Jurnal Manajemen Hutan Tropika, *30*(3), 376–389, December 2024
EISSN: 2089-2063
DOI: 10.7226/jtfm.30.3.376

Scientific Article
ISSN: 2087-0469

The Potential Ecological Impact of Oil Palm Agroforestry as Term of Improvement for Restoring Harapan Rainforest

Tabah Arif Rahmani[1], Dodik Ridho Nurrochmat[2], Mi Sun Park[3], Rizaldi Boer[4], Meti Ekayani[5*]

[1]Graduate Program of Forest Management Science, Department of Forest Management, Faculty of Forestry and Environmental, IPB University, Academic Ring Road Campus IPB Dramaga, Bogor, Indonesia 16680
[2]Department of Forest Management, Faculty of Forestry and Environmental, IPB University, Academic Ring Road Campus IPB Dramaga, Bogor, Indonesia 16680
[3]Graduate School of International Agricultural Technology, Institutes of Green-Bio-Science & Technology, Seoul National University, 1447 Pyeongchang-daero, Daehwa-myeon, Pyeongchang-gun, Gangwon-do, Republic of Korea 25354
[4]Centre for Climate Risk and Opportunity Management in Southeast Asia Pacific (CCROM-SEAP), IPB University, Campus IPB Baranangsiang Jalan Pajajaran, Bogor, Indonesia 16143
[5]Department of Resource and Environmental Economics, Faculty of Economics and Management, IPB University, Academic Ring Road Campus IPB Dramaga, Bogor, Indonesia 16680

Received April 12, 2024/Accepted November 5, 2024

Abstract

Around 20.000 ha of forestland in the Harapan Rainforest, Jambi Province, Indonesia, is currently under encroachment by local communities. Local communities encroach on forest land converted into oil palm plantations. Expanding oil palm plantations into forest areas led to biodiversity loss and massive carbon emissions. The annual net carbon emissions of oil palm transformation from the forest in Indonesia is around 12.41–25.83 ton^{-1} ha^{-1} year^{-1}. Oil palm agroforestry is considered to be able to increase carbon sequestration and the biodiversity level. CRC-990/EFForTS has established an oil palm agroforestry experimental plot in Jambi Province, Indonesia, namely B11 plot. This study compares the carbon sequestration and biodiversity level between oil palm monoculture and agroforestry. The data collected in this study was obtained from the CRC-990 experimental plots. We collected data on the CRC-990 oil palm agroforestry plot in 6 plots of 40 m × 40 m and 6 plots of 20 m × 20 m. We chose the location and theme of this research because, until now, no research has been conducted yet to calculate the potential carbon absorption capacity and biodiversity level of oil palm agroforestry patterns in B11 plot. This study uses an allometric equation and IPCC guidelines to estimate biomass and carbon sequestration. SNI 8014 is used to evaluate the biodiversity level. This study found that oil palm agroforestry has more significant carbon sequestration. Increasing intercropping in oil palm agroforestry will increase the amount of carbon sequestration. This study also found that oil palm agroforestry has a higher biodiversity level. The species diversity of oil palm agroforestry is moderate, while oil palm monoculture is low. These potential ecological impacts can be considered an initial step in restoring the Harapan Rainforest. It is important to choose appropriate intercrops and proper management to increase the successful implementation of oil palm agroforestry.

Keywords: *biodiversity, carbon sequestration, ecological impacts, forest restoration, oil palm agroforestry*

**Correspondence author, email*: *meti@apps.ipb.ac.id*

Introduction

Palm oil is one of the most widely used agricultural commodities globally (Pendrill et al., 2019; Nurrochmat et al., 2020). Regarding Corley (2009), oil palm is adequate to fulfill the world demand for vegetable oils, estimated to reach over 240 million tons by 2050. Over the last twenty years, several countries such as Malaysia and Indonesia have used palm oil as their main export commodity (Pendrill et al., 2019; Nurrochmat et al., 2020; Purnomo et al., 2020). The total production of crude palm oil in Indonesia was more than 50 million tons in 2022 (MoA, 2023) and about 32 million tons of them were allocated for export (BPS, 2023). Several studies have also found that the palm oil trade positively impacts rural employment opportunities, economic benefits for smallholders, increased livelihoods, and economic growth. In Indonesia, oil palm cultivation is the livelihood for more than 4.5 million people who work in the oil palm plantation (Nurrochmat et al., 2020). However, most palm oil-producing countries are classified as developing countries, with around 38% predominantly poor (Khasanah et al., 2020; Nurrochmat et al., 2020). For example, in Indonesia, palm oil contributed around 3.2% of Indonesia's gross domestic products in 2022 (BPS, 2023), or more than USD35.79 billion (BPS, 2023), making palm oil the biggest agricultural export in Indonesia.

