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Assessing Carbon Pool Dynamics Under Coffee Agroforestry and Forest Management Systems

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Abstract: Approximately 40.42 % of the forest in the province of East Nusa Tenggara is a protected forest, 23.68 % production forest, conservation forest 19.37 %, 10.90 % limited production forest and 5.63 % is convertible forest. Its still needs better management to optimize outcomes from these resources. Analysis of dry forest composition, calculation of carbon pools availability, carbon sequestration and its behavior in East Nusa Tenggara, Indonesia are carried out to achieve these objectives. The result shows that a total of 2097 tree individuals, it's representing 94 species, 72 genera and 45 families, were found in the research sites. Eucalyptus urophylla were found to be the most dominant species in the research sites and Elattostachys verrucosa have potential to replace Dryobalanops aromatic. Most of family distribution models can describe the stand structure in research sites. And carbon stock of the living, litter and soil all decreased from virgin forest to the conventional logging ang reduced impact logging, carbon concentration of these biomass in the coffea agroforestry system were slightly higher than those of virgin forest and logging treatments (ranging 0 – 52 %). Carbon stock of the living and soil increased with a decreasing harvest and reached the highest stock in the coffea agroforestry.

Keyword : Carbon sequestration; Carbon storage; Land use; Species composition

Introduction

Dry forests provide many important ecosystem services, including wildlife habitat, recreation, soil protection, clean air and water, and timber production (Bonan, 2008). The conditions of dry forest show specific in structure, species composition and potential value, as well as variation in stand density, and death and growth rate (Lewis, 2004). Information on composition, diversity of tree species and species-rich communities is primary importance in the planning and implementation of biodiversity conservation efforts (Suratman, 2012).

As we face unprecedented global challenges in the twenty-first century, forests are also increasingly recognized for other services, including the ability to store carbon and mitigate the impacts of climate change (Njana et al., 2021; Psistaki et al., 2024). Soil organic carbon (SOC), the major component of soil organic matter, plays a key role in the terrestrial carbon cycle and thus has drawn great attention from scientific community (Guo et al., 2023). It is a dynamic component of terrestrial systems, affecting carbon exchange between terrestrial ecosystem and the atmosphere (Li et al., 2021; Tian et al., 2022).

Here, I report on the tree species community and forest structure of dry forest in East Nusa Tenggara, Indonesia and to reduce carbon emissions effectively I have to take into account all existing and potential land-based sources of emission. In this case, we examine the contribution of virgin dry forest, logging practices (conventional logging (CL), reduced impact logging

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(RIL)) and coffee-based agroforestry systems to changes in carbon stock. To address the effects of these contribution on carbon storage in East Nusa Tenggara province, the Carbon accounting simulation software (CASS), was applied to evaluate the temporal patterns of carbon storage on the dry forest of East Nusa Tenggara province during 1000 years.

The objectives of this study are: 1) to study the forest structure and composition in dry forest of East Nusa Tenggara, Indonesia; 2) to investigate the temporal patterns of carbon storage on the dry forest of East Nusa Tenggara province, Indonesia; and 3) to identify the relative contribution of treatments (virgin dry forest, logging practices (conventional logging (CL), reduced impact logging (RIL) and coffee-based agroforestry systems to the carbon storage changes.

Method

Research locations

The study was located at Kupang District, East Nusa Tenggara Province, Indonesia (Fig. 1). Despite the high annual rainfall (2,000–5,000 mm) of Indonesia, 3.3 × 10^6 ha area of East Nusa Tenggara province receives annual rainfall between 1,000 and 2,000 mm with 5 - 8 dry months (<100 mm rainfall), and about 1 × 10^6 ha area receives <1,000 mm annual rainfall with 8 - 10 dry months. About 1.7 × 10 6 ha land is mountainous (>30% slope), and 1.5 × 10 6 ha is hilly (15 – 30 % slope) (Balitklimat, 2004). With the short duration of wet months, rainfall tends to be very high (200–500 mm monthly rainfall) during the wet months and so is rainfall intensity. About 71% area are hilly (15–30% slope) to mountainous (>30% slope). The high-intensity rainfall during the rainy season and steep slope topography cause high soil erosion (Mulyani et al., 2013).

Figure 1. Research Location

Plant Census

A 8-ha permanent sampling plot was set up within the nature for the survey of the dry forest. A design of research plots is a permanent plot, with a plot size of 100 x 100m and was divided into 16 subplots with a size of 25 x 25 m (Fig. 2). The data collection is based on the stands inventory by census in research plots. All individual trees ≥5 cm diameter at breast height (DBH) were tallied, tagged, and recorded by species name and DBH.

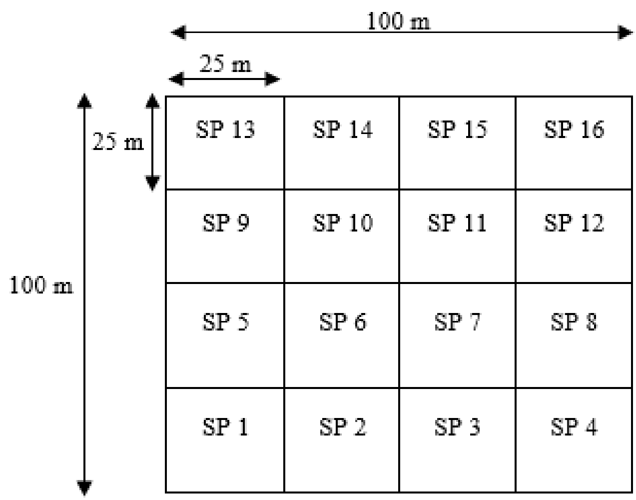


Figure 2. Design of sample plots

Determination of Importance Value Index (IVI)

IVI was used for the assessment of the distribution of species abundance which is calculated in the following formula:

IVI = relative frequency+ relative density+ relative dominance

Simulation scenarios

We contrasted three different scenarios to explore the long-term effects of different forest management on carbon pools (Tab. 1). In scenario 1 (virgin dry forest and coffea agroforestry), we assumed there was no timber harvesting activity. Virgin dry forest was used as a null model for comparison purposes, since we simulated an expected behavior in the absence of any specific processes. We hypothesized that virgin dry forest, by virtue of their longstanding protection status, would be older than forests in surrounding landscapes, and forest C stocks and stock changes are affected by natural disturbances.

