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GROWTH AND ABOVEGROUND CARBON OF TREES ESTIMATED USING THE FORCASTREE (SEXI-FS) MODEL: POSSIBLE INPUTS FOR LAND RESTORATION AND CARBON PROJECT IN THE PHILIPPINES

A TECHNICAL REPORT

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TABLE OF CONTENTS

TABLES & FIGURES

TABLES

FIGURES

Image Source: World Agroforestry/Kelvin, "Regreening Africa", (2022). Retrieved from: https://www.flickr.com/photos/icraf/52334862902/in/album-72177720301870353/

SUMMARY

Kennemer Eco Solutions (KenEco) program of Kennemer Foods International, Inc. (KFI) aims to develop a carbon offsetting scheme using tree-based practices that can reconcile carbon and income benefits for smallholder's livelihoods. Therefore, KenEco is interested in exploring several options for tree-based practices, especially for the context of southern Philippines, which can generate such benefits.

In this report, we present the results of a projection of potential aboveground carbon storage of four tree-based practices using FORCASTREE (a model **FOR** simulating growth and **CA**rbon of fore**ST** and agroforest t**REE**s): a tree-tree growth and interaction model, formerly known as SExI-FS (Spatially Explicit Individual-based Forest Simulator), developed by the World Agroforestry (ICRAF). The four tree-based practices combine fast- and slow-growing and native and exotic tree species: (1) a mixture of different Dipterocarp species, (2) native and exotic non-Dipterocarp species, (3) Dipterocarp, fruit trees, and cacao, and (4) Dipterocarp species, native non-Dipterocarp species, fruit trees, and cacao. Scenarios of tree mortality (with or without mortality) and tree density (400 or 1100 trees per hectare) were considered for each practice.

The results show that while Practice 1 could generate high carbon storage with a relatively slow carbon sequestration rate across 50 simulation years, Practice 2 is suitable for accumulating high carbon storage (although the final projection is lower than that of Practice 1) with a quick sequestration rate at early years after tree planting. Practices 3 and 4 are good options for accumulating high carbon storage with potential economic co-benefit (although this benefit was not estimated in this report) from fruit trees or high-value crops such as cacao.

Tree mortality rate is higher in Practice 2 which likely indicates a strong space and light competition between Acacia mangium as an exotic species and Eucalyptus deglupta as a native species. The latter is the species which suffers the most because of the competition. Increasing tree density does not necessarily result in a higher accumulated carbon storage. Competition in space and light resources among trees has constrained tree growth.

Future studies should try to collect primary data on tree growth (stem diameter, tree height, or canopy shape and size) to better calibrate the model. The framework and assessment results described in this study can provide inputs to the KenEco program or encourage a wider application in other regions of the Philippines or other countries, to support land restoration or carbon projects.

1 BACKGROUND

Kennemer Foods International, Inc. (KFI) is a Philippine agribusiness company specializing in sustainable growing, sourcing, and trading of high-quality agricultural crops sourced from smallholder farmers. For example, for fermented cacao beans, they engage with smallholder farmers in Mindanao, Visayas, and Palawan.

KFI has an Afforestation, Reforestation, and Revegetation (ARR) program under their Mindanao Tree Planting Program for Climate and Communities (MinTrees). The ARR program aims to integrate several financing strategies for rural development and sustainable agri-business including soft loan agri-lending, development grants, and climate finance. The ARR's expected outcomes include (1) the establishment of the first climate-financed mechanism for smallholders with agroforestry in the Philippines, (2) improvement and diversification of livelihood of smallholder farmers in the project sites, (3) maintenance and improvement of agricultural production of more than 50,000 ha of land, and (4) ecological reforestation of degraded lands for biodiversity and climate benefits. KFI also has a Kennemer Eco Solutions (KenEco) program which aims to develop a carbon offsetting scheme for the carbon market. KenEco is interested in examining the carbon potential of different tree-based practices as possible inputs for the ARR program in Southern Mindanao.

The World Agroforestry (ICRAF) and KFI have been collaboration partners in the Sustainable Farming in Tropical Asian Landscapes (SFITAL) project in Davao de Oro, Mindanao region of the Philippines since 2020. The SFITAL project aims to link small-scale producers to global supply chains in an environmentally sustainable, economically viable, and socially responsible manner. The project also addresses the mitigation potential of tree-based practices, especially cacao-based practices, in the context of capacity for greenhouse gas removal. KFI through the KenEco program worked with ICRAF in conducting a potential carbon assessment of tree-based practices using ICRAF's tree growth and carbon assessment tool called FORCASTREE (a model **FOR** simulating growth and **CA**rbon of fore**ST** and agroforest t**REE**s) formerly known as Spatially Explicit Individual-based Forest Simulator (SExI-FS) (Harja and Vincent, 2008).

This technical report aims to describe the methodological framework and assessment results of an estimation of potential aboveground carbon storage of several tree-based practices using the FORCASTREE model. The framework and assessment results can provide inputs to the KFI's ARR program or encourage a wider application in other regions of the Philippines or other countries, to support land restoration or carbon projects.

2 METHODS

2.1 METHODOLOGICAL FRAMEWORK

The assessment was conducted in four steps (Figure 1). A literature review using research articles, official or project reports, newsletters, and academic theses, was done (step 1) to identify options for tree species for land restoration and carbon accumulation in the Mindanao region of the Philippines. The tree species can be those cultivated in any farming or forestry practice including agroforestry and forest plantation, in low or uplands, and private or community lands. KenEco selected the tree species for the model's simulation.

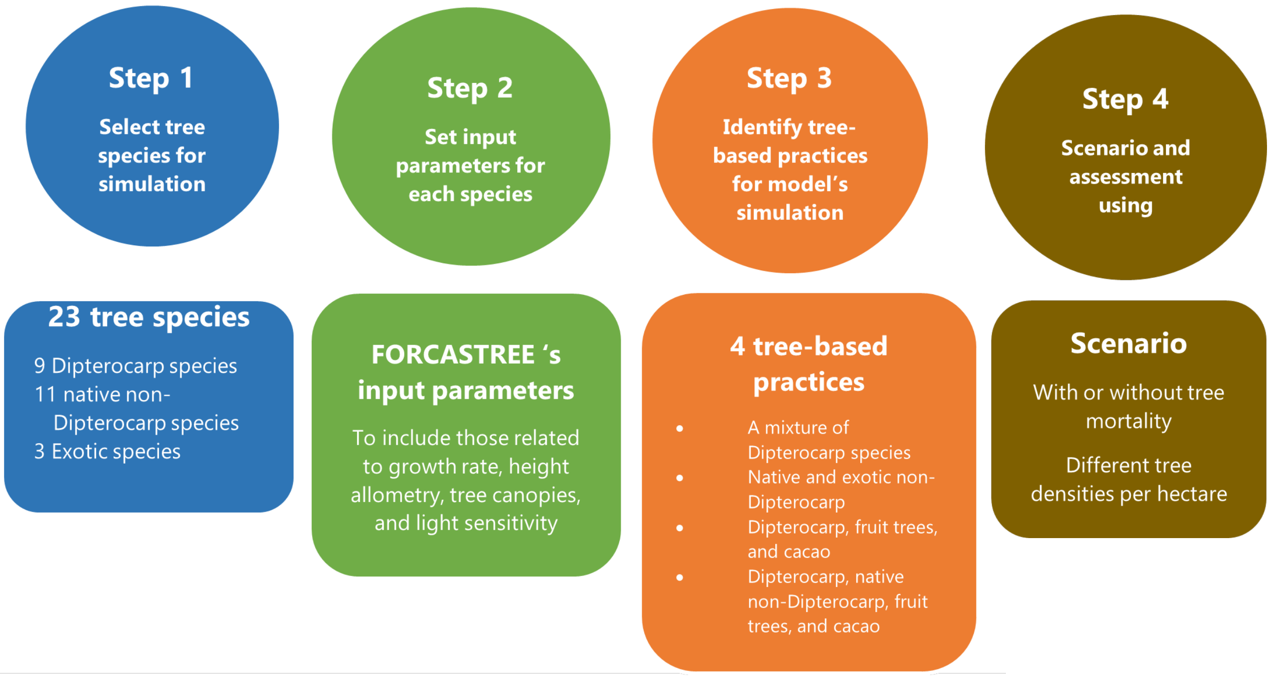

Figure 1. Four-step assessment of potential aboveground carbon of tree-based practices

The next step was to set the input parameters of each selected tree species (step 2). We first verified the growth characteristics of the selected tree species using a literature review, for example, if the species is fast or slow growing and if it is shade tolerant or light demanding. Thereafter, we estimated species-specific parameters using observed growth data from the literature. For species without observed data, we used parameters of similar tree species from the FORCASTREE's library. We assumed that all tree species grow in optimal growing conditions.

FORCASTREE simulates a forest or agroforestry stand at a 1-hectare scale. Therefore, in the third step, KenEco and ICRAF discussed the tree-based practices for the model's simulation and the species composition and density of each practice. Finally, in the fourth step, simulations using the model were conducted for each practice under the scenario of tree mortality and tree densities per hectare.

2.2 FORCASTREE (SEXI-FS) MODEL

FORCASTREE is a tool to simulate aboveground tree-tree (or woody shrubs, such as coffee or cacao) growth and interactions in uniform or mixed multi-species stands. The model uses an object-oriented approach where each tree is represented by a generic class of virtual trees. The growth of the simulated trees, while governed by parameters of stem or height allometric equations as inputs, is affected by the availability of two major aboveground resources: space and light. Therefore, tree growth is determined by plant metabolism and the 'carrying capacity' of the stands. The aboveground accumulated carbon of tree-based practices is calculated using the estimated stem diameter of individual trees within the stand and allometric equations linking the stem diameter and aboveground biomass. The latter is assumed to contain 46% carbon.

