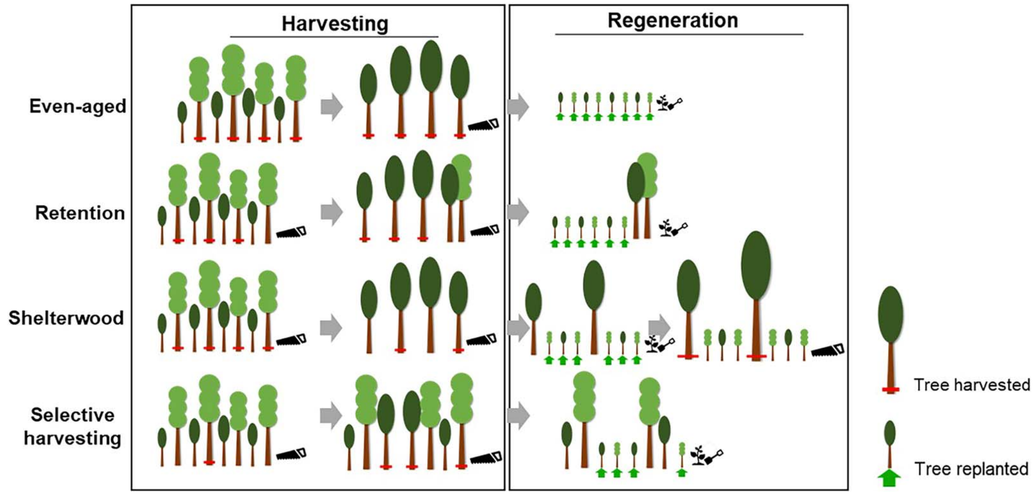


**Figure 2.** Overview of key management intervention in mixed-species stands managed according to CTN management practices

Finally, we included '*Selective Harvesting*' as a CTN management practice. Under selective harvesting management, individual trees are harvested during harvesting interventions if they have reached maturity (e.g. a specified target size). Immature trees are left to continue growing. Regeneration of new trees takes place continuously to ensure a steady supply the mature trees. This management approach results in an uneven-aged stand where no clearcutting takes place. Selective harvesting was implemented in the simulation model using a species-specific individual tree target dbh and a harvesting interval. At each harvest event, the number of trees above the target dbh were determined and harvested. As 3PGmix is a cohort-level growth model (and not an individual tree model) and to ensure modeling consistency, selective harvesting was in practice implemented as a heavy thinning from above, where *most* trees above the target size are harvested, as well as a fewer smaller trees.

The integration of the CTN management options into the forest economic model is described in further detail in Supplementary 1.

## Biodiversity indicators

We further integrated four biodiversity indicators in the forest economic model following the recommendations of Blattert et al. (2017), namely *tree species diversity*, *structural diversity*, *deadwood volume*, and *presence of large (habitat) trees*. All indicators could be calculated directly from the model's forest growth outputs and can in practice be calculated from conventional forest inventory data (Table 3). The indicators represent important characteristics and preconditions for a species-rich forest ecosystem (Lindenmayer et al. 2012; Felton et al. 2017; Biber et al. 2020). For the presence of large trees, we quantified the proportion of time during which >10 large trees per hectare were present in the simulated stands. The presence of relatively few large trees could already have a substantial impact on the habitat availability in plantation forests ( Lindenmayer et al. 2003, 2012). Accordingly, the indicator applied in this study gives a measure for the continuity of this habitat availability. Alternative measures, such as average number of large trees, could be strongly influenced by the temporal distribution of these trees within the simulation period, which would introduce ambiguity in the interpretation of the resulting indicator values.

## Economic and carbon sequestration performance

We used NPV to measure the economic (i.e. financial) performance of the modeled stands. NPV represents the sum of the discounted cash flows (which includes both revenues and costs) for a specific period of time (Equation 1). We calculated the NPV using a discount rate of 8% ( Cubbage et al. 2007, 2020) and a simulation period of 80 years (2020–2100).

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

where $T$ is the end of the simulation periods (in years), $CF_t$ is the cashflows (USD/ha) occurring in each time $t$, and $r$ is the discount rate. Due to the long simulation period, the economic performance evaluation can span multiple rotations or harvest cycles (depending on the length of these cycles). Accordingly, in later optimization steps, the opportunity cost of delaying future harvest events (i.e. land rent (Wagner 2012)) is considered. At the applied discount rate, potential cashflows after the simulation

**Table 2.** Harvesting parameters and thresholds for CTN management options.

| Management practice | Harvesting parameters | |
|---|---|---|
| | *Type* | *Description* |
| Even-aged | Target mean dbh | Species-specific target mean dbh. When this mean dbh threshold is exceeded all trees of the respective species are harvested |
| Retention forestry | Target mean dbh | *See above* |
| | Area retained | Size of area that remains unharvested. Preset to 10% |
| Shelterwood cutting | Target mean dbh | *See above*—when only one species remains in the stands the shelterwood cutting sequence is initiated |
| | Shelterwood BA | The BA of trees left as shelter during final harvesting (i.e. BA of shelterwood) |
| | Shelterwood duration | Time shelter trees are left in the stand before also being harvested |
| Selective harvesting | Individual tree target dbh | Species-specific target dbh. Tree individuals with larger dbh are harvested during the harvest interventions |
| | Time of first harvesting | Preset to year 15 |
| | Harvesting interval | The time between harvesting interventions |

period have little effect on the calculated NPV (the discount factor after 80 years is <0.002). The calculated NPV can hence be considered an approximation of the land expectation value. The value of the remaining stand at the end of the simulation period is not considered in the valuation. Due to the high discount rate, the value of the remaining stand would have to exceed 100 000 USD/ha in order to substantially affect the economic simulation outcomes. This is far beyond any cashflow observed in any of the simulation scenarios (see Supplementary 3).

To measure the carbon sequestration performance of the modeled stands we calculated the mean carbon stored in living tree biomass (Schroeder 1992) (Equation 2).

$$\overline{C.stand} = \frac{\sum_{m=1}^{M}\left(C.stem_m + C.foli_m + C.root_m\right)}{M} \tag{2}$$

where $\overline{C.stand}$ is the modeled mean stand carbon stored in living trees at any point in time within the planning period, $m$ are individual monthly periods (the simulation model used simulates in monthly intervals), $M$ is the total number of monthly periods simulated, $C.stem_m$, $C.foli_m$, and $C.root_m$ are the carbon stored in living tree stems, foliage, and roots in the individual monthly period.

## Selected stands for optimization

On the study site, the selected species were planted in mixed-species plantations containing two or three tree species. For the CTN management optimization, we selected the four mixtures *H. alchorneoides–D. retusa*, *T. grandis–D. oleifera*, *V. guatemalensis–D. oleifera*, and *V. guatemalensis–D. oleifera–D. retusa*. The mixtures *T. grandis–D. oleifera*, *V. guatemalensis–D. oleifera*, and *V. guatemalensis–D. oleifera–D. retusa* were identified as mixtures of high economic and carbon sequestration potential on the site under even-aged management, while *H. alchorneoides–D. retusa* showed poor performance (Pinnschmidt et al. 2023b). Table 4 shows the applied planting schemes. The tree species in the mixtures were mixed tree-by-tree with equal spacing.

For the selected species, we used the 3PGmix parameters published by Nölte et al. (2022) and applied the fertility ratings model-fitted for the study site (Table 5). Nölte et al. (2022) calibrated and validated 3PGmix parameters for the 5 study species based on time-series inventory data from 113 different monoculture and mixed-species plantations across Central America (including the study site of this study).