In scenario 2, conventional logging (CL) was result 21 % harvesting disturbance of stem with logging rotation 40 year and 80 years. As well as the application of reduced impact logging (RIL), resulting in damage to the stem around 19 % disturbance by harvesting of stem with logging rotation 40 year and 80 years (scenario 3). Although in reality, site treatments such as burning or scarification may have been undertaken following harvesting, for simplicity these have been ignored in the simulations. All residual dead organic matter associated with harvest slash was assumed to be additional litter input to the decomposing forest floor (Jiang et al., 2002).

Table 1. Main parameters used for simulating the dry forest of East Nusa Tenggara, Indonesia

Parameters	Conventional Logging		Reduced Impact Logging		Coffee-based Agroforestry Systems	Sources
	Disturbance Frequency 40 years	Disturbance Frequency 80 years	Disturbance Frequency 40 years	Disturbance Frequency 80 years	Disturbance Frequency 10 years	
Leaf (%)	10	10	20	20	0	Muhdi et al. (2012)
Stem (%)	21	21	19	19	0	Muhdi et al. (2012)
Leaf litter	5	5	5	5	5	Roxburgh (2004)
Stem litter	5	5	5	5	5	Roxburgh (2004)
Humus	5	5	5	5	5	Roxburgh (2004)
Rate of succession	1.05	1.05	1.05	1.05	1.05	Roxburgh (2004)
Litter	0.1	0.1	0.1	0.1	0.1	Roxburgh (2004)
Atmosfer	0.1	0.1	0.1	0.1	0.1	Roxburgh (2004)
Fuelwood	0.1	0.1	0.1	0.1	0.1	Roxburgh (2004)
Longterm	0.7	0.7	0.7	0.7	0.7	Roxburgh (2004)

Carbon accounting simulation software (CASS)

The philosophy underlying the CASS model is that carbon in terrestrial ecosystems can be partitioned into a number of separate pools. At the coarsest level there are four major pools (1) carbon present in living vegetation (2) carbon in dead vegetation (litter) and (3) carbon in the soil. The final pool, (4), is carbon as CO_2 in the atmosphere, although this pool is not explicitly included in the model. Sub-pools can be defined within each of these major pools. The number of sub-pools varies considerably among different carbon models. For example, the 'Century' model is commonly used in studies of climate change, and it has two living pools, four litter pools and six soil pools. The CASS model contains three living pools (leaves, stems and roots), three litter pools (leaf litter, stem litter and root litter) and two soil pools (fast turnover 'humus' and slow turnover 'stable soil C') (Roxburgh, 2004).

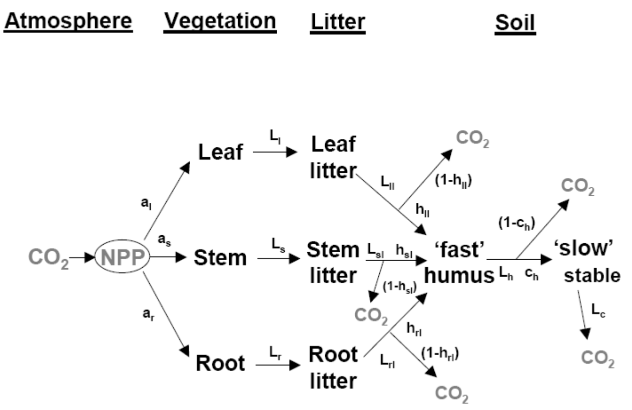


Figure 3. The overall structure of the model

To interpret the diagram first start at the left-hand side, with atmospheric carbon being fixed into solid form by photosynthesis at a rate determined by the Net Primary Productivity (NPP), measured in units gC/m^2/yr. Some of this fixed carbon is incorporated into leaf biomass, some into stem biomass, and some into root biomass. The parameters al, as and ar are proportions which define this partitioning, and sum to 1 (Roxburgh, 2004).

Result and Discussion

Dry Forest Composition

A total of 2097 tree individuals, representing 94 species, 72 genera and 45 families, were identified within the 8.0 ha area survey. The highest IVI value was that of *Ceriops tagal* (113.88 %). Based on IVI values, *Eucalyptus urophylla* were found to be the most dominant species in the study area and *Elattostachys verrucosa* have potential to replace *Dryobalanops aromatica* as dominant species Figure 4.

Forest Management Rotation Implications to Soil Carbon Dynamics

To analyze the carbon stocks, we distinguished between three different carbon pools: carbon stored in the living, carbon in the litter and carbon stored in the soil (Parkatti et al., 2023; Zeng et al., 2024). According to the simulation, the virgin dry forest stored 42 % carbon in the living, 3 % in the litter and 55 % in the soil.

The value of net biome productivity (NBP) in the virgin dry forest was a increased during the first 100 years of simulation, during this phase the value reach about 101,58. After about 100 years of simulation the NBP got slow decreased with values between 1.5 gC/m²/year and 7.2 gC/m²/year.