Key input parameters of the model include coefficients of allometric equations for stem diameter, tree height, and canopy, and those representing the light sensitivity of tree species. These parameters govern tree growth and competition among growing trees within the stand. Apart from the tree species library, an online tool (https://degi.shinyapps.io/app_afmodel/) is available to help users parameterize the model.

In FORCASTREE, diameter at breast height (DBH) is estimated using the following formula:

$$DBH = DBH_{max}\left(1 - e^{-k.t}\right)^{c} \qquad (1)$$

DBH_{max} is the maximum diameter of the species (cm), t is time or tree age (year), e is a constant, and k and c are species-specific constants.

The DBH increment is calculated using similar constants:

$$DBH_{inc} = DBH_{init} \cdot c \cdot k \left[\left(\frac{DBH_{init}}{DBH+}\right)^{-\frac{1}{c}} - 1\right] \qquad (2)$$

DBH_{init} is the initial diameter at breast height (cm) and can be assumed as 1 cm for most tree species.

Tree height (m) is calculated using the estimated DBH:

$$height = \alpha \cdot DBH^{\beta} \quad (3)$$

With α and β as species-specific constants.

The canopy (or 'crown') width is also estimated using DBH, where a and b are species-specific constants:

$$crown_{width} = a + b \cdot DBH \quad (4)$$

Other most important parameters are those indicating the light requirement and sensitivity of each tree species. These parameters could be estimated using the ecological information of the species and classifying the species into e.g., light-demanding, relatively shade tolerant, or shade-demanding species.

Finally, the potential aboveground biomass of individual trees is calculated using the allometric equation from Chave et al. (2005):

$$\text{Aboveground biomass} = 0.0509 \times \rho * (DBH)^2 * \text{tree height} \quad (5)$$

Where ρ is species-specific wood density and can be known from e.g., ICRAF's wood density database (http://db.worldagroforestry.org/wd).

The model can be used to simulate tree mortality and assisted or natural regeneration processes. Tree mortality can occur due to strong competition in space and light among individual trees. The competition generates a level of stress which affects tree survival.

As part of the outputs, the model generates a 3D visualization of tree growth and vertical projection of the one-hectare simulated stand (shown later below using simulated results of the current study). For more detailed information about the model, please refer to the user guide[1].

2.3 SELECTED TREE SPECIES FOR SIMULATION

KenEco and ICRAF selected 23 tree species for the simulation. The growth characteristics of each species based on a literature review are described in Annex 1. The 23 species can be classified into 9 Dipterocarpaceae species, 11 native, and 3 exotic non-Dipterocarpaceae species. Additional information for each species is given below[2].

[1] https://apps.worldagroforestry.org/sea/Products/AFModels/SExI/source/sexi_2.1.0/sexi_userguide.pdf
[2] Please also see "Philippine Native Trees 101 (2012) and 202 (2015)" published by the Green Convergence for Safe Food, Healthy Environment and Sustainable Economy, and Hortica Filipina Foundation, Inc. in 2012.

Dipterocarpaceae species

1. Apitong (*Dipterocarpus grandifloras*) is a slow-growing tree that requires shade in its earlier growth stage, suitably grows on clay-rich soils, and can adapt to drought-prone areas in Southern Asia.
2. Yakal-Saplungan (*Hopea plagata*) is one of the fastest-growing dipterocarp species that requires well-drained soils. It is drought-intolerant and should be mulched to help retain soil moisture.
3. Bagtikan (*Parashorea malaanonan*) is a moderately slow dipterocarp species that is tolerant to direct sunlight and can act as a nurse tree to shade-demanding species. Bagtikan is normally planted in easily accessible lowland areas.
4. Almon (*Shorea almon*) is a relatively slow dipterocarp species that can be found in undulated hills, or well-drained soils in low-altitude areas. Almon seedlings require shade, while mature Almon trees require full sun.
5. White lauan (*Shorea contorta*) is considered an emergent tree that usually occurs in low-altitude forests.
6. Mayapis (*Shorea palosapis*) is a slow dipterocarp species that usually grows in primary forests at low and medium altitudes. Mayapis is considered critically endangered (IUCN [2011] as cited by Calago and Diola (2022).
7. Tanguile (*Shorea polysperma*) can be found throughout the Philippines. It is considered a slow-growing species. The seedlings of Tanguile need shade while the mature trees require full sun. Tanguile is also called “Philippine mahogany”.
8. Palosapis (*Anisoptera thurifera*) is a fast dipterocarp species that can regenerate in secondary forests. Palosapis is the only dipterocarp species that can readily reinvade cultivated lands.
9. Hagakgak (*Dipterocarpus validus*) is a slow-growing species that is classified as critically endangered by the IUCN. Hagakhak can grow in primary and secondary forests, flat lands, freshwater swamps, riverbanks, and lands up to 300 masl.

Image Source: World Agroforestry/Kelvin, “Regreening Africa”, (2022). Retrieved from: https://www.flickr.com/photos/icraf/52334862902/in/album-72177720301870353/

Native non-Dipterocarpaceae species

10. Narra (*Pterocarpus indicus*) grows best in the open. Narra is commonly found on sandy or clay loams with neutral or slightly acid reaction (ICRAF database, http://db.worldagroforestry.org//species).
11. Dao (*Dracontomelon dao*) is a fast-growing species that is mostly found in riverine and limestone forests. Its seedlings or saplings need shade/filtered light while mature Dao needs full sun.
12. Lamio (*Dracontomelon edule*) is a moderately fast-growing non-dipterocarp species commonly found in lowland primary forests, along riverbanks, and on hills.
13. Toog (*Petersianthus quadrialatus*) can be found in Agusan, Surigao, Davao del Norte, Leyte, Samar, Negros, Masbate, Laguna, Sorsogon, and Bataan. Toog thrives near riverbanks or on hillsides, in swampy and cool places.
14. Malapapaya (*Polyscias nodosa*) grows in open thickets and second-growth forests (ideal for plantation establishment) in low and medium altitudes. It also grows in moist areas along creeks (Cadiz et al., 1991).
15. Kalumpit (*Terminalia macrocarpa*) is a fast native tree species that is widely distributed in primary forests. Full sun is needed by Kalumpit.
16. Bagras (*Eucalyptus deglupta*) is also called the Rainbow tree. It is a fast-growing species that is becoming threatened in its natural habitat. Full sun is ideal for Bagras. It is also being grown in plantations for pulp production.
17. Nato (*Palaquium luzoniense*) is well distributed throughout the Philippines. It is usually found in primary forests in low and medium altitudes and dry and limestone areas.
18. Kalantas (*Toona calantas*) is identified as a critically endangered species by DENR DAO 2007-1 and IUCN Red List 2004. It is a moderately fast-growing species that can be found in primary rainforests in low and medium altitudes.
19. Mangium (*Acacia mangium*) is an exotic fast-growing species that can be planted as wind or firebreak. Mangium is being used for soil and water conservation. The ideal soil type for Mangium is deeply weathered or alluvial soils (ICRAF database).
20. Durian (*Durio zibethinus*) is an exotic fruit tree that grows in deep, well-drained, light sandy, or loamy soil (ICRAF database).

Exotic non-Dipterocarpaceae species

21. Lanzones (*Lansium domesticum*) is a very slow-growing tree species. It could take up to 15 years to bear fruit.
22. Rambutan (*Nephelium lappaceum*) is a fast fruit tree species that can be found throughout the Philippines. Rambutan needs full sun to slight shade.
23. Cacao (*Theobroma cacao*) is an exotic high-value crop. It is a fast-growing understorey plant that is ideal to be grown in elevations ranging from 100-300 masl. Cacao is a tap-rooted plant that requires deep well-drained soils (ICRAF database).

Image Source: World Agroforestry/Kelvin, "Regreening Africa", (2022). Retrieved from: https://www.flickr.com/photos/icraf/52334862902/in/album-72177720301870353/

We could find (in the literature) reported stem diameter, tree height, or canopy of all 23 species, but not all these growth indicators are available for each species. In addition, that information is available for certain tree ages only. Annex 2 provides the list of references that we found for each tree species for the case of the Philippines.

2.4. SIMULATED TREE-BASED PRACTICES

Four tree-based practices were simulated: (a) a mixture of different Dipterocarp species (Practice 1); (b) a combination of native and exotic non-Dipterocarp species (Practice 2); (c) a combination of Dipterocarp, fruit trees, and cacao (Practice 3); and (d) a mixture of Dipterocarp species, native non-Dipterocarp species, fruit trees and cacao (Practice 4). The species composition of each practice is shown in Tables 1-4. The initial density of all practices is 400 trees per hectare and trees are planted randomly over the one-hectare simulated stand.

Table 1. Species composition of Practice 1 for 1 ha land

Species	Growth rate	No. of trees	Percentage
White Lauan	Slow	40	10%
Mayapis	Slow	40	10%
Tanguile	Slow	40	10%
Apitong	Medium	30	7.5%
Bagtikan	Medium	30	7.5%
Almon	Medium	30	7.5%
Hagakhak	Medium	30	7.5%
Yakal-Saplungan	Fast	80	20%
Palosapis	Fast	80	20%

Table 2. Species composition of Practice 2 for 1 ha land

Species	Group	Growth rate	No. of trees	Percentage
Bagras	Native	Fast	200	50%
Mangium	Exotic	Fast	200	50%

Table 3. Species composition of Practice 3 for 1-ha land

Species	Group	Growth rate	No. of trees	Percentage
White Lauan	Diptero	Slow	40	10%
Bagtikan	Diptero	Medium	40	10%
Yakal-Saplungan	Diptero	Fast	80	20%
Durian	Fruit	Medium	60	15%
Lanzones	Fruit	Slow	40	10%
Rambutan	Fruit	Fast	80	20%
Cacao	High-value crop	Fast	60	15%

Table 4 Species composition of Practice 4 for 1-ha land

Species	Group	Growth rate	No. of trees	Percentage
White Lauan	Diptero	Slow	40	10%
Bagtikan	Diptero	Medium	40	10%
Yakal-Saplungan	Diptero	Fast	80	20%
Narra	Native non-Diptero	Slow	40	10%
Toog	Native non-Diptero	Medium	40	10%
Dao	Native non-Diptero	Fast	40	10%
Lanzones	Fruit	Slow	40	10%
Durian	Fruit	Medium	40	10%
Rambutan	Fruit	Fast	40	10%
Cacao	High value crop	Fast	40	10%

It is worth noting that the current version of the FORCASTREE model does not have a module that can suggest the 'best' composition and density of input tree species for optimal carbon storage of a 1-ha simulated stand. It can only simulate growth and provide a carbon estimation of tree-based practices with a pre-determined composition and density of tree species by the users.