The rapid expansion of oil palm into tropical forests has

Jurnal Manajemen Hutan Tropika, *30*(3), 376–389, December 2024
EISSN: 2089-2063
DOI: 10.7226/jtfm.30.3.376

Scientific Article
ISSN: 2087-0469

caused significant damage to tropical biodiversity, especially in Southeast Asia (Margono et al., 2014; Rahmani et al., 2021). Tropical rainforests in Southeast Asia are rapidly disappearing due to the expansion of commercial agriculture (Guillaume et al., 2018; Luke et al., 2020). Some concerns are that expanding oil palm plantations into tropical rainforests has left an undesirable ecological footprint. Some reports stated that the enormous transformation of tropical rainforests into oil palm is suspected of biodiversity loss, massive carbon emissions, and the social crisis in Southeast Asia (Azhar et al., 2014; Guillaume et al., 2018; Cooper et al., 2019). As a result of the dramatic loss of biodiversity, it is estimated that the loss of ecosystem function may outweigh the loss of species diversity (Azhar et al., 2014; Immerzeel et al., 2014).

In the last few decades, palm oil production in Indonesia has been the focus of debate on greenhouse gas (GHG) emissions and the loss of major tropical biodiversity (Immerzeel et al., 2014). The annual net carbon emissions of oil palm transformation from the forest in Indonesia is around 12.41–25.83 ton^{-1} ha^{-1} year^{-1} (Guillaume et al., 2018; Rahman et al., 2018). Indonesia has an emissions reduction target (NDC) of 915 million tons of CO_2e, or around 41% in 2030. Thus, it is important to implement appropriate management to reduce emissions from deforestation and forest degradation caused by converting forests to oil palm plantations.

Some reports suggested integrating biodiversity conservation into managing oil palm plantations for more diverse landscapes (Harbi et al., 2018; Khasanah et al., 2020; Rahmani et al., 2021; Rahmani et al., 2022). One step to increase a landscape's diversification is to plant native trees (Teuscher et al., 2016). The enrichment planting of oil palm monocultures in forest areas can be considered a step to restore landscapes, biodiversity, and forest function. In this study, the enrichment planting between oil palms is named oil palm agroforestry. Agroforestry can increase structural complexity in the agricultural landscape, making landscapes more friendly for native species (Teuscher et al., 2016; Nurrochmat et al., 2021), and also improving local welfare (Harbi et al., 2018). Even small "tree islands" can increase bird activity and thus trigger seed dispersal to encourage the creation of larger tree islands. Therefore, oil palm agroforestry can be a bridge to achieve land savings through more efficient land use (Khasanah et al., 2020). This study defines oil palm agroforestry is that the existing oil palm is enriched with intercrop subtrees. The term palm oil agroforestry in this paper refers to oil palm located in forest areas, not community-owned plantations on their land, or large-scale plantations that already have business use rights (*hak guna usaha*/HGU).

Regarding those previous studies, there is a lot of ecological impact of oil palm agroforestry implementation, such as increasing biodiversity, making the landscape more friendly for native species, and improving bird activity. This study addresses the knowledge gaps on the other ecological impact of oil palm agroforestry, which is carbon sequestration and biodiversity level. We studied the CRC-990/EFForTS's oil palm agroforestry experimental plot in Jambi. CRC-990 successfully integrated the oil palm with trees such as *jengkol* or dog fruit (*Archidendron pauciflorum*), *petai* (*Parkia speciosa*), *durian* (*Durio zibethinus*), *sungkai* (*Peronema canescens*), *meranti* (*Shorea leprosula*), and *jelutung* (*Dyera lowii*). We hypothesize that oil palm agroforestry has a more significant carbon sequestration and biodiversity than oil palm monoculture. This study assumes that forest has greater carbon sequestration and biodiversity than oil palm plantation. Thus, if oil palm agroforestry has greater carbon sequestration and biodiversity level, the oil palm agroforestry can be considered as a bridge for forest restoration of the Harapan Rainforest. The novelty of the study is the oil palm option as a solution to incorporate ecological and economic interest in forest areas through oil palm agroforestry.