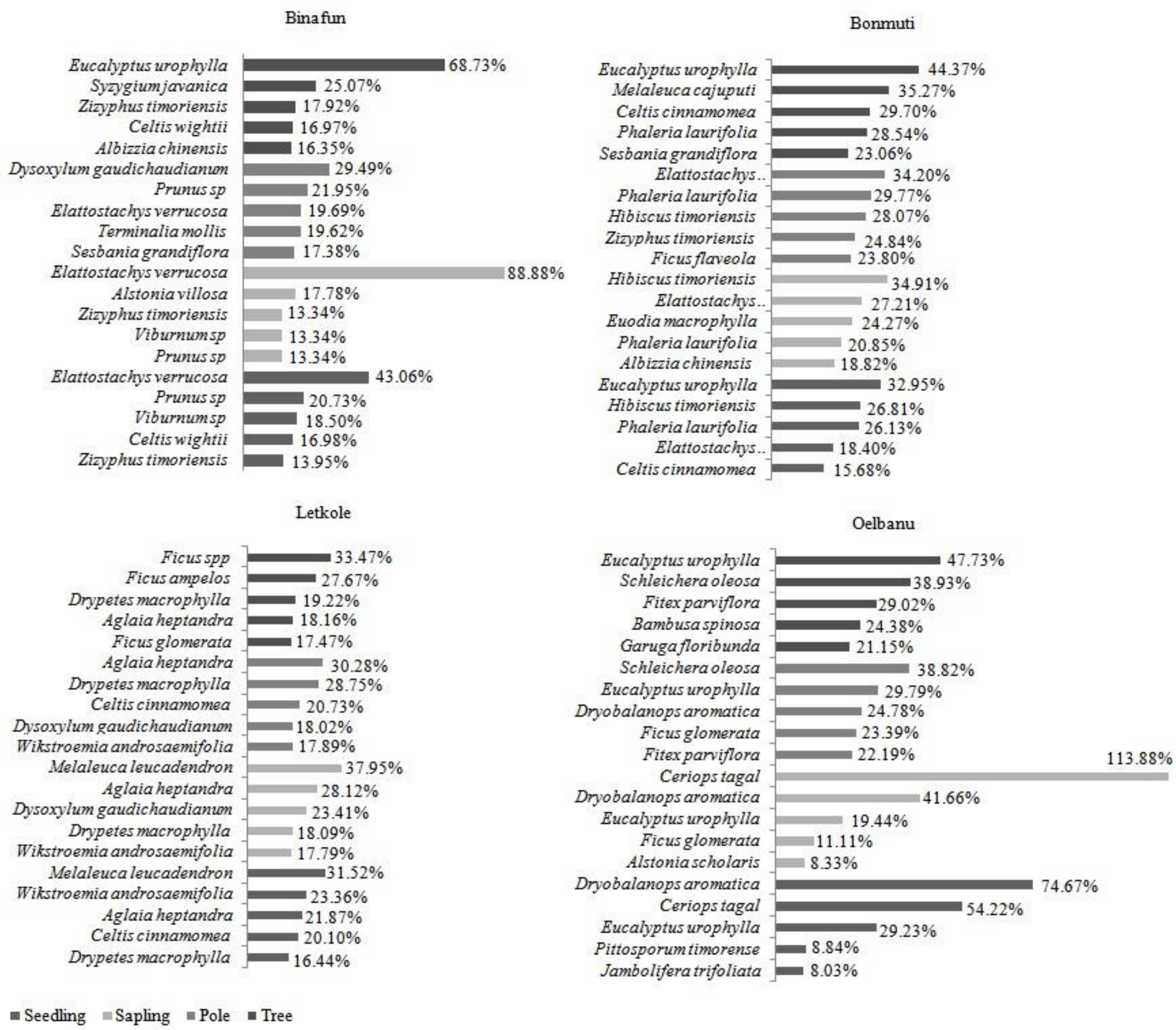
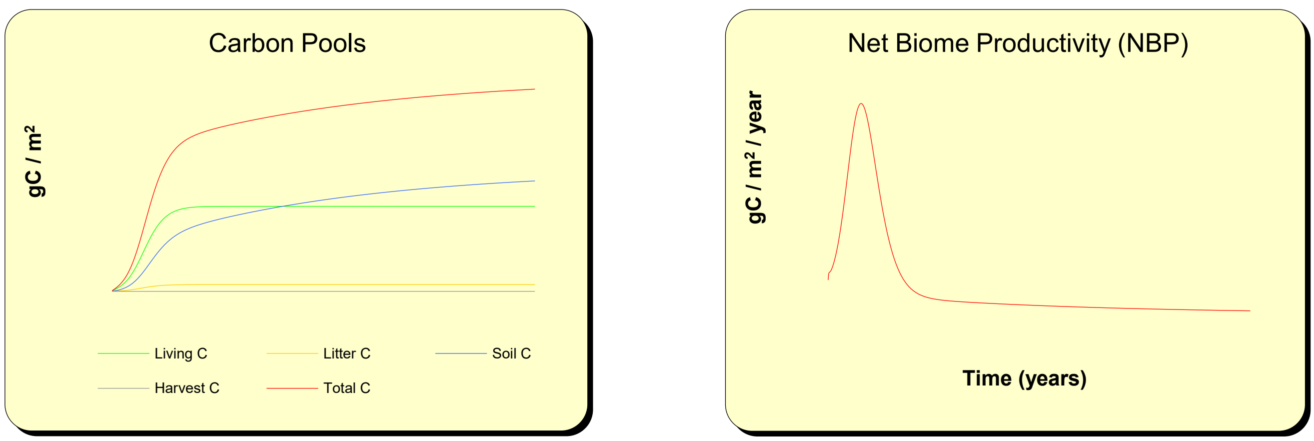


Figure 4. Five highest IVI for each research sites



(a) (b)

Figure 5. dynamics in the virgin dry forest: (a) . Carbon pool; (b) Net Biome Productivity (NBP)

Based on Figure 5, some of this fixed carbon is incorporated into leaf biomass is about 0.30, some into stem biomass 0.50 and some into root biomass 0.20, it means that 30 % of the carbon being fixed by the plant is converted into leaf biomass, 50 % into stem biomass, and 20 % into root biomass. From one year to the next some of this carbon will be retained in the leaves about 270 gC/m² with average ½ of the total leaf carbon is lost to the leaf litter pool (135 gC/m²/year) on the rate of humification around 0.4. In the leaf is about 4950 gC/m², where around 1/22 for every year of the total stem carbon will released to the stem litter pool is around 225 gC/m²/year. As well as in the root about 450 gC/m² with average 1/5 for every year root carbon will lost to the root litter pool about 90 gC/m². All of the carbon pools have no different value in the longevity and humification rate is about 1 year and 0.40, respectively.