2.5 SCENARIOS OF TREE MORTALITY AND DENSITIES

We simulated the tree-based practice 1-4 with or without tree mortality, and at two planting densities namely, 400 trees/ha and 1100 trees/ha. In the scenario without tree mortality, tree density is constant across the simulation. No tree regeneration process was simulated because of a lack of input data for the model's calibration. We simulated each practice for 50 simulation years.

Image Source: World Agroforestry/Kelvin. "Regreening Africa". (2022). Retrieved from: https://www.flickr.com/photos/icraf/52334862902/in/album-72177720301870353/

3 RESULTS AND DISCUSSION

3.1. ESTIMATED GROWTH OF EACH TREE SPECIES

The input parameters used to estimate tree growth are given in Annex 3. The DBH across tree age for all selected species is shown in Figure 2.

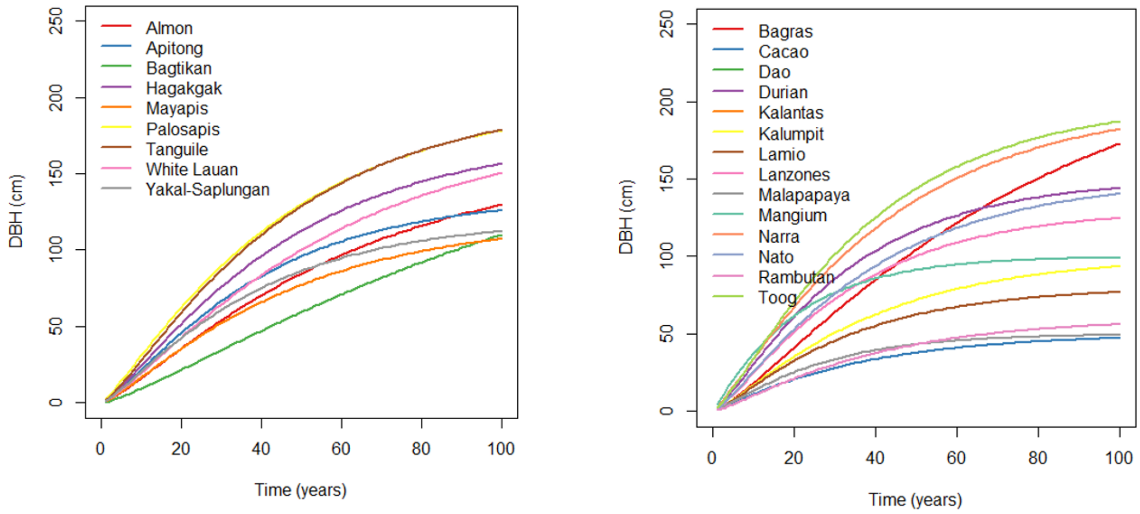

Figure 2. DBH size across tree age for Dipterocarp (left) and non-Dipterocarp (right) species

The DBH increment across a range of DBH is shown in Figure 3.

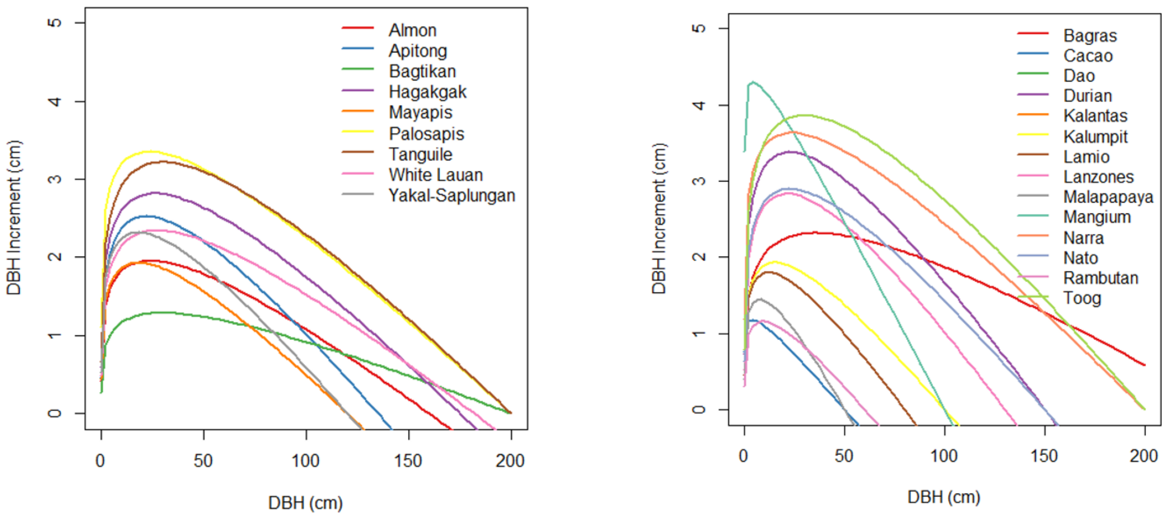

Figure 3. DBH increment of Dipterocarpus (left) and non-Dipterocarpus (right) species

Tree heights and canopy width estimated from DBH are illustrated in Figures 4 and 5 below.

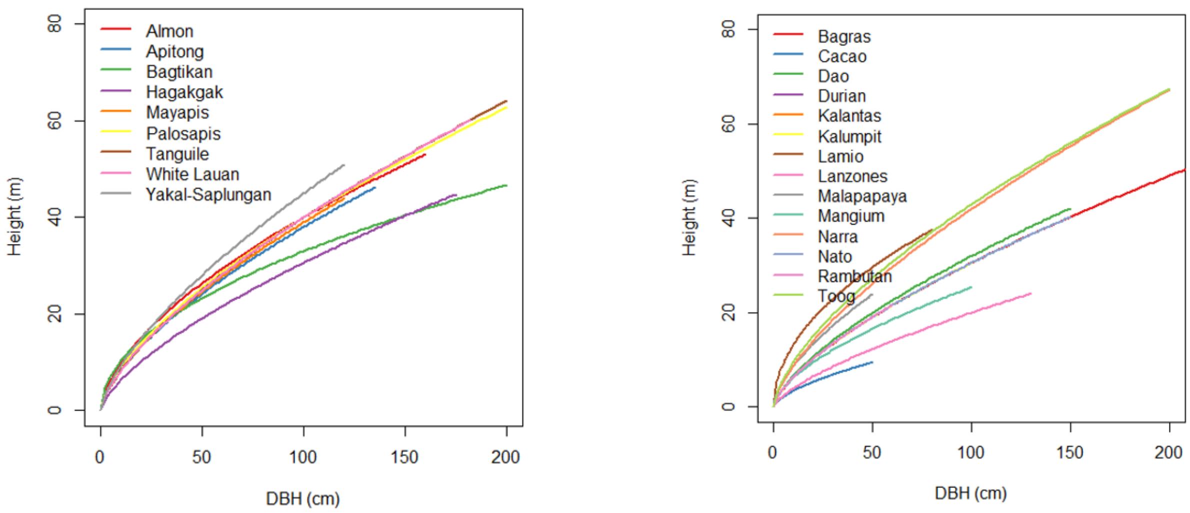

Figure 4. Estimated height of Dipterocarpus (left) and non-Dipterocarpus (right) tree species

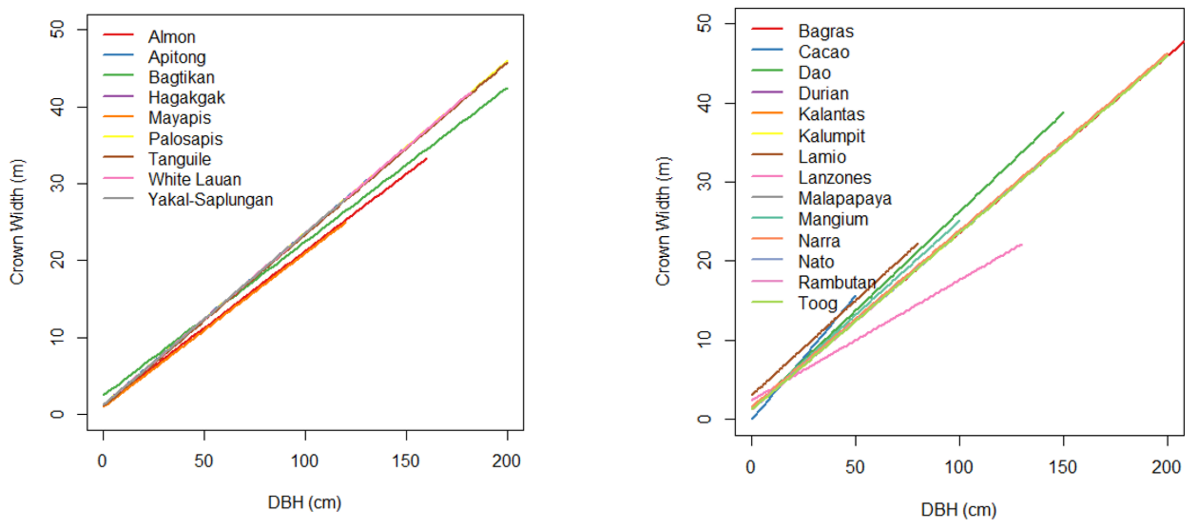

Figure 5. Estimated canopy width of Dipterocarpus (left) and non-Dipterocarpus (right) species

3.2 ESTIMATED CARBON STORAGE OF TREE-BASED PRACTICES

3.2.1 WITHOUT TREE MORTALITY

Figure 6 shows the estimated carbon storage of the four tree-based practices assuming no tree mortality, with a density of 400 trees/ha. The carbon storages are comparable among the different practices up to 30 simulation years. Thereafter, the carbon storage keeps increasing except in Practice 2. Among the four practices, Practice 2 has the lowest accumulated carbon at simulation year 50, although it has the fastest carbon sequestration rate during the first 5 simulation years. The presence of *Acacia mangium* trees as the fast-growing species of this practice likely influences the trend.