### Optimization

We assumed that the objective of commercial plantations is to maximize profitability. Accordingly, we aimed to optimize the management parameters to maximize the NPV of the modeled CTN-managed stands. Generalized, the optimization objective can be described by Equation 3.

$$\max\left\{NPV_{\mathrm{BA1,BA2},HP,RS}\right\} \tag{3}$$

where $NPV$ is the NPV of the modeled stand, $BA1$ is the applied upper BA threshold to initiate thinning, $BA2$ is the applied target BA after thinning, $HP$ are the applied harvesting parameters further specified for each CTN management practice (Table 6), and $RS$ is the applied relative spacing threshold for underplanting.

Specifically, for even-aged and retention forestry management the optimization objective was defined as Equation 4.

$$\max\left\{NPV_{\mathrm{BA1,BA2},TD}\right\} \tag{4}$$

where $TD$ was the species-specific target mean dbh. As simulated even-aged managed stands were regenerated after clearcutting $RS$ was not included in the optimization.

For shelterwood cutting, the optimization objective was defined as Equation 5.

$$\max\left\{NPV_{\mathrm{BA1,BA2},TD,SBA,SD,RS}\right\} \tag{5}$$

where $SBA$ is the shelterwood BA, and $SD$ is the shelterwood duration.

Finally, the optimization objective for selective harvesting managed stands was defined as Equation 6.

$$\max\left\{NPV_{\mathrm{BA1,BA2},iTD,HI,RS}\right\} \tag{6}$$

where $iTD$ is the species-specific individual tree target dbh and $HI$ is the harvesting interval.

The optimization was performed using a genetic (Differential Evolution) optimization algorithm from the R package '*DEOptim*'

**Table 3.** Biodiversity indicators with equations.

| Biodiversity indicator | | Equations | Description |
|---|---|---|---|
| Type | Indicator | | |
| *Tree species diversity* | Shannon Index alpha diversity | $\overline{D.Species} = \frac{\sum_{m=1}^{M} D.Species_m}{M}$ Where: $H.Species_m = -\sum_{i=1}^{S} p_{i,m} \ln (p_{i,m})$ $D.Species_m = \exp (H.Species_m)$ | Where $\overline{D.Species}$ is the mean tree species diversity of the modeling period, $D.species_m$ is the tree species alpha diversity based on the BA by individual tree species occupied, $m$ are individual monthly periods, $M$ is the total number of monthly periods simulated, $S$ is the number of tree species in the stand, $H.Species_m$ is the Shannon index, and $p_i$ is the relative BA share of species $i$ in period $m$. |
| *Structural diversity* | Post hoc Index alpha diversity | $\overline{D.Struct} = \frac{\sum_{m=1}^{M} D.Struct_m}{M}$ Where: $H.dbh_m = -\sum_{n=1}^{N.dbh} p_{n,m} \ln (p_{n,m})$ $H.h_m = -\sum_{k=1}^{N.h} p_{k,m} \ln (p_{k,m})$ $D.Struct_m = \exp \left(\frac{H.dbh_m + H.h_m}{2}\right)$ | Where $\overline{D.Struct}$ is the mean stand vertical and horizontal structural diversity in the modeling period based on tree height and dbh, $D.Struct$ is the structural diversity in the monthly period $m$, $H.dbh_m$ and $H.h_m$ are the Shannon indices applied to the stands diameter and height classes, respectively, $N.dbh$ and $N.h$ are the number of dbh and height classes, and $p_{n,m}$ and $p_{k,m}$ are the relative BA in dbh and height class. |
| *Deadwood volume* | Standing or lying deadwood volume | $\overline{V.Dead} = \frac{\sum_{m=1}^{M} \sum_{i=1}^{S} V.Dead_{i,m}}{M}$ | Where $\overline{V.Dead}$ is the mean volume of deadwood present in the stand during the modeling period, including harvest residues and $V.dead_{i,m}$ is the volume of species $i$ in the monthly period $m$. |
| *Presence of large (habitat) trees* | Min. 10 trees/ha of dbh > 40 cm | $\overline{HT} = \frac{\sum_{m=1}^{M} HT_m}{M}$ Where: $\begin{cases} HT_m = 1 \text{ if } \mathbf{min}.10 \text{ trees with } dbh \geq 40 \\ HT_m = 0 \text{ if less } 10 \text{ trees with } dbh \geq 40 \end{cases}$ | Where $\overline{HT}$ is the proportion of time periods with at least 10 trees/ha of dbh > 40 cm and $HT_{,m}$ indicates the presence of >10 large trees per ha in monthly period $m$. |

**Table 4.** Planting schemes of the selected mixed-species stands.

| Species combination | Initial planting density |
|---|---|
| | *Trees/ha* |
| *H. alchorneoides–D. retusa* | 400–400 |
| *T. grandis–D. oleifera* | 400–400 |
| *V. guatemalensis–D. oleifera* | 400–400 |
| *V. guatemalensis–D. oleifera–D. retusa* | 400–200–200 |

**Table 5.** Fertility ratings for the selected species on the study site model-fitted in Nölte et al. (2022).

| Species | Fertility rating |
|---|---|
| *D. oleifera* | 1.338 |
| *D. retusa* | 0.567 |
| *H. alchorneoides* | 0.478 |
| *T. grandis* | 1 |
| *V. guatemalensis* | 0.402 |

(Mullen et al. 2011). The population-based optimization algorithm is inspired by natural selection, iteratively searching for optimal solutions within a candidate population. It is particularly useful for solving complex optimization problems where traditional optimization methods may struggle to approximate the global optimum.

To ensure that the modeled CTN stands managed using shelterwood cutting or selective harvesting did not undergo clearcutting, we implemented a penalty constraint that required the average distance between trees to be no more than 1 tree length. We maximized NPV for a planning period of 80 years (i.e. 2020–2100).

The applied harvesting parameters' parameter bounds can be found in Table 6. Parameter bounds for *BA1* and *BA2* were 4–40 $m^2$/ha while the parameter bounds for *RS* were 0–4. We ran each optimization with 100 iterations.

## Optimization scenarios

We ran optimizations for multiple (nested) scenarios regarding (i) species combinations (i.e. planting schemes), (ii) stand establishment, (iii) management, and (iv) valuation. An overview of the optimization scenarios is given in Table 7

For each species combination, we considered two stand establishment scenarios. In the first scenario, the modeled stands were established on bare land (i.e. reforestation/afforestation of unforested land such as former pastures). In the second scenario, mature monoculture stands were transformed into mixed-species CTN-managed plantations. For each mixture, we selected the species in the mixtures that showed the highest economic potential on the study site when grown as a monoculture to be the baseline for the stand transformation. Hence, the mixtures *T. grandis–D.oleifera*, *V. guatemalensis–D. oleifera*, and *V. guatemalensis–D. oleifera–D. retusa* were established by transforming a mature *D. oleifera* monoculture, while the mixture *H. alchorneoides–D. retusa* was established by transforming a mature *D. retusa* monoculture (Pinnschmidt et al. 2023a).

The modeled mixed-species stands were managed either through even-aged management, retention forestry, shelterwood cutting, or selective harvesting.

Finally, we considered four different valuation scenarios. In the first scenario, we only considered revenues from timber sales.