Based on this research, the acculumation of humus carbon in the soil pool is about 3600 gC/m² with the rate of carbonisation and time of residence on 0.05 and 20, its mean around 1/20/year humus carbon will lost to the stable soil carbon (3762.1 gC/m²) with the time of residence is about 500. In this process, each of pools carbon was released CO_2 to the atmosfer, the highest is in the humus carbon (171 gC/m²).

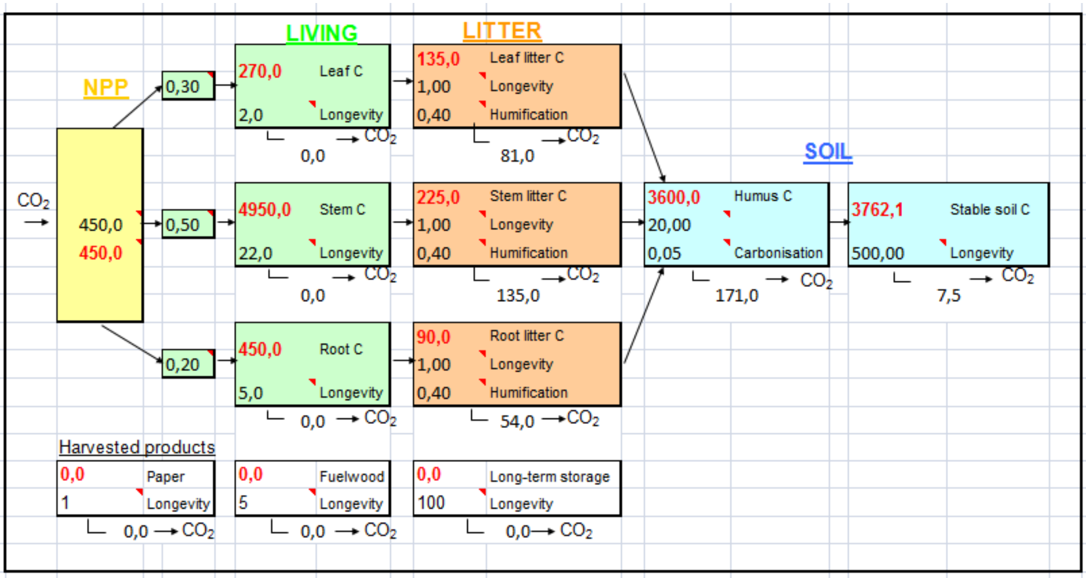
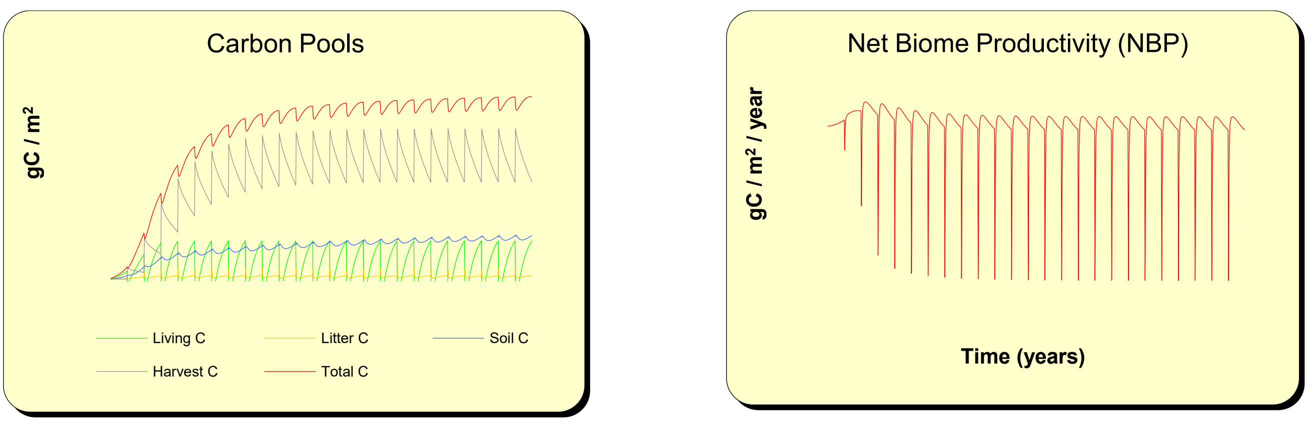


Figure 6. Soil carbon potential in the virgin forest

According to the simulation of conventional logging for rotation 40 year, the proportion of carbon in the living is about 21 %, carbon litter about 2 % and 24 % in the soil. When conventional logging is applied at year 40, the forest carbon stock can be seen to decrease more dramatically (Qin et al., 2024). These changes are similarly reflected in the NBP figure, with a marked increase in instantaneous emissions after year 40. In this study, the same pattern is apply on logging scenario (CL 80 year, RIL 40 and 80 year).



(a) (b)

Figure 7. Soil carbon dynamics in a conventional logging system for 40 year rotation: (a) Carbon Pools; (b) Net Biome Productivity (NBP)

In the scenario of conventional logging for 40 year rotation, from one year to the next some of carbon will be retained in the leaves about 270 gC/m² with average ½ of the total leaf carbon is lost to the leaf litter pool (135 gC/m²/year) on the rate of humification around 0.4. In the leaf is about 3451.7 gC/m², where around 1/22 for every year of the total stem carbon will released to the stem litter pool is around 153.7 gC/m²/year. About 450 gC/m² root with average 1/5 for every year root carbon will lost to the root litter pool about 90 gC/m². No different value in the longevity and humification rate was results potential of humus carbon about 2467.9 gC/m², 2364.4 gC/m² for stabil soil carbon and 116.6 gC/m² for highest released carbon in to the atmosfer (humus carbon).