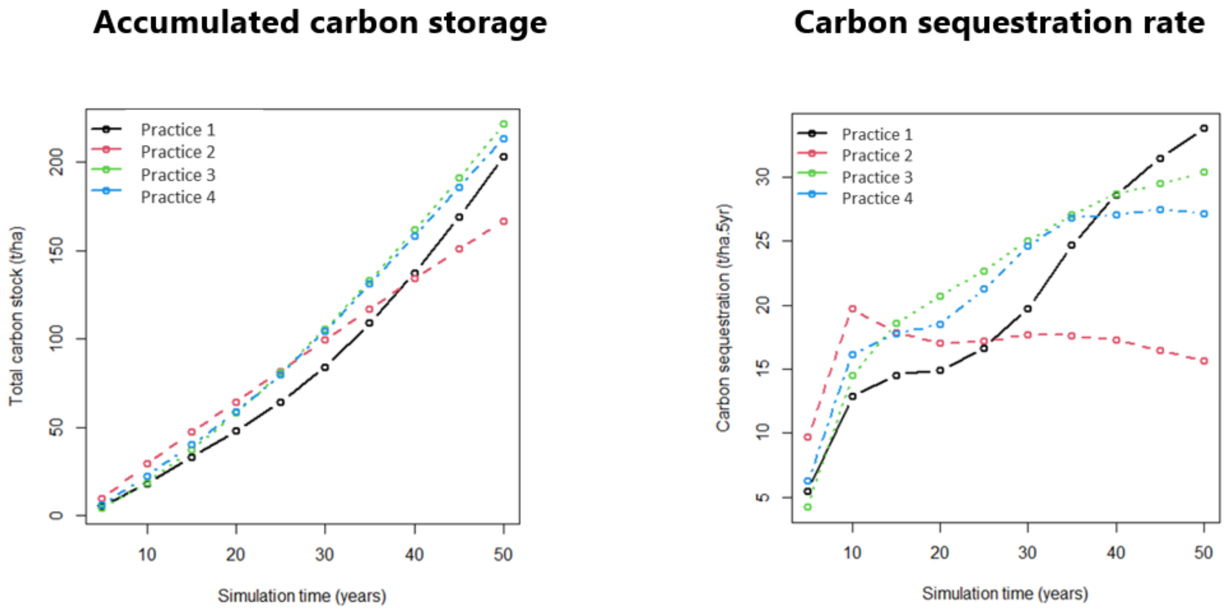

Figure 6. Estimated carbon storage and sequestration rate without tree mortality

3.2.2 WITH TREE MORTALITY

The tree mortality rate is higher in Practice 2 (Figure 7) which likely indicates a strong space and light competition between Acacia mangium and Bagras, in which the latter species suffers the most because of the competition (please see also Annex 4). The tree mortality rate in each practice keeps increasing during the first 20 simulation years and slowly declining thereafter. The estimated carbon storage in the scenario with tree mortality (Figure 8) is slightly lower than that in the scenario without tree mortality.

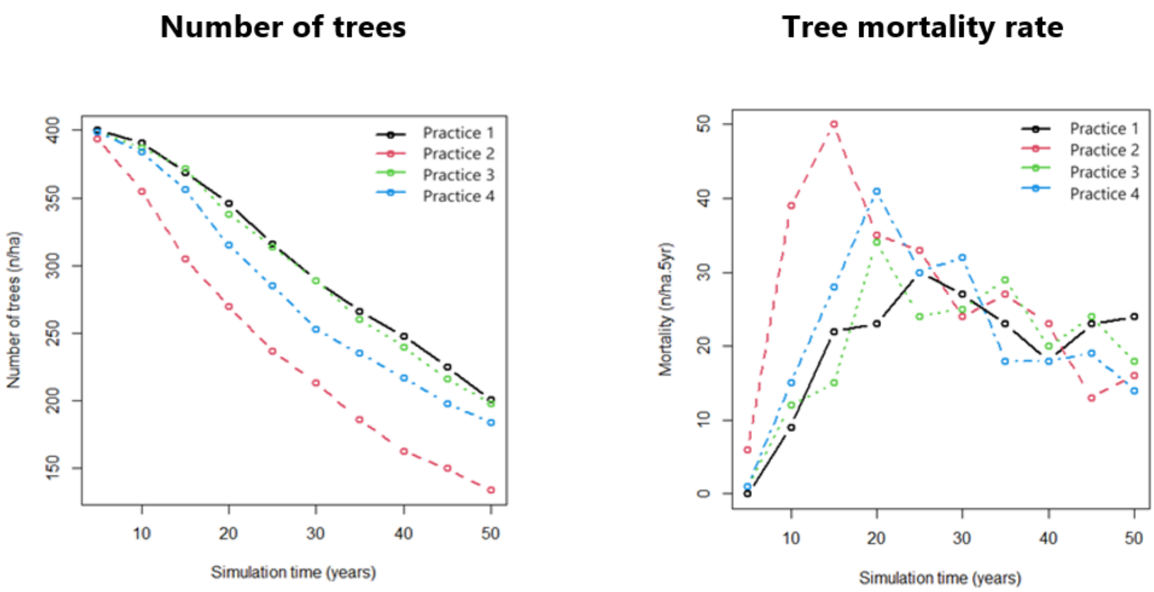

Figure 7. Number of trees per hectare and mortality rate

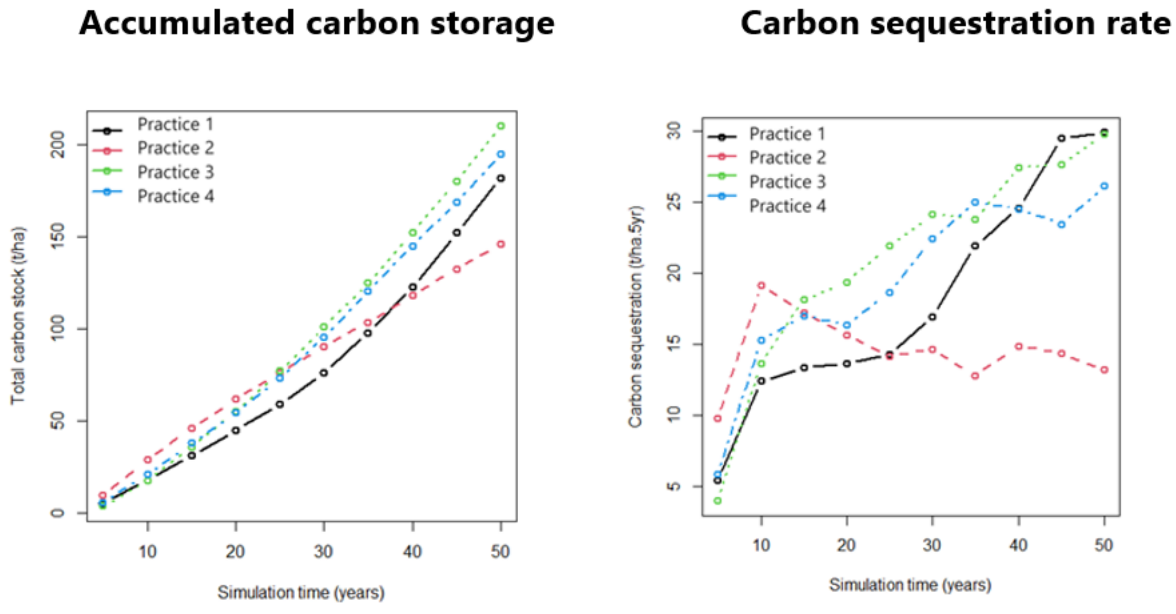

Figure 8. Accumulated carbon storage and sequestration rate with tree mortality

As in the scenario without tree mortality, Practice 2, as compared to other practices, shows a relatively different trend of accumulated carbon storage across the 50 simulation years. Among the three other practices, Practice 1 starts with a slower carbon accumulation rate but the final carbon storage at simulation year 50 is relatively comparable with the two other practices (please also see Annex 5). A higher density of slow-growing dipterocarps than other tree species in Practice 1 likely explains the trend.

3.3. IMPACT OF TREE DENSITIES

The simulation results (Figures 9-12) show that increasing tree density does not necessarily lead to higher accumulated carbon storage. Competition in space and light resources among trees has constrained tree growth.