**Table 6.** CTN management harvesting parameters and optimization parameters bounds.

| Management practice | Harvesting parameters | Included in optimization | Parameter bounds | |
|---|---|---|---|---|
| | *Type* | | *Lower* | *Upper* |
| Even-aged | Target mean dbh | Yes | 10 cm | 60 cm |
| Retention forestry | Target mean dbh | Yes | 10 cm | 60 cm |
| | Area retained | No | | |
| Shelterwood cutting | Target mean dbh | Yes | 10 cm | 60 cm |
| | Shelterwood BA | Yes | 0 $m^2$/ha | 40 $m^2$/ha |
| | Shelterwood duration | Yes | 1 year | 15 years |
| Selective harvesting | Individual target dbh | Yes | 10 cm | 60 cm |
| | Time of first harvesting | No | | |
| | Harvesting interval | Yes | 1 year | 15 years |

**Table 7.** Overview of optimization scenarios.

| Scenario type | Scenario | Description |
|---|---|---|
| Species combination | 1) *D. oleifera* (monoculture)<br>2) *D. retusa* (monoculture)<br>3) *H. alchorneoides* (monoculture)<br>4) *T. grandis* (monoculture)<br>5) *V. guatemalensis* (monoculture)<br>6) *H. alchorneoides–D. retusa*<br>7) *T. grandis–D. oleifera*<br>8) *V. guatemalensis–D. oleifera*<br>9) *V. guatemalensis–D. oleifera–D. retusa* | Mixtures and monocultures of the selected study species. Monocultures were only optimized under even-aged management practices. The same fertility ratings were applied for species grown in mixed and monoculture stands (Table 5). All stands were modeled at an initial planting density of 800 trees/ha. |
| Establishment | 1) From bare land<br>2) From mature monoculture | Stand condition at the start of the simulation period. Reforestation of unforested land was considered 'from bare land'.<br>In 2) CTN-managed mixed stands were established by transforming monoculture plantations that had reached their harvest time (i.e. target tree size). |
| Management | 1) Even-aged<br>2) Shelterwood cutting<br>3) Retention forestry<br>4) Selective harvesting | Alternative management options. |
| Valuation | 1) '*Timber*': No carbon payments<br>2) '*pC10*': Carbon payments at 10 USD/tCO2e<br>3) '*pC50*': Carbon payments at 50 USD/tCO2e<br>4) '*pC100*': Carbon payments at 100 USD/tCO2e | In 1) only costs and revenues associated the stand establishment, tending, and timber sales were considered. In 2)–4) also costs and revenues associated to carbon credit certification and sales were included at varying carbon credit prices. |

In the remaining scenarios, we also included revenues and costs from carbon credits in the stand valuation. For stands established from bare land, we used the Afforestation/Reforestation (A/R) carbon crediting methodology, while for stands established by transforming mature monocultures, we used the IFM methodology (Pinnschmidt et al. 2023a). We considered carbon credit prices of 10, 50, and 100 USD/tCO2e.

For later comparisons, we further optimized the management of the five study species grown in even-aged monocultures in the same way as described for the CTN managed stands.

## Output and sensitivity analysis

We compared the economic, carbon, and biodiversity outcomes of the modeled CTN-managed mixed-species plantations with those of the modeled monoculture plantations under optimized management.

To assess the commercial competitiveness of tropical CTN-managed plantations, we calculated the NPV surplus (i.e. negative opportunity costs) that could be achieved of applying CTN management practices instead of monocultures. The CTN-managed stands were compared against the best-performing species grown as a monoculture. CTN-managed mixed-species plantations established on bare land were further compared against the weighted average on the modeled monoculture plantations. The weight of each monoculture was determined based on the stem number of each tree species in the mixed-species plantations at the time of planting.

From the opportunity costs, we further calculated the changes in costs or timber revenues needed for the CTN-managed stands to break even with the best-performing monocultures. Finally, we calculated the carbon credits price and annual biodiversity payments required for the CTN-managed stands to break even. These biodiversity payments can be thought of as hypothetical annual easement payments required for covering the opportunity costs of implementing CTN management practices.

## Results

In this study, we compared the economic potential, carbon sequestration, and biodiversity potential of CTN managed plantations to conventional monoculture plantations on a study site in Central America. We also evaluated the impact of carbon payments on the economic performance of CTN-managed plantations. The study examined two establishment

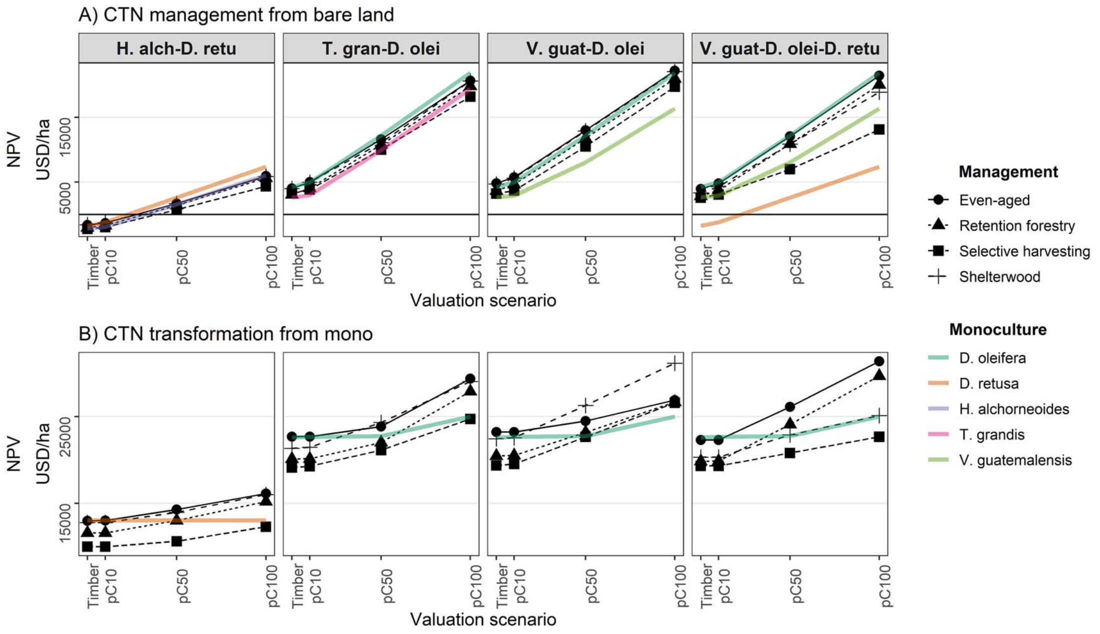


**Figure 3.** The economic potential of CTN-managed plantations evaluated based on two establishment scenarios: (A) reforestation of bare land and (B) transformation of mature even-aged monoculture plantations. In the 'Timber' valuation scenario, only revenues from timber sales were considered (i.e. the carbon price equals 0 USD/tCO2e). In the 'pC10', 'pC50', and 'pC100' scenarios, payments for carbon credits were also included in the valuation at prices of 10, 50, and 100 USD/tCO2e, respectively. The colored lines in the figure represent the economic potential of even-aged monoculture plantations. The horizontal distances between the valuation scenarios equal the differences in carbon prices.

scenarios: reforestation on bare land and transformation of mature monoculture stands.

## Economic potential of CTN management

First, we examined the economic potential of CTN-managed plantations established either on bare land or by transforming mature even-aged monoculture plantations. Figure 3 presents the economic potential of CTN-managed plantations under optimized management. The optimized management parameters can be found in Supplementary 2. When only revenues from timber sales were considered in the valuation, all CTN management types were economically viable on the study site for the mixtures *T. grandis–D. oleifera* (3073–4016 USD/ha), *V. guatemalensis–D. oleifera* (3225–4827 USD/ha), and *V. guatemalensis–D. oleifera–D. retusa* (2597–3952 USD/ha) at a discount rate of 8% when plantations were established on bare land. The mixture *H. alchorneoides–D. retusa* was not economically viable under any management type. Mixed-species stands managed under even-aged management had the highest economic potential across all mixtures, while stands managed through selective harvesting had the lowest economic potential. The even-aged managed and shelterwood-managed stand *V. guatemalensis–D. oleifera* (4827 and 4694 USD/ha) had a higher economic performance than the best-performing optimized monoculture plantation (*D. oleifera*: 4237 USD/ha) on the site.

When CTN-managed plantations were established by transforming mature monoculture stands, all CTN management strategies were economically viable for all mixtures when considering only revenues from timber sales in the valuation. Again, even-aged managed mixtures had the highest economic potential while selective harvesting had the poorest performance.