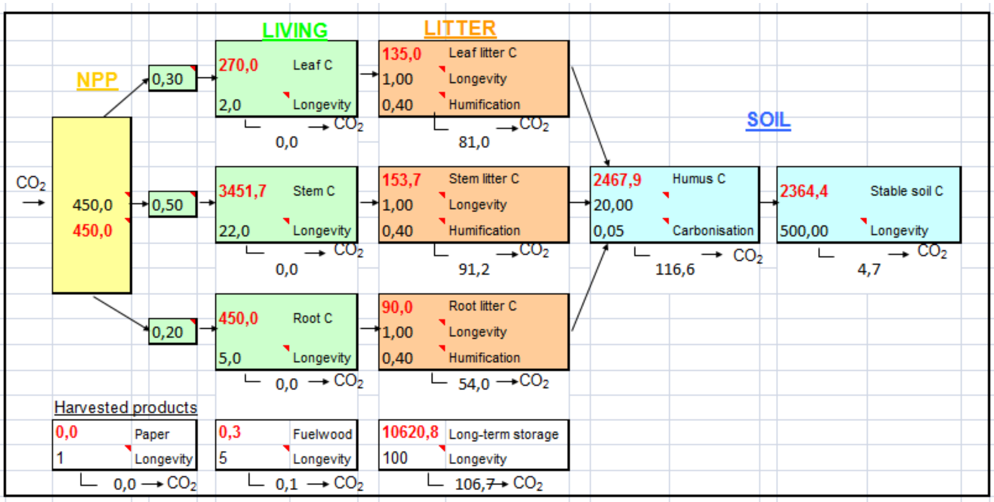
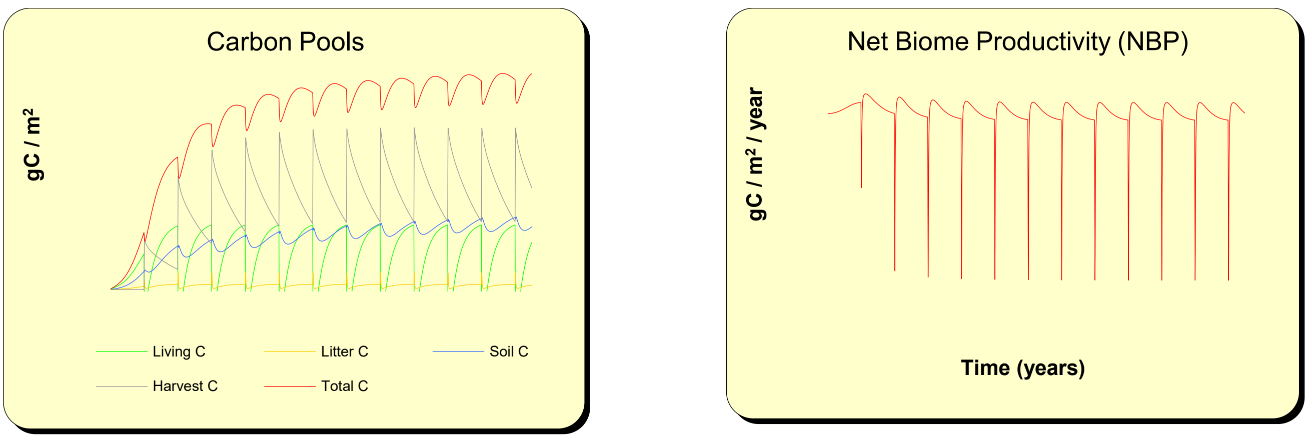


Figure 8. Soil carbon potential in in a conventional logging system for 40 year rotation

According to the simulation of conventional logging at rotation 80 year, the proportion of carbon in the living is about 22 %, carbon litter about 2 % and 29 % in the soil, respectively. This value is higher than virgin dry forest and RIL 40 year



(a) (b)

Figure 9. Soil carbon dynamics in a conventional logging system for 80 year rotation

In the scenario of conventional logging for 80 year rotation, from one year to the next some of carbon will be retained in the stem about 3233.9 gC/m² with average 1/22 of the total leaf carbon is lost to the leaf litter pool (143 gC/m²/year) on the rate of humification around 0.4. No different value with conventional logging for 40 years rotation in the longevity and humification rate was results potential of humus carbon about 2467.9 gC/m², 2364.4 gC/m² for stabil soil carbon and 116.6 gC/m² for highest released carbon in to the atmosfer (humus carbon). The acculumation of humus carbon in the soil pool is about 2444.6 gC/m² with the rate of carbonisation and time of residence on 0.05 and 20, its mean around 1/20/year humus carbon will lost to the stable soil carbon (2859.4 gC/m²) with the time of residence is about 500. In this process, humus carbon have a decrease tendency to released CO_2 to the atmosfer (115.5 gC/m²).