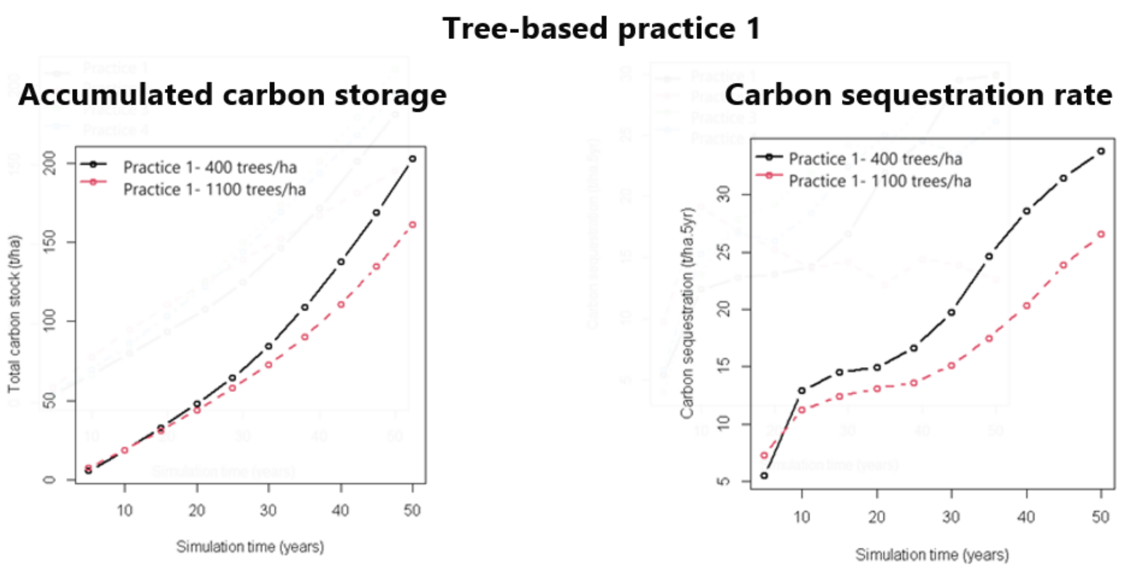

Figure 9. Impact of tree density on tree-based practice 1

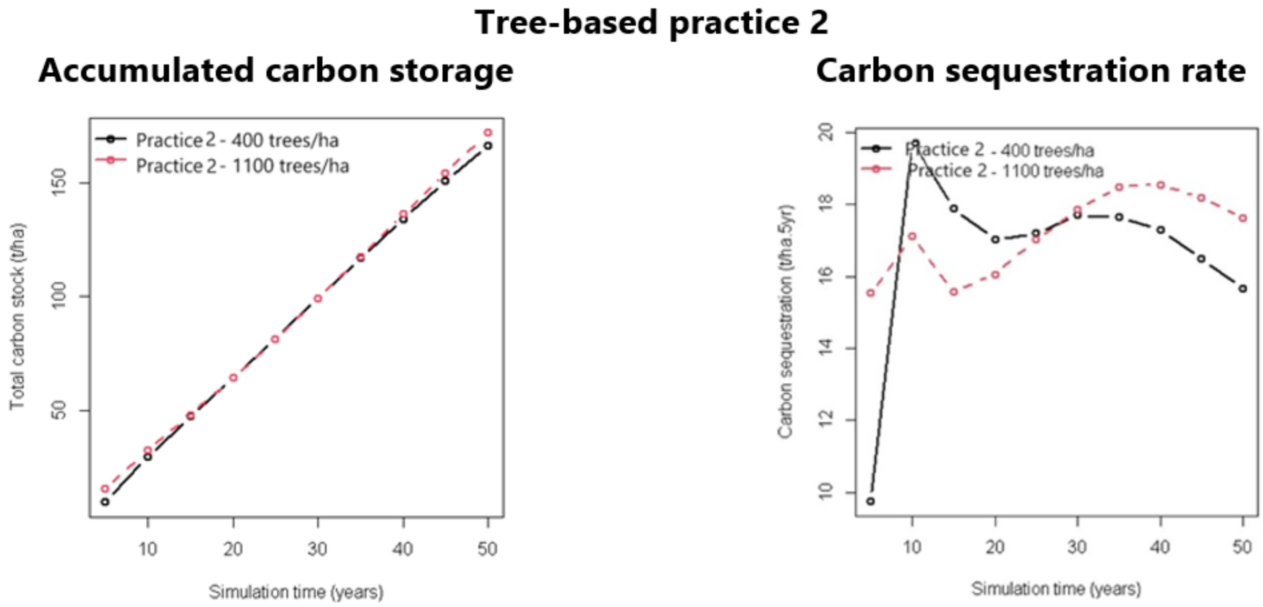

Figure 10. Impact of tree density on tree-based practice 2

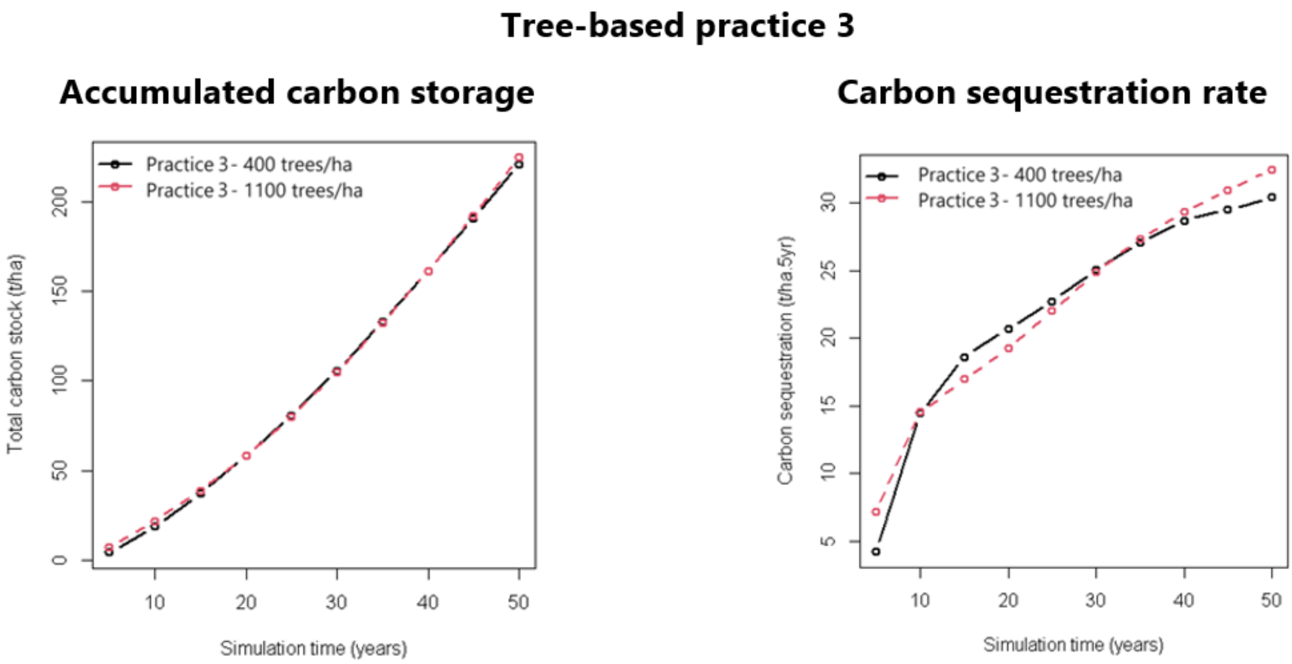

Figure 11. Impact of tree density on tree-based practice 3

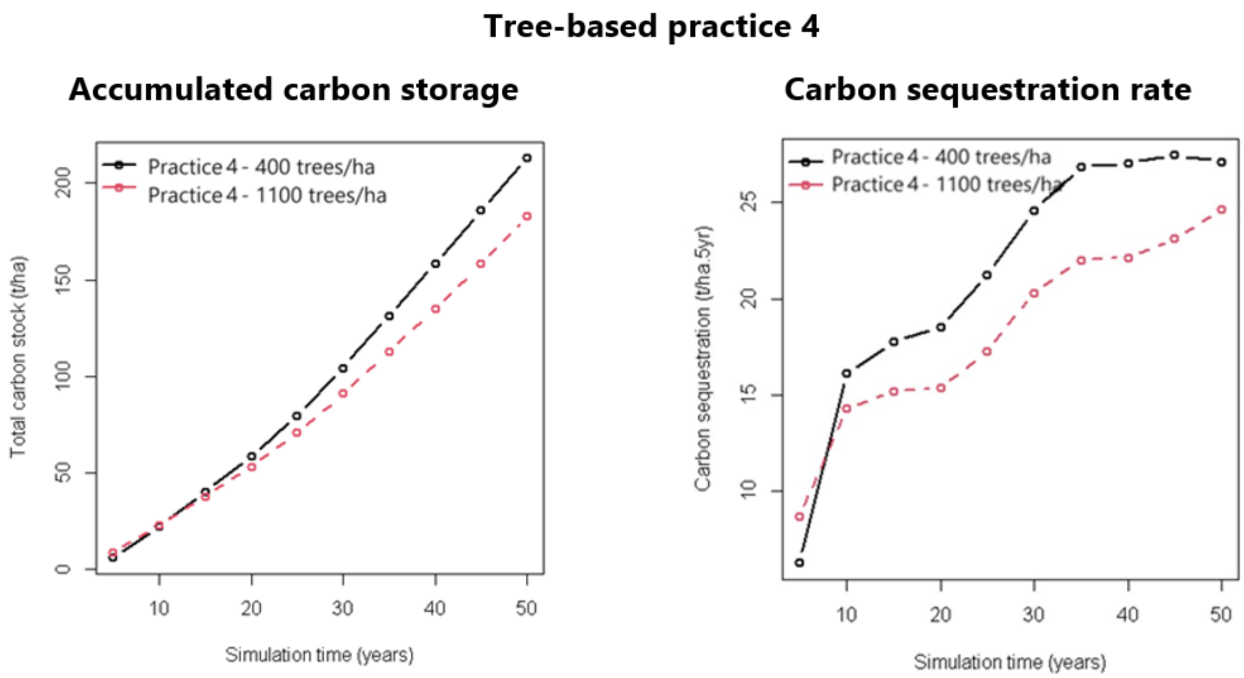

Figure 12. Impact of tree density on tree-based practice 4

A 3D visualization of growing trees in Practice 1 and 2D vertical projection for the case of no tree mortality are shown in Figure 13. Annex 6 shows the vertical projection for other practices.