Including carbon payments in the valuation significantly increased the economic potential of CTN-managed plantations established on bare land or by transforming mature monoculture stands. The improvements in economic potential ranged from 0–1009 USD/ha, 621–8194 USD/ha, and 2297–17 478 USD/ha at carbon prices of 10, 50, and 100 USD/tCO2e, respectively.

We then compared the NPV performance of CTN-managed mixed-species stands against the performance of monoculture plantations under optimized management. For plantation established on bare land (Fig. 4), CTN-managed plantation generally under-performed the best-performing species grown in even-aged monocultures both when plantations were managed only for timber production and when carbon payments were considered in the management. Generally, the underperformance of CTN-managed stands compared to the best-performing monocultures increased with increasing carbon prices. Only the mixture *V. guatemalensis–D. oleifera* managed through even-aged management or shelterwood cutting consistently outperformed the best-performing monoculture. Overall, the positive NPV surplus achieved by some CTN-managed stand was relatively small (12–818 USD/ha) compared to the negative surplus incurred by most other CTN-managed stands (51–8762 USD/ha).

When comparing the performance of CTN-managed mixed-species stands against the average performance of the same species grown in monocultures, all CTN-managed mixed-species plantations achieved a positive NPV surplus when even-aged or shelterwood management practices were applied. For the mixtures *H. alchorneoides–D. retusa* and *T. grandis–D. oleifera*, this outperformance dissipated with increasing carbon prices.

Transforming mature monocultures to CTN-managed mixed-species stands generally came with a very high negative NPV surplus (i.e. a high opportunity cost) or rarely small positive surplus when managing plantations solely for timber production and timber sales (Fig. 5). However, when carbon payments were considered in CTN management, and with increasing carbon prices, this opportunity cost decreased. At a carbon price of 100 USD/tCO2e, all CTN-managed mixed-species plantations outperformed the monocultures, except mixed-species stands managed through selective harvesting.

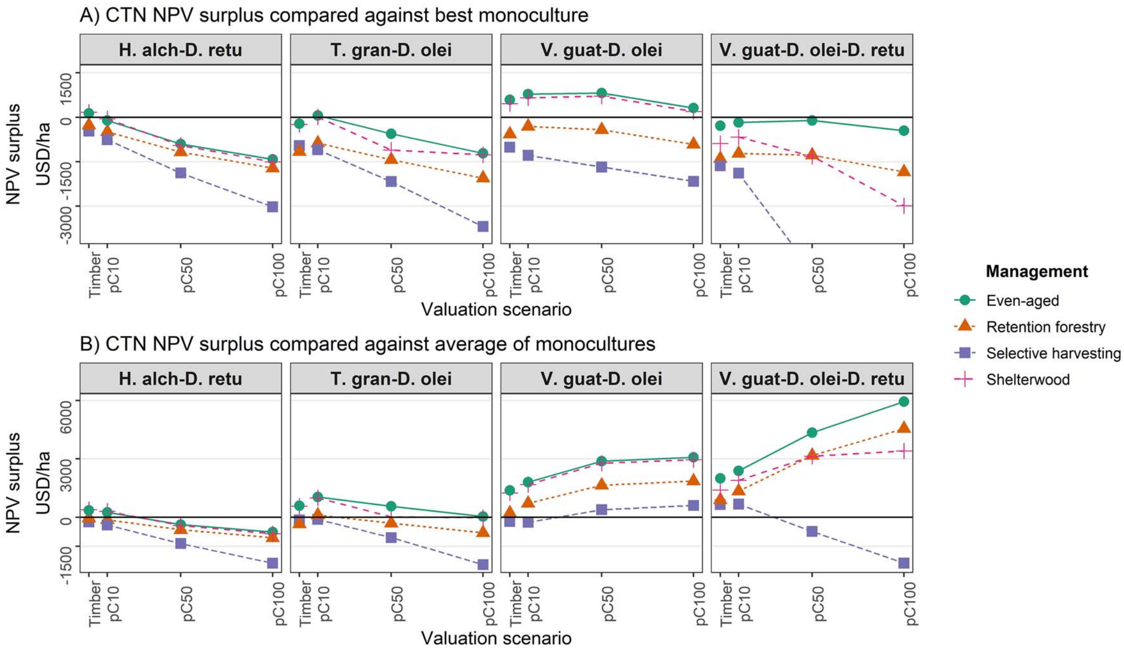


**Figure 4.** NPV surplus achieved by CTN-managed plantations established on bare land under optimized management when compared against (A) the best performing species of the respective mixture grown in monoculture and (B) the average NPV achieved by species of a respective mixture grown in monocultures. A positive NPV surplus indicates that CTN-managed mixed plantations outperformed the comparison monoculture(s). In the 'Timber' valuation scenario, only revenues from timber sales were considered (i.e. the carbon price equals 0 USD/tCO2e). In the 'pC10', 'pC50', and 'pC100' scenarios, payments for carbon credits were also included in the valuation at prices of 10, 50, and 100 USD/tCO2e, respectively. The horizontal distances between the valuation scenarios equal the differences in carbon prices.

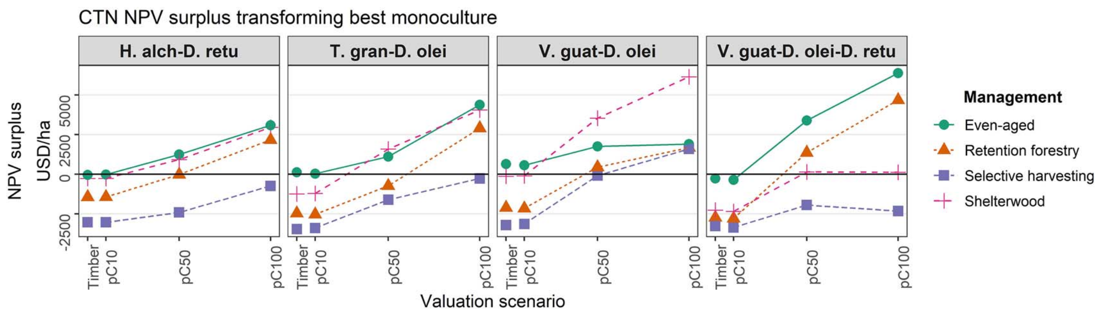


**Figure 5.** NPV surplus achieved by CTN-managed plantations established by transforming mature monocultures under optimized management when compared against the best performing species of the respective mixture grown in monoculture. A positive NPV surplus indicates that CTN-managed mixed plantations outperformed the comparison monoculture. In the 'Timber' valuation scenario, only revenues from timber sales were considered (i.e. the carbon price equals 0 USD/tCO2e). In the 'pC10', 'pC50', and 'pC100' scenarios, payments for carbon credits were also included in the valuation at prices of 10, 50, and 100 USD/tCO2e, respectively. The horizontal distances between the valuation scenarios equal the differences in carbon prices.

If monocultures were excluded from receiving carbon payments, most CTN-managed stands outperformed the best-performing monocultures at carbon prices above 50 USD/tCO2e regardless of the initial stand scenario (see Supplementary 2).

## Carbon sequestration and biodiversity potential

Carbon storage within the certification period in CTN-managed stands was generally similar to that of conventional even-aged monoculture stands (ranging from 23.6 to 63.6 tons C per hectare) when CTN-managed stands were solely managed for timber sales (Fig. 6). Stands managed through selective harvesting showed the lowest carbon storage of the CTN-managed stands when the plantations were established on bare land, while even-aged mixtures showed the lowest carbon storage when CTN stands were established through the transformation of a mature monoculture. The inclusion of carbon payments in the valuation resulted in consistently increasing carbon storage with increasing carbon prices. At a carbon price of 100 USD/tCO2e, carbon storage in CTN-managed stands increased by up to 8.6–97.9% compared to stands solely managed for timber sales.