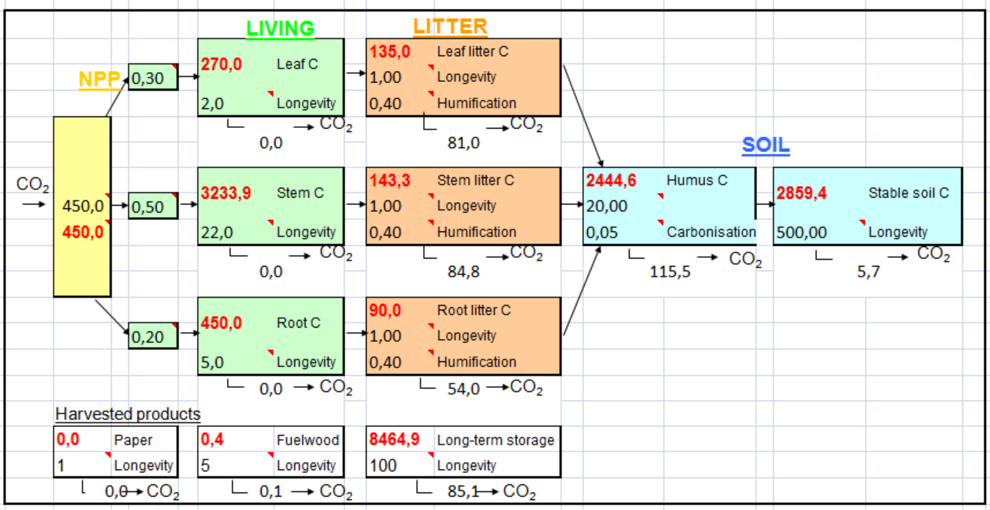
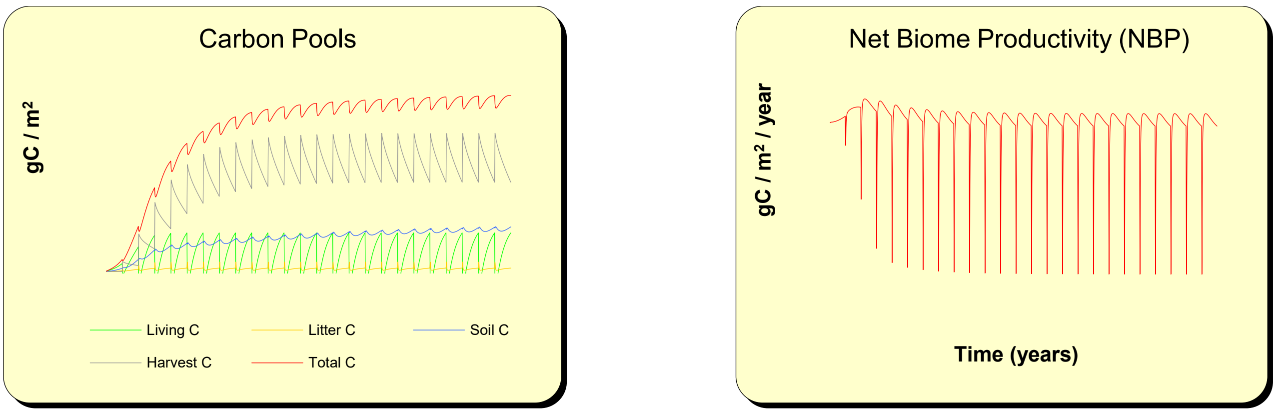


Figure 10. Soil carbon potential in in a conventional logging system for 80 year rotation



(a) (b)

Figure 11. Soil carbon dynamics in a reduced impact logging system for 40 years rotation

The proportion of carbon in the living is about 22 %, carbon litter about 2 % and 26 % in the soil (RIL 40 year). In the scenario of reduced impact logging (RIL) for 40 years rotation, some of carbon will be retained in the stem about 3556.0 gC/m² with average 1/22 of the total leaf carbon is lost to the leaf litter pool (158.6 gC/m²/year) on the rate of humification around 0.4 and potential of humus carbon about 2542.4 gC/m², 2455.3 gC/m² for stabil soil carbon and 120.1 gC/m² for highest released carbon in to the atmosfer (humus carbon).

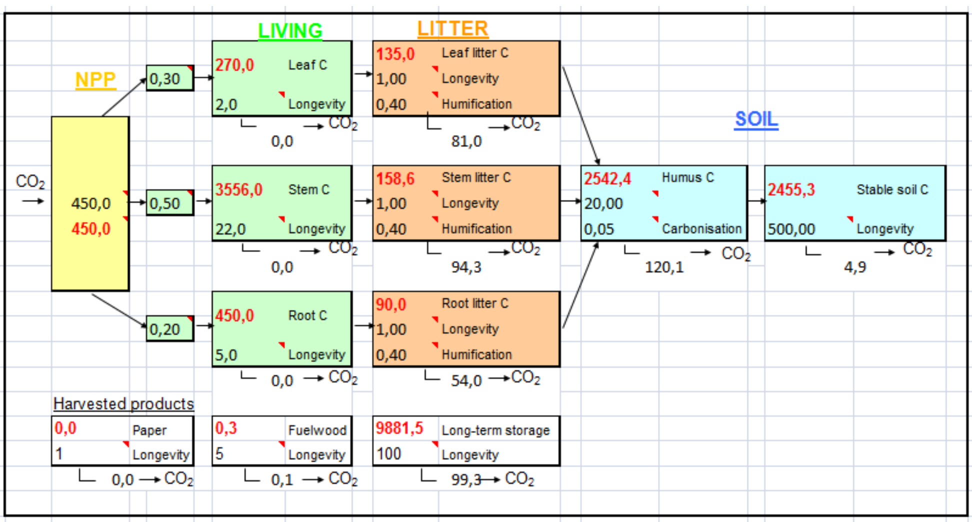
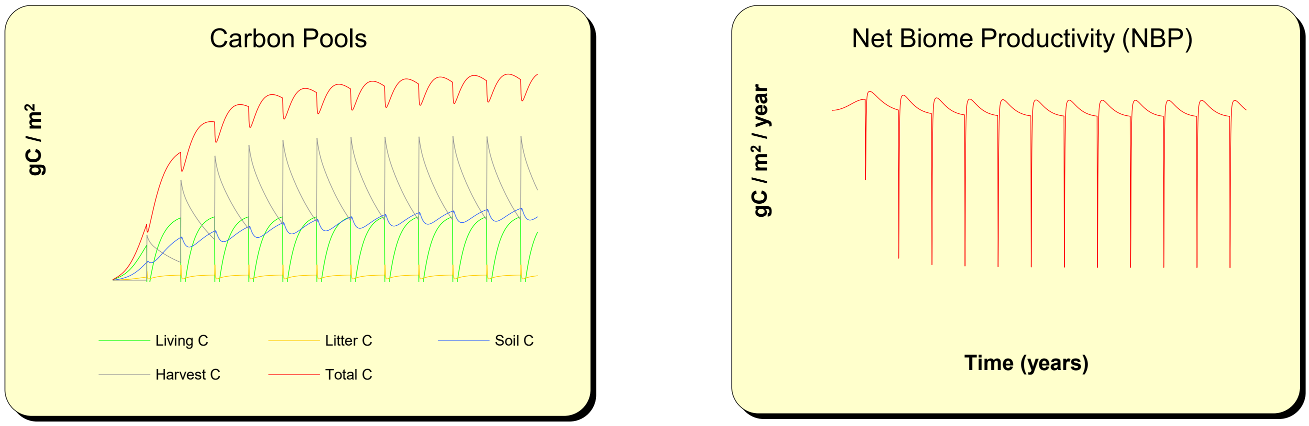