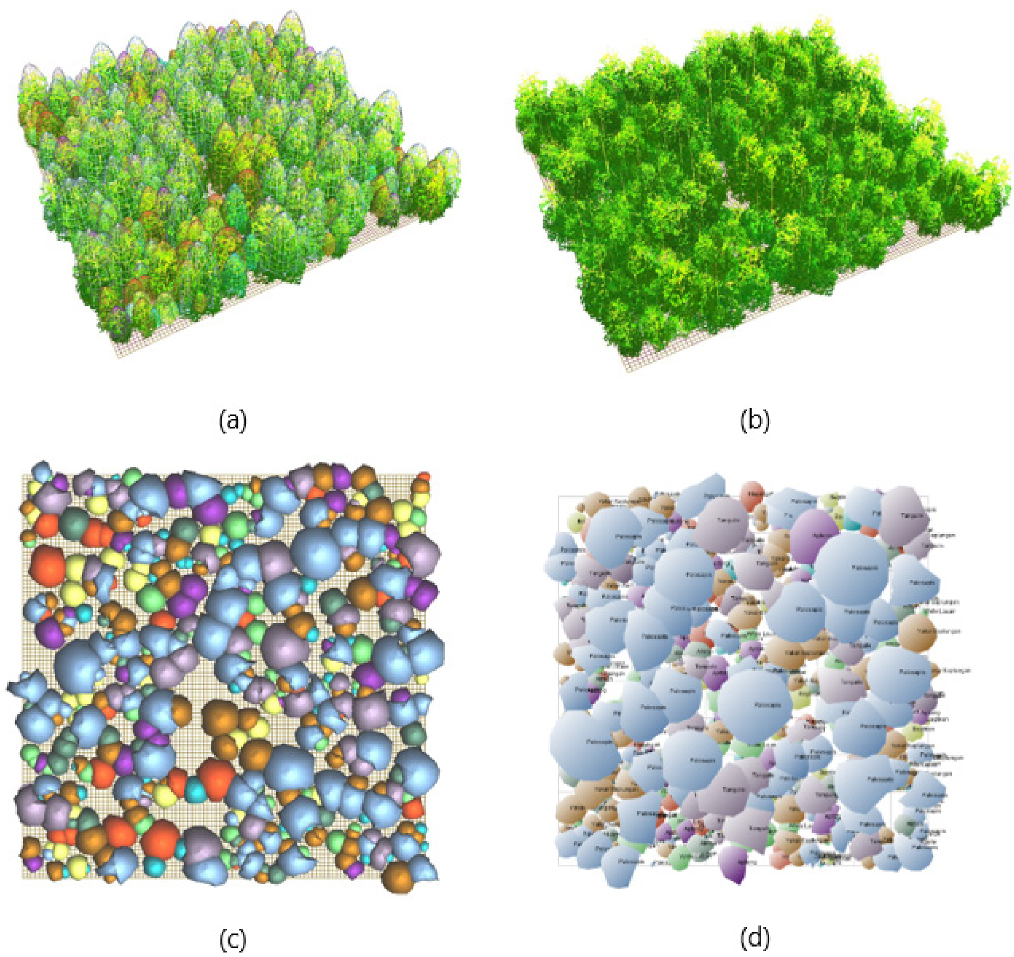

Figure 13. 3D visualization of growing trees (a and b) and vertical projection (c) at simulation year 20,

3.4. CARBON STORAGE OF TREE-BASED PRACTICES REPORTED IN THE LITERATURE

The estimated aboveground carbon storages of the simulated tree-based practices (with a density of 400 trees/ha) range from 18-30 tonC/ha, 84-106 tonC/ha, and 160-225 tonC/ha at simulation years 10, 30, and 50, respectively, for the case of no tree mortality (please see again Annex 4). If tree mortality was considered, the carbon storages ranged from 17-29 tonC/ha, 75-102 tonC/ha, and 145-210 tonC/ha at simulation years 10, 30, and 50, respectively.

Some studies in the literature reported accumulated aboveground carbon in mature forest or agroforest stands in the Philippines (e.g., Labata et al. 2021, Lasco et al. 2001a, Zaragoza et al. 2016). However, only a few studies provide information on the age of trees and/or tree density. These few studies suggest that the estimated carbon storages of the four tree-based practices are likely reasonable. For example, the study by Origenes and Lapitan (2021) reported aboveground carbon storage of 19-year-old agroforest (tree density 410 trees/ha), mixed forest (633 trees/ha), and plantation forest (310 trees/ha) in Misamis Oriental, and the carbon storage reached 70.6, 72.2, and 118.9 tonC/ha respectively.

In the other study, Lasco et al. (2001b) estimated the aboveground carbon of Gmelina arborea-cacao agroforestry (15-year-old Gmelina and 12-year-old cacao trees) grown in Makiling, Los Banos with a density of 900 trees/ha. They reported that the total aboveground carbon of the agroforestry practice (the total for the two tree species) was about 115 tonC/ha. If we rescaled into 400 trees/ha, then the estimated carbon was about 51 tonC/ha.

Another relevant study was from Reyes (2019) who reported aboveground carbon storage of a 50-year-old Mahagony plantation (586 trees/ha) in Loboc and Bilar, Bohol province. The carbon storage reached about 197 tonC/ha, and if we rescaled it into 400 trees/ha, the estimated carbon was about 135 tonC/ha. It is worth noting again that the model's simulation in the current study assumed an optimal, except for space and light resource, growing condition. Therefore, the estimated carbon storage from the model can be expected to be slightly higher than those reported in the literature.

Image Source: World Agroforestry/Kelvin, "Regreening Africa", (2022). Retrieved from: https://www.flickr.com/photos/icraf/52334862902/in/album-72177720301870353/

4 CONCLUSION

- In this study, we estimated the potential aboveground carbon storage of four tree-based practices using the FORCASTREE: an ICRAF's tree-tree growth and interaction model.
- The four tree-based practices combine fast- and slow-growing and native or exotic tree species that have different growth characteristics: (1) a mixture of different Dipterocarp species, (2) a combination of native and exotic non-Dipterocarp species, (3) a combination of Dipterocarp, fruit trees, and cacao, and (4) a mixture of Dipterocarp species, native non-Dipterocarp species, fruit trees and cacao. The scenario of tree mortality (with or without mortality) and tree density (400 or 1100 trees per hectare) for each practice were considered.
- The results show that Practice 1 could generate high carbon storage with a relatively slow carbon sequestration rate across the 50 simulation years. Practice 2 is suitable for accumulating high carbon storage (although the final projection is lower than that of Practice 1) with a quick sequestration rate in the early years after tree planting. Practices 3 and 4 are good options for accumulating high carbon storage with potential economic co-benefit from fruit trees or high-value crops such as cacao.
- The tree mortality rate is higher in Practice 2 which likely indicates a strong space and light competition between Acacia mangium as an exotic and Eucalyptus deglupta as a native species. The latter is the species which suffers the most because of the competition. The tree mortality rate in each practice keeps increasing during the first 20 simulation years and slowly declining thereafter.
- Increasing tree density does not necessarily result in higher accumulated carbon storage. Competition in space and light resources among trees has constrained tree growth.
- Future studies should try to collect primary data on tree growth (stem diameter, tree height, or canopy shape and size) to better estimate input parameters for the model's simulation.
- The framework and assessment results described in this study can provide inputs to KenEco or KFI's ARR program or encourage a wider application in other regions of the Philippines or other countries, to support land restoration or carbon projects.

Image Source: World Agroforestry/Kelvin, "Regreening Africa", (2022). Retrieved from: https://www.flickr.com/photos/icraf/52334862902/in/album-72177720301870353/

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ANNEXES

Annex 1. Tree species selected and their growth characteristic according to the literature[3]

No.	General description								Mean annual increment	
	Common name	Scientific name	Eco class	Growth rate	Max. DBH (cm)	Max. height (m)	Ave. wood density (g/cm³)	Sensitivity to light	MAID (cm/yr)	MAIH (m/yr)
Dipterocarpaceae species										
1	Apitong	*Dipterocarpus grandiflorus*	Indigenous	Slow	135	50	0.67	Need shade for seedling; full bright light for mature trees	0.69	0.71
2	Yakal-Saplungan	*Hopea plagata*	Indigenous	Fast	120	45	0.89	Bright shade or part sun	0.57	0.75
3	Bagtikan	*Parashorea malaanonan*	Indigenous	Moderately slow	200	60	0.44	Sun tolerant	0.62	0.89
4	Almon	*Shorea almon*	Indigenous	Slow	160	70	0.39	Shade as seedlings; full sun as adults	0.74	0.86
5	White lauan	*Shorea contorta*	Endemic	Slow	182	50	0.59	Full sun to bright shade	0.87	0.97

[3] Main references:
1. For the Eco Class, Fast/Slow, Max DBH, Max Height, and Sensitivity to the light: Galang, AP., Mesina, SR., Marciano, MR., Tungol, AM., Sarmiento, IP., Madulid, DA., and Coronel, RE. 2012 and 2015. Philippine Native Trees 101 and 202: UP Close and Personal. Green Covergence for Safe Food, Healthy Environment and Sustainable Economy. (note: no link since these are books from Ecosystems Research and Development Bureau's Library)

2. Wood Density: From ICRAF Database http://db.worldagroforestry.org//wd

3. MAID and MAIH: Schneider, T., Ashton, M.S., Montagnini, F., Milan, P.P. 2013. Growth performance of sixty tree species in smallholder reforestation trials in Leyte, Philippines. New Forests. DOI 10.1007/s11056-013-9393-5 (https://www.researchgate.net/publication/258164722_Growth_performance_of_sixty_tree_species_in_smallholder_reforestation_trials_on_Leyte_Philippines)