Contextual background The expansion of oil palm into forest areas in Indonesia is quite large. About 3.4 million hectares of oil palm plantations are located in state forest areas (Figure 1) (Sudarwanto et al., 2022; BPS, 2023). The expansion of oil palms in Indonesia has occurred mostly in the tropical lowland rainforest of Sumatra and Kalimantan (Sumarga & Hein, 2016; Purnomo et al., 2020). These two islands house around 90.7% of Indonesia's oil palm plantation (BPS, 2023). The two most common management systems used in oil palm cultivation in Indonesia are corporate estates and smallholdings (Azhar et al., 2014). The expansion of oil palm plantations in Indonesia has reduced forest cover (Sumarga & Hein, 2016; Vijay et al., 2016; Cooper et al., 2019).

The large area of oil palm plantations on Sumatra Island has reduced forest cover in several provinces of Sumatra, one of which is Jambi Province (BPS, 2023; MoEF, 2023). Jambi is a province in Sumatra that has experienced a significant reduction in forest cover (Figure 2). For example, in 2018, around 20,000 ha of forestland in the Harapan Rainforest, Jambi Province, Sumatra, Indonesia, has been designated by the Indonesian government for the restoration of lowland rainforest ecosystems but is currently under encroachment by local communities and converted into oil palm plantations (Tambunan, 2018). From the results of our visual interpretation of Google satellite imagery in 2021, we found that almost half of the Harapan Rainforest area in Jambi Province had been encroached on by local communities with oil palm (Figure 3). Harapan Rainforest is a production forest managed by PT Restorasi Ekosistem Indonesia (PT REKI)

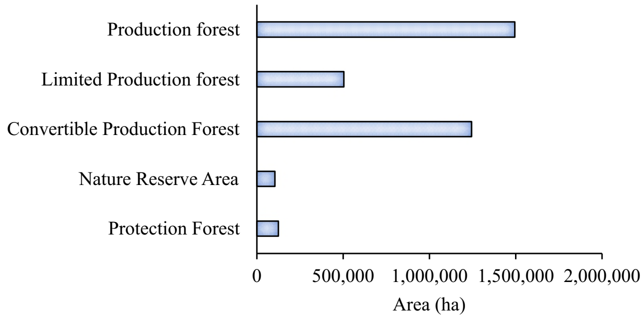

Figure 1 The coverage of oil palm plantations in forest areas is based on forest function in Indonesia (KEHATI, 2019).

Jurnal Manajemen Hutan Tropika, *30*(3), 376–389, December 2024
EISSN: 2089-2063
DOI: 10.7226/jtfm.30.3.376

Scientific Article
ISSN: 2087-0469

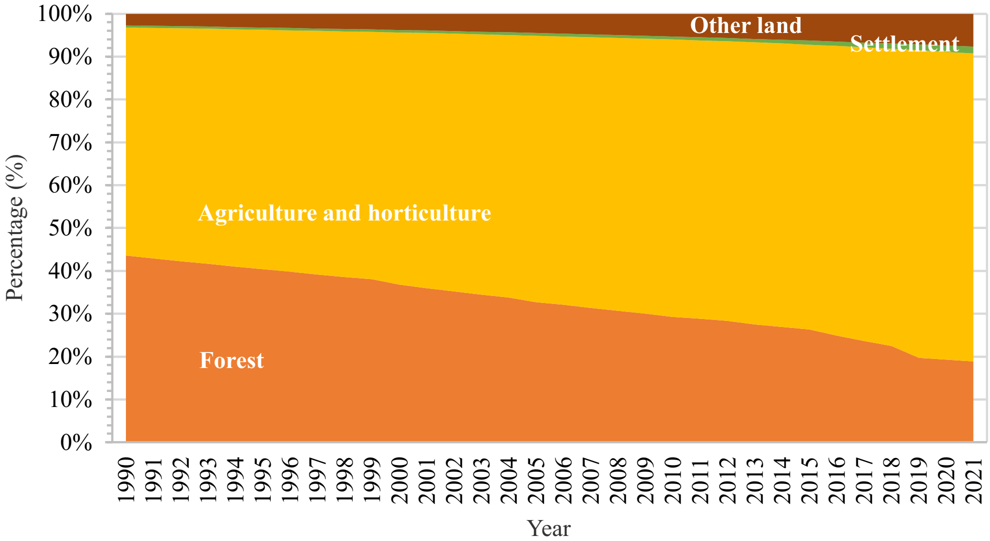

Figure 2 Percentage of land covers in Jambi Province from 1990 to 2021 (Drescher et al., 2016; BPS, 2023; MoA, 2023; MoEF, 2023).