Figure 12. Soil carbon potential in in a reduced impact logging system for 40 year rotation



(a) (b)

Figure 13. Soil carbon dynamics in a reduced impact logging system for 80 year rotation

According to the simulation of reduced impact logging (RIL) for rotation 40 year, the proportion of carbon in the living is about 23 %, carbon litter about 2 % and 31 % in the soil. In the scenario of reduced impact logging (RIL) for 80 years rotation, some of carbon will be retained in the stem about 3389.4 gC/m² with average 1/22 of the total leaf carbon is lost to the leaf litter pool (150.7 gC/m²/year) on the rate of humification around 0.4 and potential of humus carbon about 2544.8 gC/m², 2941.3 gC/m² for stabil soil carbon and 120.3 gC/m² for highest released carbon in to the atmosfer (humus carbon).

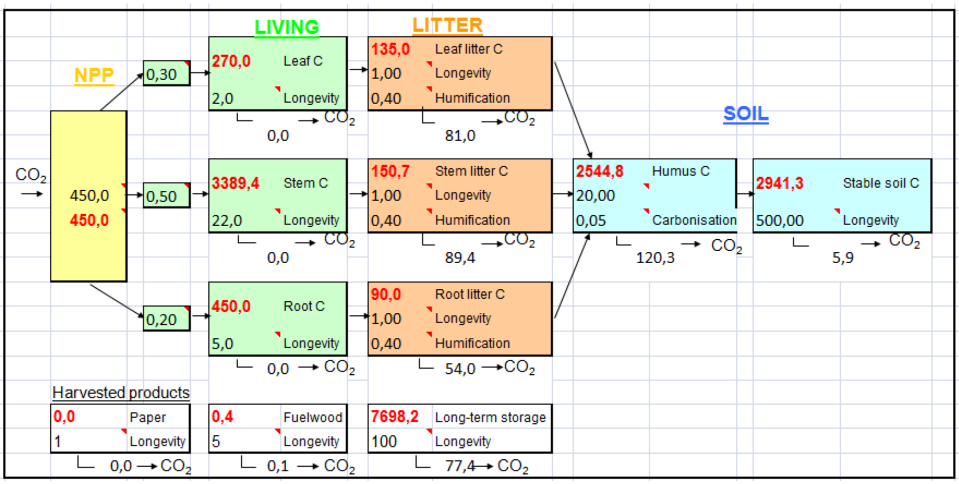
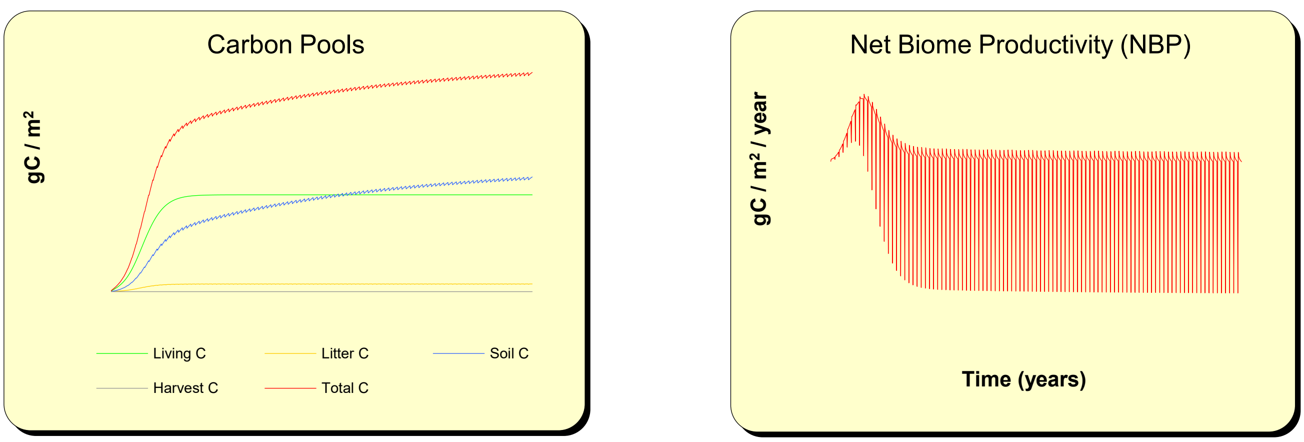


Figure 14. Soil carbon potential in a reduced impact logging system for 80 year rotation



(a) (b)

Figure 15. Soil carbon dynamics in coffee-based agroforestry systems

For Coffee-based Agroforestry sample from the studied area (Figure 15), the fitted carbon pools increment curves reached a maximum in the first 100 years (51 %), this is due to the dominance of an increase in soil carbon around 32 %. Totaly, in this area, they have increasing pattern to conserve carbon pools. This is higher than the first 100 years reported in others type of land use.

In the scenario of coffee based agroforestry system, some of carbon will be retained in the stem about 4861.5 gC/m² with average 1/22 of the total leaf carbon is lost to the leaf litter pool (220.8 gC/m²/year) on the rate of humification around 0.4 and potential of humus carbon about 3280.1 gC/m², 3363.3 gC/m² for stabil soil carbon and 155.5 gC/m² for highest released carbon in to the atmosfer (humus carbon).