The carbon storage in CTN-managed stands established on bare land and those established by transforming mature monocultures were largely similar. Thus, establishing CTN-managed stands on bare land or land with relatively low above-ground biomass, such as pastures, would result in a considerably larger net climate benefit through carbon sequestration compared to transforming mature monocultures. In fact, under optimized management, the transformation of mature monocultures to CTN-managed stands only resulted in increased carbon storage consistently when the stands received carbon payments (i.e. CTN stands solely managed for timber sales did not consistently achieve increased carbon storage compared to monocultures).

Regardless of the initial stand scenario, CTN-managed stands only consistently achieved increased carbon storage compared to monoculture stands when monoculture stands did not receive carbon payments (see Supplementary 2). Modeled *D. oleifera*

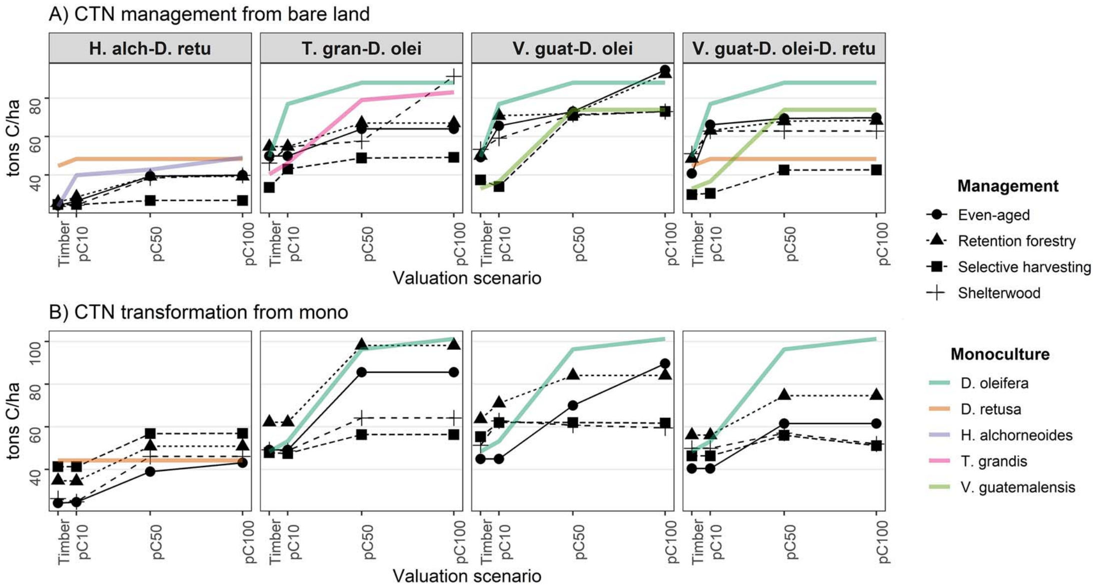


**Figure 6.** Mean stand carbon stored in living trees during the certification period by (A) reforesting bare land or (B) transforming mature even-aged monoculture plantations. In the 'Timber' valuation scenario, only revenues from timber sales were considered (i.e. the carbon price equals 0 USD/tCO2e). In the 'pC10,' 'pC50,' and 'pC100' valuation scenarios, payments for carbon credits were also included at carbon prices of 10, 50, and 100 USD/tCO2e, respectively. The colored lines show the carbon storage potential of even-aged monoculture plantations.

monocultures partly achieve a considerable higher carbon storage within the certification period than the comparison CTN-managed stands when carbon payments were included in the valuation.

Figure 7 presents biodiversity indicator values for CTN-managed plantations established on bare land. Biodiversity indicator values for CTN-managed plantations established by transforming mature monocultures can be found in Supplementary 2 (but are largely similar). Overall, CTN-managed plantations exhibited higher biodiversity indicator values compared to monoculture plantations for indicators of structural diversity, species diversity, and partially for the presence of large trees (expect when compared with monocultures of *V. guatemalensis* at high carbon prices). In contrast, biodiversity indicator values for deadwood volume and partially for the presence of large trees were within the range of values modeled in monoculture plantations. Even-aged mixed-species stands and shelterwood stands generally had the lowest values for structural diversity and species diversity among CTN-managed plantations.

There was no clear or consistent effect of carbon payments or increasing carbon prices on the biodiversity indicators. These effects appeared to be highly stand-specific, meaning they were specific to individual species combinations and management strategies. The only consistent trend was an increase in the presence of large trees with increasing carbon prices for CTN stands managed through selective harvesting. In some cases, the biodiversity indicators showed hints of a downward concave curve with increasing carbon prices, such as for all biodiversity indicators for *V. guatemalensis–D. oleifera* (especially under retention forestry or even-aged management) or the structural diversity of *T. grandis–D. oleifera*. This suggests that in specific cases biodiversity indicators may initially increase with the inclusion of carbon payments and increasing carbon prices under optimized management, but decrease once a certain carbon price threshold is exceeded.

## Breaking even with conventional monocultures

As shown previously, CTN-managed plantations generally had lower economic potential compared to the best-performing monocultures when only considering revenues from timber sales in the valuation. To compensate for these opportunity costs, total discounted costs would need to be reduced by 5–33.1% for CTN plantations on bare land or 1.6–104.2% for CTN plantations transformed from mature monocultures. If only planting costs were reduced (e.g. through using natural regeneration), planting costs would need to be reduced by 70.3–930.4%. See Supplementary 2 for details on opportunity costs and break-even points.

When considering carbon credits in the valuation and management optimization, underperforming CTN plantations would break even with the best-performing monocultures at carbon prices ranging from 2.2 to 21.9 USD/tCO2e for CTN plantations established on bare land, or 2 USD/tCO2e to >100 USD/tCO2e for CTN plantations transformed from mature monocultures (estimated through linear interpolation, excluding CTN-managed stands that achieved negative opportunity costs), assuming monocultures do not receive carbon credits (Fig. 8). Even-aged mixtures would require the lowest carbon prices to break even with monocultures, while stands managed through selective harvesting would require the highest carbon prices. Additionally, annual 'biodiversity payments' of 19.6–145.5 USD/ha for CTN plantations established on bare land or 4.5–308.2 USD/ha for CTN plantations transformed from mature monocultures would be necessary for CTN plantations to break even with the best-performing monocultures.

# Discussion

In this study, we aimed to evaluate the economic feasibility of CTN management of tropical timber plantations in comparison to conventional monoculture plantations. We also examined the potential for carbon payments to fund CTN management practices and the possibility for CTN management to provide additional carbon sequestration and biodiversity benefits alongside timber production. To our knowledge, this study is the first to assess the potential of tropical CTN-managed plantations on the basis of detailed process-based forest growth simulations.