No.	General description								Mean annual increment	
	Common name	Scientific name	Eco class	Growth rate	Max. DBH (cm)	Max. height (m)	Ave. wood density (g/cm^3)	Sensitivity to light	MAID (cm/yr)	MAIH (m/yr)
6	Mayapis	*Shorea palosapis*	Endemic	Slow	120	30	0.52	Gradual exposure to full light	1.71	1.53
7	Tanguile	*Shorea polysperma*	Endemic	Slow	200	50	0.65	Full sun; seedlings need shade	0.79	0.94
8	Palosapis	*Anisoptera thurifera*	Indigenous	Fast	200	60	0.71	Open; full sun	0.72	0.79
9	Hagakgak	*Dipterocarpus validus*	Indigenous	Slow	175	45	0.63	Full sun for mature		
Non-Dipterocarpaceae species										
10	Narra	*Pterocarpus indicus*	Indigenous	Slow	200	40	0.74		0.89	0.8
11	Dao	*Dracontomelon dao*	Indigenous	Fast	150	35	0.53	Full sun for mature	0.98	0.89
12	Lamio	*Dracontomelon edule*	Endemic	Moderately fast	80	55	0.53	Full sun	0.68	0.87
13	Toog	*Petersianthus quadrialatus*	Endemic	Fast	200	40	0.59	Full sun	0.43	0.45
14	Malapapaya	*Polyscias nodosa*	Indigenous	Fast	50	25	0.36		0.86	0.68
15	Kalumpit	*Terminalia microcarpa*	Indigenous	Fast	100	30	0.57	Full sun	1.42	1.18
16	Bagras	*Eucalyptus deglupta*	Indigenous	Fast	240	75	0.49	Full sun		0.6

No.	General description								Mean annual increment	
	Common name	Scientific name	Eco class	Growth rate	Max. DBH (cm)	Max. height (m)	Ave. wood density (g/cm^3)	Sensitivity to light	MAID (cm/yr)	MAIH (m/yr)
17	Nato	*Palaquium luzoniense*	Endemic	Moderately fast	150	40	0.71	Full sun		
18	Kalantas	*Toona calantas*	Endemic	Moderately fast	100	25	0.43	Full sun		
19	Mangium	*Acacia mangium*	Exotic	Fast	100	35	0.53			
20	Durian	*Durio zibethinus*	Exotic	Moderately fast	150	40	0.56		0.57	0.68
Exotic non-Dipterocarpaceae species										
21	Lanzones	*Lansium domesticum*	Indigenous	Very slow	130	30	0.58	Bright shade or partial shade	0.34	0.45
22	Rambutan	*Nephelium lappaceum*	Indigenous	Fast	60	20	0.76	Full sun to slight shade	0.69	0.56
23	Cacao	*Theobroma cacao*	Exotic	Fast	50	10	0.42		0.44	0.49

Annex 2. References of secondary data of tree growth indicators

x = information available, although for certain tree ages only

Species	References	DBH	Height	Crown
Apitong	Pasamonte (2020) Balane (1999) Calago & Diola (2020) Ore Asia Mining and Development Corporation (1988)	x	x	
Yakal-Saplungan	Nguyen et al. (2014) Balane (1999) Ayson et al. (2017) Dierick & Hölscher (2009)	x	x	x
Bagtikan	Bullecer & Socorin, (2013) Balane (1999) Herbohn & Gregorio 2010. Ore Asia Mining and Development Corporation (1988)	x	x	x
Almon	Balane (1999) Herbohn & Gregorio 2010. Ore Asia Mining and Development Corporation (1988)	x	x	
White lauan	Martin et al. (2010) Aguilos et al. (2020) Pasamonte (2020) Balane (1999) Bullecer & Socorin (2013) Ayson et al. (2017) Herbohn & Gregorio 2010. Malabrigo et al. (2007) Dierick & Hölscher (2009) Engay-Gutierrez et al. (2022) Lillo et al. (2019)	x	x	x
Narra	Martin et al. (2010) Aguilos et al. (2020) Nguyen et al. (2014)	x	x	
Dita	Orwa et al. (2009)	x	x	
Bagras	Palma et al. (2014) Orwa et al. (2009)	x	x	
Mangium	Jusoh (2017)	x	x	
Cacao	Nguyen et al. (2014)	x		
Durian, Rambutan	Nguyen et al. (2014)	x		
Toog	Aguilos et al. (2020) Mongabay Environmental News. (2020, August 27).	x	x	
Palosapis	Calago & Diola (2022) Ayson et al. (2017) Ore Asia Mining and Development Corporation (1988)	x	x	
Tanguile	Aguilos et al. (2020) Nguyen et al. (2014) Bullecer & Socorin (2013)	x	x	x

Species	References	DBH	Height	Crown
	Lillo et al. (2019) Calago & Diola (2022) Ayson et al. (2017) Herbohn & Gregorio 2010 Malabrigo et al. (2007) Ore Asia Mining and Development Corporation (1988)			
Hagakhak	Pasamonte (2020) Herbohn & Gregorio 2010	x	x	
Narra	Gonzalvo et al. (2013) Lillo et al. (2019) Bullecer & Socorin (2013) Ayson et al. (2017) Herbohn & Gregorio 2010 Ore Asia Mining and Development Corporation (1988) Engay-Gutierrez et al (2022)	x	x	x
Lamio	Bullecer & Socorin (2013)	x	x	x
Toog	Malabrigo et al. (2007) Ore Asia Mining and Development Corporation (1988)	x	x	
Malapapaya	Malabrigo et al. (2007) Ore Asia Mining and Development Corporation (1988)	x	x	
Nato	Herbohn & Gregorio 2010 Malabrigo et al. (2007)	x	x	
Mayapis	Bullecer & Socorin (2013) Nguyen et al. (2014)	x	x	
Kalantas	Engay-Gutierrez et al (2022)	x	x	x
Dao	Nguyen et al. (2014) Bullecer & Socorin (2013) Ayson et al. (2017)	x	x	x
Kalumpit	Nguyen et al. (2014)	x		

Annex 3. Input parameters used for the model's simulation

Coefficients of the allometric equation to estimate diameter at breast height

	Species	Max DBH (cm)	k	c
Diptero	Almon	160	0.019	1.3
	Apitong	135	0.03	1.35
	Bagtikan	200	0.01	1.3
	Hagakgak	175	0.025	1.3
	Mayapis	120	0.025	1.3
	Palosapis	200	0.024	1.2
	Tanguile	200	0.025	1.3
	White Lauan	182	0.02	1.3
	Yakal-Saplungan	120	0.03	1.3
Non-Diptero	Bagras	240	0.015	1.3
	Cacao	50	0.03	1.1
	Dao	150	0.03	1.3
	Durian	150	0.035	1.3
	Kalantas	100	0.03	1.3
	Kalumpit	100	0.03	1.3
	Lamio	80	0.035	1.3
	Lanzones	130	0.035	1.35
	Malapapaya	50	0.045	1.3
	Mangium	100	0.05	1.05
	Narra	200	0.026	1.2
	Nato	150	0.03	1.3
	Rambutan	60	0.03	1.3
	Toog	200	0.03	1.3

Maximum height and allometric coefficient parameters

Group	Species	Max height (m)	alpha	beta
Diptero	Almon	70	40	0.6
	Apitong	50	38	0.65
	Bagtikan	60	33	0.5
	Hagakgak	45	30.6	0.68
	Mayapis	30	39	0.66
	Palosapis	60	40	0.65
	Tanguile	50	40	0.68
	White Lauan	50	40	0.68
	Yakal-Saplungan	55	45	0.68
Non-Diptero	Bagras	75	30.6	0.68
	Cacao	20	14.63	0.63
	Dao	35	32	0.68
	Durian	50	30.6	0.68
	Kalantas	25	30.6	0.68
	Kalumpit	30	30.6	0.68
	Lamio	55	42	0.5
	Lanzones	35	20	0.7
	Malapapaya	25	37	0.63

Group	Species	Max height (m)	alpha	beta
	Mangium	50	25.36	0.61
	Narra	40	42	0.68
	Nato	40	30.6	0.68
	Rambutan	20	30.6	0.68
	Toog	40	43	0.65

Crown (or canopy) properties of selected tree species

Group	Species	Crown porosity	Crown shyness	a	b
Diptero	Almon	0.5	1	1.29	20
	Apitong	0.5	1	1.29	22.34
	Bagtikan	0.5	1	2.5	20
	Hagakgak	0.5	1	1.29	22.34
	Mayapis	0.5	1	1	20
	Palosapis	0.5	1	1.29	22.34
	Tanguile	0.5	1	1.1	22.34
	White Lauan	0.5	1	1.29	22.34
	Yakal-Saplungan	0.5	1	1.29	22.34
Non-Diptero	Bagras	0.5	1	1.29	22.34
	Cacao	0.5	1	0	31.4
	Dao	0.5	1	1.3	25
	Durian	0.5	50	1.29	22.34
	Kalantas	0.5	1	1.29	22.34
	Kalumpit	0.5	1	1.29	22.34
	Lamio	0.5	1	3.1	24
	Lanzones	0.15	50	2.44	15.2
	Malapapaya	0.5	1	1.29	22.34
	Mangium	0.3	50	1.407	23.727
	Narra	0.5	1	1.6	22.34
	Nato	0.5	1	1.29	22.34
	Rambutan	0.5	1	1.29	22.34
	Toog	0.5	1	1.29	22.34

Light requirement and sensitivity parameters

Groups	Species	Minimum (%)	Optimum (%)	Tree sensi	Tree flexi	Crown sensi	Crown flexi
Diptero	Almon	0.05	1	1	0.3	1	0.3
	Apitong	0.05	1	1	0.3	1	0.3
	Bagtikan	0.1	1	1	0.3	1	0.3
	Hagakgak	0.05	1	1	0.3	1	0.3
	Mayapis	0.1	1	1	0.3	1	0.3
	Palosapis	0.15	1	1	0.3	1	0.3
	Tanguile	0.05	1	1	0.3	1	0.3
	White lauan	0.1	1	1	0.3	1	0.3
	Yakal-Saplungan	0.1	1	1	0.3	1	0.3
Non-diptero	Bagras	0.15	0.8	1	0.3	1	0.3
	Cacao	0.05	0.3	1	0.3	1	0.3
	Dao	0.15	0.8	1	0.3	1	0.3