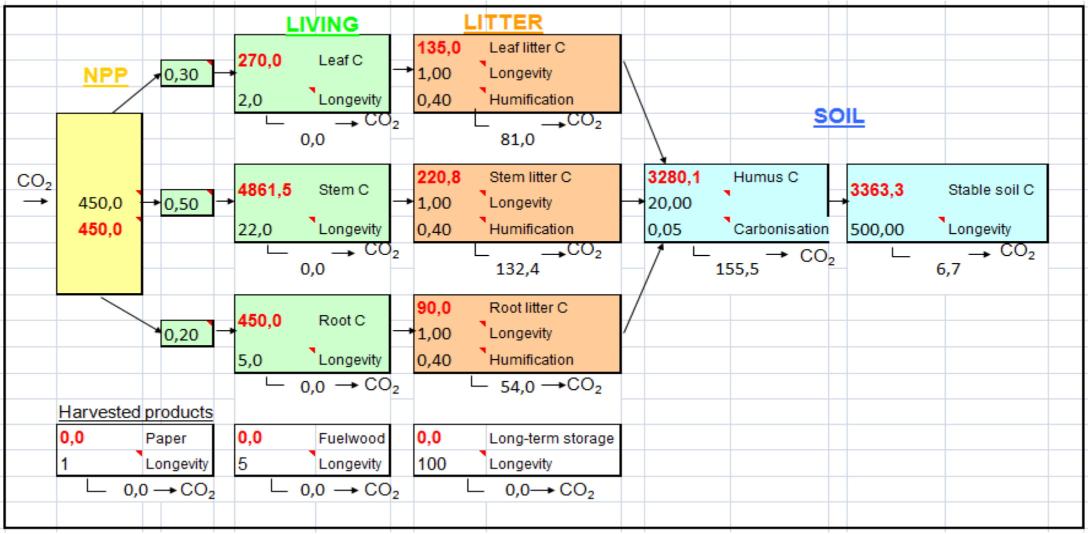


Figure 16. Soil carbon potential in coffee-based agroforestry systems

Soil Carbon Pool Dynamics in Dry Forest

Carbon stocks produced using the Carbon accounting simulation software (CASS) for improved forest management were clearly influenced by presence or absence of harvesting activities (Boukhris et al., 2025; Braga et al., 2024). Virgin dry forest and coffee-based agroforestry system scenarios were optimal for carbon stocks, but we did not consider leakage, land-use change nor natural disturbance risk from wind and fire (Pramulya et al., 2021; Santhyami & Roziaty, 2022). Carbon stock of the living, litter and soil all decreased from virgin forest to the conventional logging ang reduced impact logging, carbon concentration of these biomass in the coffea agroforestry system were slightly higher than those of virgin forest and logging treatments (ranging 0 – 52 %) (Wijaya, 2024). Carbon stock of the living and soil increased with a decreasing harvest and reached the highest stock in the coffea agroforestry (Gomes et al., 2025)as shown in Figure 17.

The substantial finding was that initial stocking were influential in determining carbon stocks for 80 years rotations (CL and RIL) and initial stocking was significant for 40 years rotations (CL and RIL). The model predictions of carbon pools (Figure) showed that carbon pools were very sensitive to the best decrease rates associated with different logging rotation and % disturbance cause by harvesting activity (Ameray et al., 2021; Pietrzykowski et al., 2024). The resulting carbon emissions due to virgin dry forest, logging treatments (CL and RIL) and coffea based agroforestry system showed a total loss or emission form each pools between 2 % and 41 % were the highest emitted from humus carbon.

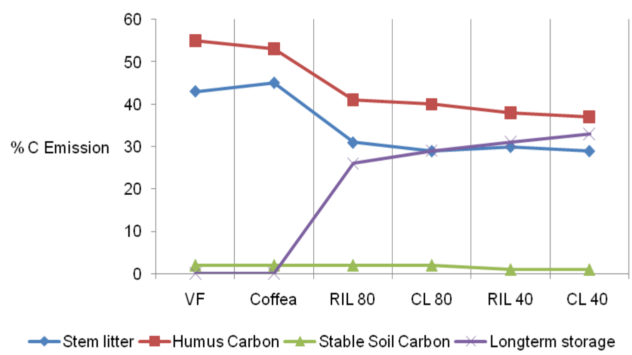


Figure 17. Percentation of carbon emission due to treatments

In the coffee agroforestry system, its showed constant accumulation of carbon in the living, litter and soil. This research demonstrates the importance of conservation- based production systems such as coffee agroforests in sequestering C alongside natural forest systems (Lugo-Pérez et al., 2023).

In this study, when logging treatments (CL and RIL) is applied at year 40 and 80 the forest carbon stock can be seen to decrease more dramatically. These changes are similarly reflected in the NBP figure, with a marked increase in instantaneous emissions after logging rotation. NBP of the managed forests is determined mainly by changes in age at which forest is usually harvested (the length of rotation) (Landry et al., 2021; Li et al., 2025). NBP is positive when the length of rotation is increasing, and negative otherwise (Sharma et al., 2023).

Conclusion

Based on the analysis presented, the following conclusions can be drawn: although the regeneration of tree species was low in several research sites, it potentially appears that the silvicultural interventions to pioneer species through thinning liberation, seeding and planting (pioneer species) could accelerate the tree species regeneration of dry forest in East Nusa Tenggara Province, Indonesia; both coffee agroforestry system and virgin dry forest in the semi arid region Nusa Tenggara Timur province store substantial amounts of carbon pools and; harvesting activities that influence carbon pools recovery, for example by affecting site quality to disturbance, are of consequence to carbon storage. In dry forests, managing the forest for timber is compatible with maximizing carbon storage if appropriate harvesting practices are used.

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Author Contributions

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Conflicts of Interest
The authors declare no conflict of interest.

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