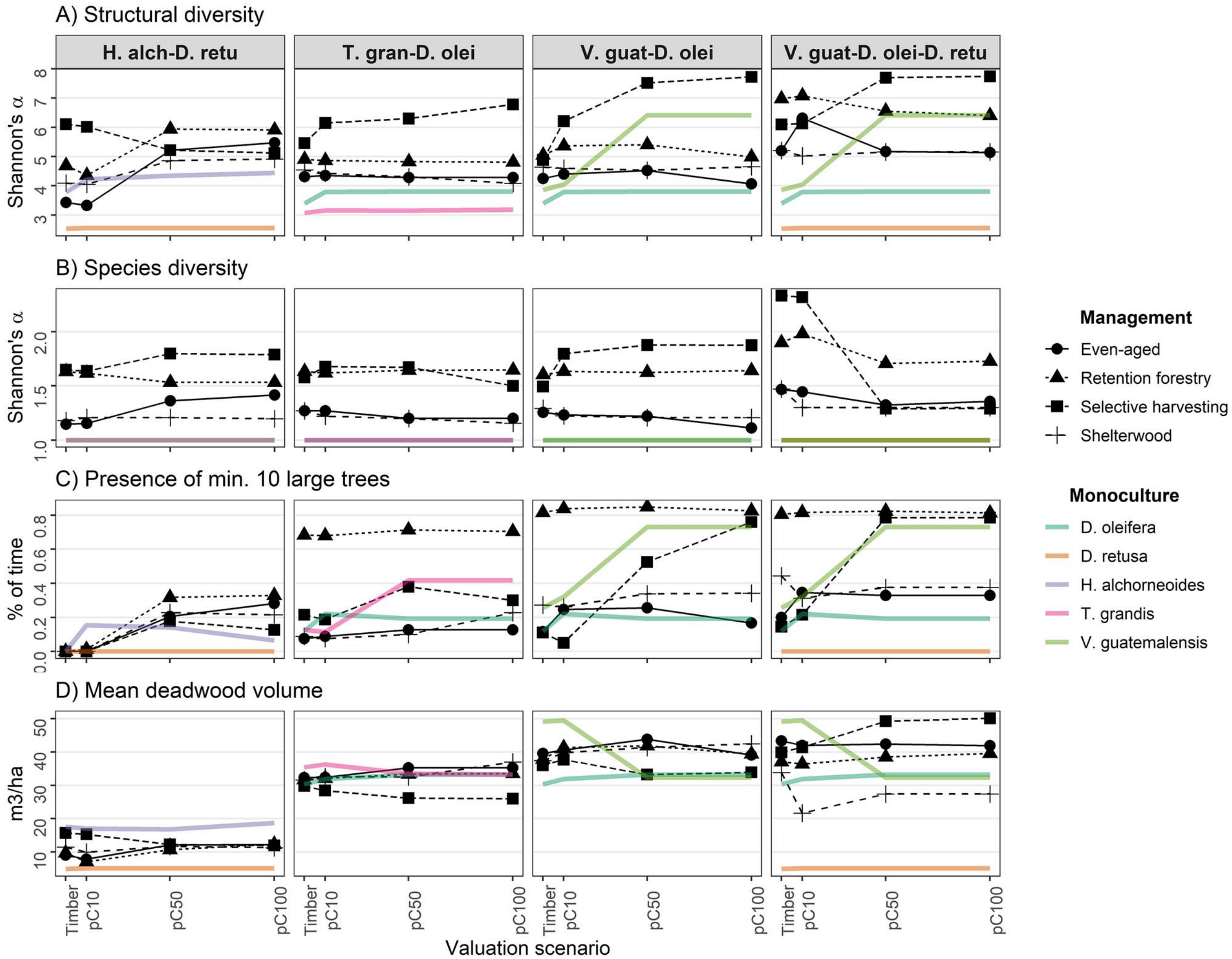


**Figure 7.** Key biodiversity indicators of CTN-managed plantations established by reforesting bare land. Results for the biodiversity indicators "structural diversity", "species diversity", "presence of min. 10 large trees", and "mean deadwood volume" are given in A, B, C, and D respectively. In the 'Timber' valuation scenario, only revenues from timber sales were considered (i.e. the carbon price equals 0 USD/tCO2e). In the 'pC10,' 'pC50,' and 'pC100' valuation scenarios, payments for carbon credits were also included at carbon prices of 10, 50, and 100 USD/tCO2e, respectively. The colored lines show the biodiversity potential of even-aged monoculture plantations. X-axes values of all subplots are identical to D.

## Economic potential of tropical close-to-nature plantations

We found that CTN management of tropical timber plantations was economically viable when only considering revenues from timber sales in the valuation. The best economic potential was achieved through even-aged management of mixed-species stands, with the performance of a given stand highly dependent on the selection of suitable tree species. *Hieronyma alchorneoides* and *D. retusa* were not commercially viable on the study site, and their mixture was not economically viable under any management type when established on bare land (as was already suggested earlier by Pinnschmidt et al. (2023b)). The inclusion of carbon payments substantially increased the economic potential of CTN-managed plantations, with the improvements ranging from 0–1009 USD/ha to 2297–17 478 USD/ha at carbon prices of 10 and 100 USD/ha, respectively. These findings largely resemble the findings of Pinnschmidt et al. (2023a). At carbon prices above 50 USD/ha, most CTN-managed stands outperformed the best-performing monoculture plantations if these monocultures did not receive carbon payments. Monoculture reforestations might increasingly not qualify for carbon credits as carbon certification schemes increasingly require reforestation projects to produce benefits beyond carbon storage, such as biodiversity benefits (VERRA 2017; Gold Standard 2019). However, if the monoculture plantations also received carbon payments, CTN-managed plantations did not consistently outperform them. These findings align with previous studies which already suggested that timber plantations of native species monocultures and even-aged mixed-species plantations could be financially viable in the tropics (Streed et al. 2006; Piotto et al. 2010; Griess and Knoke 2011; Sinacore et al. 2022; Pinnschmidt et al. 2023a; Pinnschmidt et al. 2023b). This study is potentially the first to demonstrate that also uneven-aged and other CTN management practices could be financially viable in a tropical plantation context.

So far, the financial feasibility of transforming monoculture plantations into CTN-managed plantations has mostly been explored in detail for temperate forests (Hanewinkel 2001; Vítková et al. 2021). In this study, the feasibility of transforming tropical monoculture plantations was explored. The transformation from mature monoculture stands to mixed-species CTN managed plantations was associated to high opportunity costs for most of the CTN practices and mixtures. High transformation costs at high discount rates were also reported by Nölte et al. (2018), who analyzed the transformation of even-aged into uneven-aged teak plantations. They also found transformation costs increased

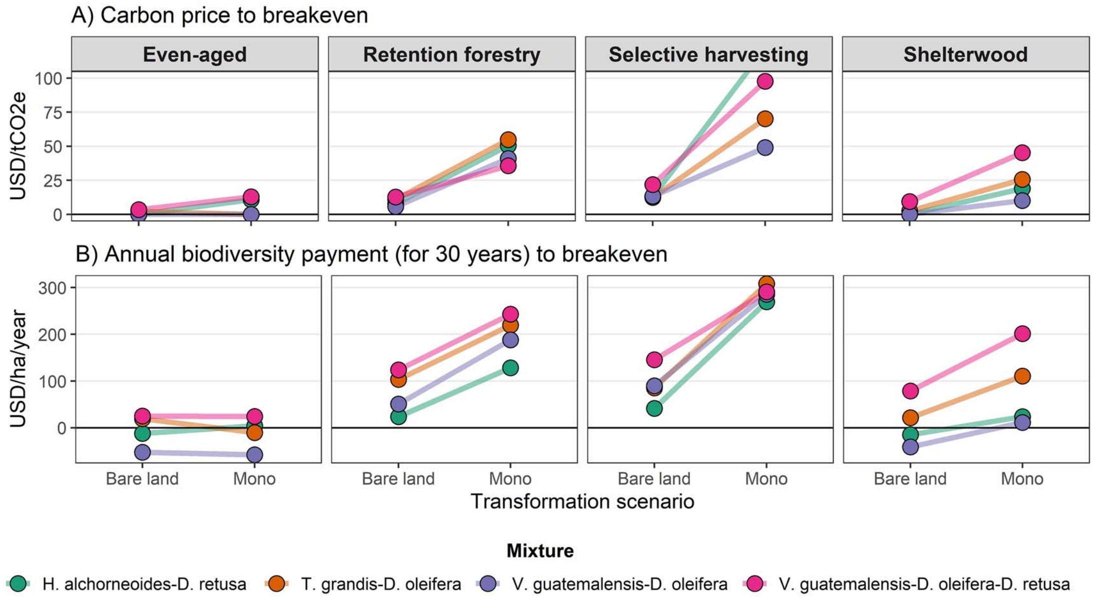


**Figure 8.** Carbon price (A) and yearly biodiversity payments (B) necessary for CTN-managed plantations to break even with the best performing even-aged monocultures if monocultures were excluded from carbon payment schemes. The transformation scenarios consider CTN-managed plantations established by reforesting bare land ('Bare land') or transforming mature even-aged monoculture plantations ('Mono'). 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