Groups	Species	Minimum (%)	Optimum (%)	Tree sensi	Tree flexi	Crown sensi	Crown flexi
	Durian	0.1	0.6	1.5	0.3	1	0.3
	Kalantas	0.15	0.8	1	0.3	1	0.3
	Kalumpit	0.15	0.8	1	0.3	1	0.3
	Lamio	0.15	0.8	1	0.3	1	0.3
	Lanzones	0.01	0.5	0.7	0.3	1	0.3
	Malapapaya	0.15	0.8	1	0.3	1	0.3
	Mangium	0.05	0.5	0.7	0.3	1	0.3
	Narra	0.1	1	1	0.3	1	0.3
	Nato	0.15	0.8	1	0.3	1	0.3
	Rambutan	0.1	0.8	1	0.3	1	0.3
	Toog	0.15	1	1	0.3	1	0.3

Annex 4. Estimated number of trees in the scenario with tree mortality

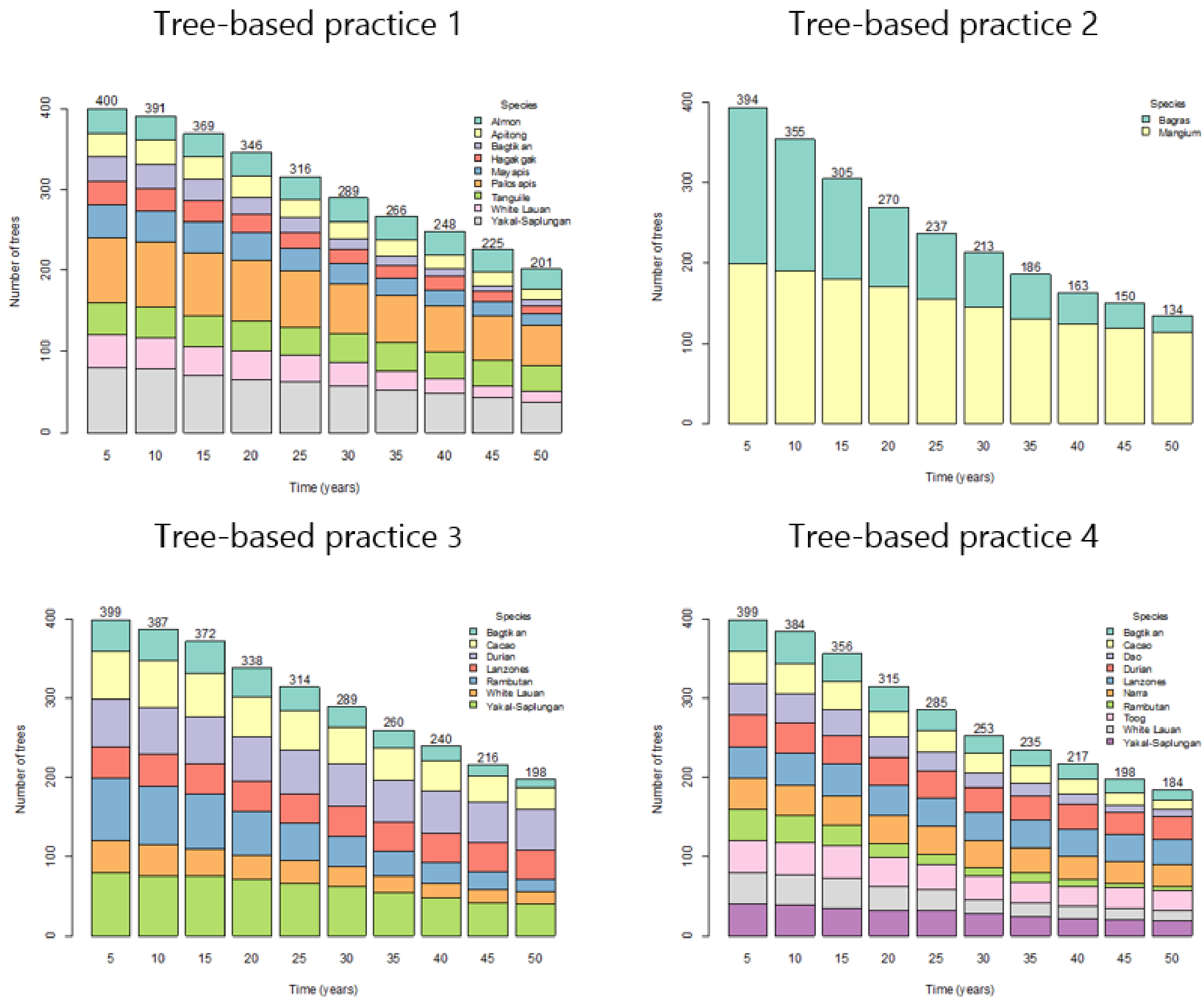
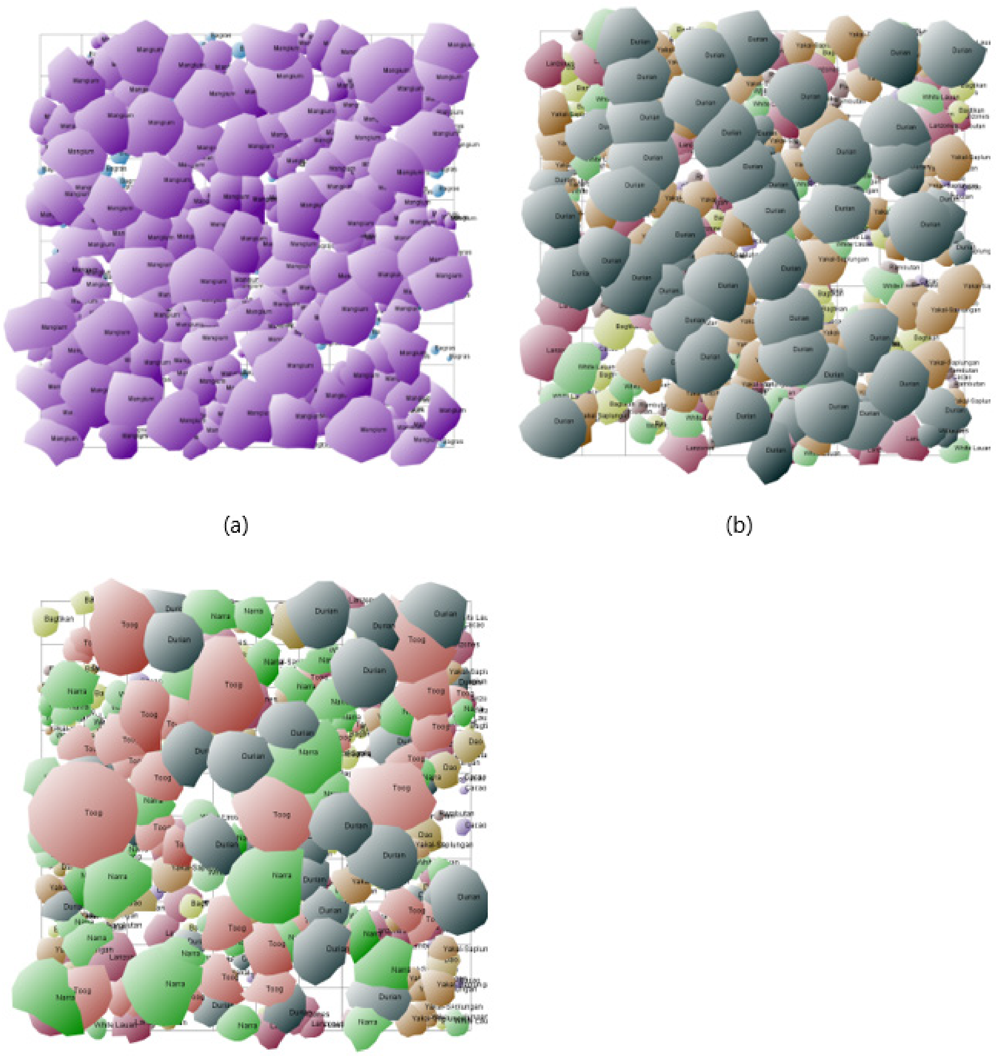


Figure 14. Number of trees across the year in the scenario with tree mortalityand final projection

Annex 5. Estimated carbon storage by practice at simulation year 10, 30 and 50

Practice	Proportion of tree species based on growth rate			Carbon stock (tC/ha)			Carbon sequestration rate (tC/ha/year)		
	Slow	Medium	Fast	Year 10	Year 30	Year 50	Year 10	Year 30	Year 50
No tree mortality									
1	30%	30%	40%	18.4	84.3	202.8	12.9	19.75	33.8
2			100%	29.5	99.3	166.4	19.7	17.7	15.7
3	20%	25%	55%	18.7	105.8	221.4	14.5	25.05	30.4
4	30%	30%	40%	22.4	104.5	212.9	16.1	24.6	27.1
With tree mortality									
1	30%	30%	40%	17.8	75.9	181.9	12.4	16.9	29.9
2			100%	28.9	90.6	145.8	19.2	14.7	13.2
3	20%	25%	55%	17.59	101.2	209.9	13.7	24.1	29.8
4	30%	30%	40%	21.1	95.6	194.7	15.3	22.4	26.1

Annex 6. Vertical projection of tree-based practices



(a) (b) (c)

Figure 15. Final (simulation year 50) vertical projection of (a) tree-based practice 2, (b) practice 3, and (c) practice 4 without mortality rate.(simulation year 50) of tree-based practice 1

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