along with structural diversity. When establishing CTN mixed-species stands on bare land, we observed lower opportunity costs compared to transformation from mature monocultures, or in some cases even negative opportunity costs. This aligns with findings from Nölte et al. (2018), who reported uneven-aged forest management to be economically attractive once the transformation was completed, and with the results of previous economic studies in temperate forests (Knoke 2012; Vítková et al. 2021). The higher opportunity cost of transforming a mature monoculture is due to the opportunity cost of forgone revenues from postponing the harvesting of the mature stand, taking into account the time value of money. Among the CTN management practices, the highest opportunity costs of transformation were observed in practices that do not allow clearcutting or that involve harvesting in intervals, such as selective harvesting. When using the best-performing monoculture as a baseline for comparison, the opportunity costs may also include the admixture of species with lower economic potential (e.g. when admixing *D. retusa,* which does not appear to be a commercially viable species on the study site).

## Carbon and biodiversity benefits

When solely managed for timber production, CTN-managed plantations had similar carbon storage levels to even-aged monoculture plantations, regardless whether established on bare land or by transforming mature monoculture stands. Biodiversity indicator values were generally higher in CTN-managed plantations compared to monoculture plantations in terms of structural diversity and species diversity, but were similar or lower in terms of deadwood volume and the presence of large trees. Thus, CTN practices could be important for increasing the biodiversity value of forest plantations, but not necessarily for enhancing its carbon storage potential. This relation between carbon payments and biodiversity values has not previously been explored for tropical plantation forests.

A significant increase in carbon storage was achieved by an increase in carbon prices. Current carbon prices could not significantly increase the carbon storage potential, as was reported previously (Derwisch et al. 2009; Nölte et al. 2018). However, with carbon prices above 50 USD/tCO2e carbon storage approximately doubled for some of the mixtures and CTN practices. The effects of carbon payments on biodiversity indicators were stand-specific and not consistent, showing that carbon storage and biodiversity protection do not always align and that the creation of performance-based biodiversity payments, or the exclusion of monocultures from current carbon certification schemes, might be necessary in order to explicitly incentivize biodiversity protection in plantation forestry.

According to previous research, mixed-species stands might be more suitable for carbon plantings than monoculture plantations due to the presence of complementary interaction effects (Hulvey et al. 2013; Schnabel et al. 2019; Le et al. 2020). However, a recent simulation study by Pinnschmidt et al. (2023a) found that tropical mixed-species plantations managed using even-aged techniques did not consistently show higher or lower carbon storage compared to monoculture plantations managed to maximize carbon sequestration. This finding also applies to the other CTN management practices studied in this study. The lack of carbon outperformance in mixed-species stands may be partly due to the limitations of the 3PGmix model, which can represent species-interaction effects related to competition for light, but not facilitative species-interaction effects. Additionally, the results of this study do not consider the ability of mixed-species stands to buffer against interannual productivity variations (Schnabel et al. 2021). It is important to note that studies exploring the overyielding effect of mixed-species stands often involve high-density research plots or natural forests. In commercial timber plantations, regardless of whether they are managed using conventional monoculture even-aged techniques or mixed-species CTN management, stand density is often reduced to promote individual tree growth in order to achieve shorter rotation times. This reduction in stand density may also weaken species interaction effects (Mina et al. 2018).

CTN-managed stands showed increased species and structural diversity compared to monoculture plantations, but not in terms of deadwood volume or the presence of large trees. The deadwood in this study consisted mainly of harvest residues and was therefore closely related to stand productivity and the occurrence of harvest activities. Even-aged mixed-species stands had the lowest species and structural diversity among CTN-managed stands but showed higher or equivalent biodiversity indicator values compared to monoculture plantations. These findings suggest that the adoption of mixed-species practices, including even-aged management of mixed-species plantations, can increase biodiversity in plantation forests and that continuous cover practices such as shelterwood cutting, selective harvesting, or retention forestry may further benefit biodiversity (Lindenmayer et al. 2003; Stephens and Wagner 2007). There was no consistent relationship between the inclusion of carbon payments in the valuation and management optimization and the biodiversity indicator values. Accordingly, optimizing stand management to increase payments for carbon credits does not necessarily lead to improved biodiversity values. The only consistent trend was an increase in the presence of large trees with increasing carbon prices. Under optimized management, increasing carbon prices often leads to increased rotation times, i.e. larger tree sizes at harvesting (Quintero-Méndez and Jerez-Rico 2019; Hou et al. 2020).

Carbon storage and biodiversity are important arguments for the adoption of CTN management practices. However, our study did not consider several other benefits of these practices. Mixed-species forestry has been demonstrated to reduce financial risk in managed forests through various mechanisms, including the stabilization of growth resulting from mixing tree species, a reduced likelihood of large-scale disasters, and the production of multiple timber products, which can mitigate market-related risk (Nichols et al. 2006; Knoke et al. 2008; Messier et al. 2021). Additionally, some CTN management strategies, such as selective harvesting, may further reduce market-related risks through risk spreading due to more frequent harvesting interventions (though the amount of harvested wood at each intervention is smaller) (Roessiger et al. 2011; Knoke 2012; Pukkala 2015).

## Modeling assumptions, limitations, and uncertainties

There are several limitations and uncertainties to consider when interpreting the results of this study on the economic, carbon, and biodiversity potential of tropical CTN timber plantations.

First, the study is based on simulations rather than real-world examples. While simulations can be useful, real-world examples of tropical CTN-managed plantations are necessary to confirm the validity of the results and to understand their broader applicability. To date, such examples of real-world CTN-managed plantations are lacking in the tropics (except even-aged, mixed-species plantations). Nonetheless, the 3PGmix forest growth model underlying our simulations has been tested extensively—and shown good predictive abilities—for a wide variety of mixed-species and uneven-aged forest stands around the world (e.g. Forrester et al. (2021); Forrester and Tang (2016); Nölte et al. (2022)).

Second, the study found that selective harvesting performed poorly compared to other CTN management strategies. This result is in contrast to the broader literature, which often suggests that selective harvesting can be more effective than even-aged stands because individual trees can be harvested closer to their economic optimum (Hanewinkel et al. 2014; Pukkala 2015). The 3PGmix model used in this study assumes a homogenous stand (i.e. tree of different species or cohorts are spread evenly across space) and does not model gaps that would be present in a real-world selective harvesting system. In practice, replanting or natural regeneration would most likely occur in the gaps left by felled trees rather than being evenly distributed throughout the stand. Additionally, in a heterogenous stand, a higher stand density and larger target diameters may be maintained, which could lead to higher productivity and better economic performance. Furthermore, selective harvesting was implemented as a special case of 'thinning from above' (due to modeling restrictions) where *most* trees above the target size were harvested during harvest interventions, while a few large (and accordingly valuable) trees were left unharvested. Therefore, the full commercial potential might not have been achieved in the simulated stands. Despite these limitations, the study highlights the potential of selective harvesting practices for improving biodiversity values, e.g. by achieving a high structural diversity.

Third, we compared the economic potential of CTN-managed plantations and monocultures assuming that both were managed to their full economic potential. In reality, there may be fewer management recommendations (or none) available for CTN-managed plantations, and monocultures may be more likely to be managed optimally. This means that the opportunity costs of CTN-managed stands may be even higher in practice than what is reflected in this study. It should here be noted that CTN-managed stands were assessed against the best-performing monocultures. This allowed for a conservative economic assessment, but it may also be too restrictive. For example, in the study region, teak plantations are the most common plantations (REDD/CCAD-GIZ-SINAC 2015). If teak monocultures had been taken as the baseline for assessment on the specific study site, the admixing of *D. oleifera* would have resulted in negative opportunity costs (i.e. would be profitable) under several CTN management scenarios.

We did not consider the opportunity cost of alternative land uses in the economic evaluation. Instead, our analysis focuses on whether the examined silvicultural production systems are financially profitable. The opportunity cost of alternative land uses is identical for all the examined scenarios, and the inclusion of these opportunity costs would not affect the main conclusions of this study. Whether CTN-managed plantations are an economically sensible land use on a given piece of land will be highly context-specific and would need to be assessed by considering the value of alternative land uses.

Finally, the study assumed that the same management costs and timber prices would apply to both CTN-managed plantations and monocultures. However, the costs of CTN plantations may differ due to the increased complexity of the management, which may require more work and the maintenance of a highly skilled crew. In uneven-aged stands, smaller trees may be damaged during the harvesting of larger trees, which could lead to the loss of trees or reduced timber quality and price. Increased costs and reduced revenues would, again, lead to increased opportunity costs for CTN management.

Clearly, the CTN management practices considered in this study and the resulting modeled stands still represent strongly simplified forest ecosystems compared to natural tropical forests where tens—or even hundreds—of tree species can coexist in close vicinity (Lieberman et al. 1996; Gillespie et al. 2009). Nonetheless, they offer a seemingly financially viable and ecologically valuable alternative to conventional even-aged monoculture plantations that can be managed based on relatively simple management heuristics. The resulting plantation might therefore rightly be described as 'closer-to-nature'. In the broader trend toward multi-purpose forest management that has also reached tropical plantation forestry, CTN managed plantations might be an important component of future tropical forest landscapes within the sparing-sharing continuum (Runting et al. 2019; Betts et al. 2021; Jones et al. 2023).

A key objective of this study was to explore and highlight the commercial and ecological potential of CTN management practices in tropical plantation forestry as an alternative to conventional monocultures. We did not present a detailed analysis of the silvicultural implications of such practices under various scenarios. In the past, management complexity has been identified as an important obstacle for the adoption of alternative management systems in plantation forestry (Nichols et al. 2006). Formulating management recommendations and guidelines that can be implemented in practice will be crucial to promote tropical CTN management practices.

## Making close-to-nature plantations competitive

The adoption of CTN management practices in tropical plantation forestry is currently largely absent. Many barriers for the adoption of such practices might still be in place. Knoke et al. (2008) and Nichols et al. (2006) point toward the increased management complexity and perceived higher risk as an important barrier to implementation of mixed-species practices in plantation forestry. This might be especially true in the tropical forestry context, where forest dynamics and related implications to forest management are still less well-understood than in temperate forests. Accordingly, more efforts must be put into understanding forest dynamics in tropical CTN-managed plantations and developing practical management guidance in accordance with these dynamics (Seydack 2002).

Gresh and Courter (2021) highlight that historical and institutional forest management paradigms might be an important factor for implementation of novel forest management practices, such as CTN forest management. In tropical plantation forestry, this historical paradigm has been dominated by exotic species monoculture plantations (FAO 2020).

Furthermore, Maennicke and Griess (2019) point out that CTN management can only be applied successfully in the long-term if the required legal structures are in place, and forest owners have a legitimate interest in sustainable management. These conditions might not have been given in some tropical countries where corruption and illegal timber harvesting has been prevalent in the forestry sector (Smith 2004).

Finally, from a forest investor perspective, there might not have been sufficient performance-based financial incentives in place to adopt CTN management practices. Based on the findings of this study, investors would likely incur an opportunity cost by applying most of the examined CTN management strategies, due to reduced economic performance and increased risk from the lack of management experience and increased management complexity. However, while some CTN management practices may not currently be competitive with the best-performing monocultures, they may still be economically viable on their own. They may therefore already be an option for forest investors who have investment objectives beyond profit maximization. Continuous cover management practices may also already be applied and economically viable in areas where frequent clearcutting is not desirable.

The competitiveness of CTN-managed stands could be improved by using natural regeneration, which reduces planting costs compared to monocultures that are commonly planted. In the tropics, using natural regeneration may reduce the cost of regeneration by 70% compared to planting (Shono et al. 2007; Nunes et al. 2020). However, in this study, even a planting cost reduction of 100% did not cover opportunity costs in several instances and does not seem like a promising driver of CTN competitiveness.

It could be speculated that timber from CTN plantations can be marketed as 'more sustainable' and achieve a price premium compared to timber from conventional plantations. However, evidence of price premiums for sustainable timber is sporadic and rarely exceeds the additional costs for certification and marketing that may occur (Nebel et al. 2005; Espach 2006; Ebeling and Yasué 2009; Chen et al. 2010).

Recently, carbon prices for carbon credits from reforestation projects reached 11–16 USD/tCO2e on the voluntary carbon market (Forest Trends' Ecosystem Marketplace 2023). At these prices, carbon payments for CTN-managed plantations could cover opportunity costs on the study site, if monocultures are excluded from carbon payments, for plantations established on bare land. Carbon prices are projected to exceed 100 USD/tCO2e in the future (Trove Research 2021; Credit Suisse 2022; The World Bank 2022). At this price, even the transformation of existing mature monocultures to CTN-managed mixed-species stands would be financially feasible, if such transformation qualifies the transformed stands for receiving carbon credits from IFM carbon crediting schemes. However, under current certification schemes, the establishment of exotic species monocultures qualify for carbon credits (if 'additionality' can be demonstrated and ecosystem safeguards are fulfilled), which may present a barrier to the widespread adoption of CTN management practices in tropical timber plantations. Nonetheless, leading carbon crediting organizations have made first attempts to exclude exotic species monocultures from their schemes (VERRA 2023b).

Currently, performance-based biodiversity credit schemes are being developed (World Economic Forum 2022). Under these schemes, the restoration of key ecosystem characteristics and functions is rewarded with biodiversity credits that can be sold on international (voluntary) markets, similar to carbon credits (Wallacea Trust 2022; Plan Vivo Foundation 2023). Based on the results of this study, the explicit remuneration of biodiversity benefits would likely favor the establishment of CTN-managed plantations, even if monocultures would also be included in such certification schemes, as CTN-managed stands generally showed higher or equivalent biodiversity indicator values. The relation between carbon credit and biodiversity credit prices may then become a key driver for the competitiveness of CTN-managed plantations.

# Conclusion

Overall, this study found that CTN management practices might be an economically viable alternative to current monoculture practices in tropical plantations forests under appropriate site and tree species selection. The application of CTN management practices could also produce considerable biodiversity benefits by increasing the structural and tree species diversity of tropical timber plantations. At current carbon prices, CTN-managed plantations might be financially competitive with monocultures if monoculture practices are excluded from carbon certification schemes. If carbon prices increase further, the sale of IFM-based carbon credits could finance the transformation of existing monoculture stands to mixed-species CTN-managed stands. The implementation of performance-based biodiversity crediting and payments could further improve the competitiveness of CTN management practices in tropical plantation forestry.

# Author contributions

Arne Pinnschmidt (Conceptualization, Formal analysis, Writing—original draft), Rasoul Yousefpour (Conceptualization,

Supervision, Writing—review & editing), Anja Nölte (Conceptualization, Writing—review & editing), and Marc Hanewinkel (Conceptualization, Supervision, Writing—review & editing)

## Supplementary data

Supplementary data are available at *Forestry* online.

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## Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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