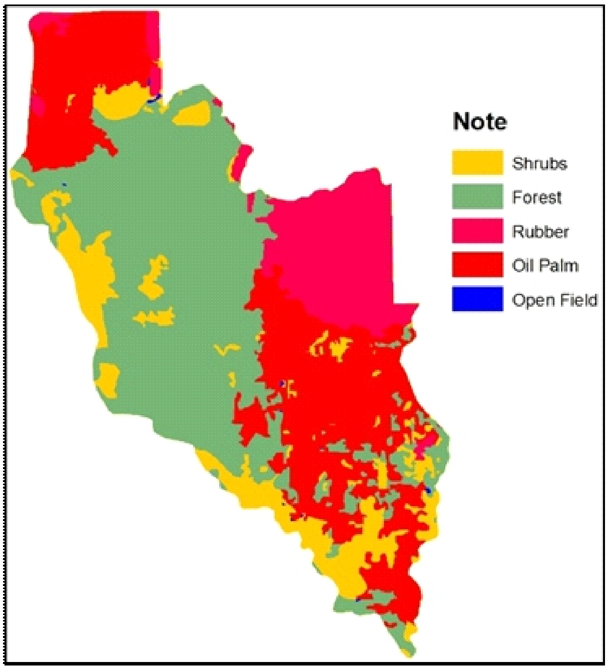

Figure 3 Harapan Rainforest's land cover (Google satellite).

with an ecosystem restoration scheme (IUPHHK-RE). The conflict of interest in the Harapan Rainforest is suspected because the local community thought that oil palm was more profitable. In contrast, the company (PT REKI) is interested in restoring the forest because the Harapan Rainforest is the only remaining lowland rainforest on Sumatra Island.

The efforts to restore the Harapan Rainforest ecosystem can not necessarily be carried out by replacing oil palm plantations owned by local communities with native trees or indigenous species. This happens because these oil palm plantations are a source of livelihood for most local communities in the Harapan Rainforest. Local communities have a high direct dependence on the Harapan Rainforest area. Thus, this paper tries to answer this challenge by taking a win-win solution for Harapan Rainforest restoration efforts through the implementation of oil palm agroforestry in the Harapan Rainforest area, which has been planted with oil palm by the local communities. We assume that the oil palm agroforestry can be a bridge for restoring the Harapan Rainforest ecosystem.

In 2014, the Collaborative Research Center 990 (CRC-990)/EFForTS established an oil palm agroforestry experimental plot in Jambi, Indonesia. The outcomes of these experiments underscore the potential of integrating oil palms and trees in the same landscape (Teuscher et al., 2016). Furthermore, numerous studies have highlighted the economic and ecological advantages of agroforestry systems in oil palm (Teuscher et al., 2016; Khasanah et al., 2020; Rahmani et al., 2021). From a smallholder's perspective, oil palm agroforestry is more profitable than oil palm monoculture and offers higher potential income. Despite the higher care intensity and farmer skill required, the average potential income of oil palm agroforestry is IDR3,763,134 (USD244.91) ha^{-1} $month^{-1}$, compared to IDR2,371,069 (USD154.31) ha^{-1} $month^{-1}$ for oil palm monoculture.

Other studies also found that the oil palm agroforestry makes the landscape more accessible to native species, forming clusters of tree islands within the oil palm plantation (Teuscher et al., 2016; Khasanah et al., 2020). Before the enrichment planting in 2013, a total of 92 plant species, 21 bird species, and 87 invertebrates of oil palm agroforestry established the bird richness was found to be (Teuscher et al., 2016). After one year of oil palm agroforestry establishment, the bird richness was found to be 30% higher and found 5 new species (Teuscher et al., 2016). Furthermore, around 179 invertebrate families and 109 plant species were also found after one year of establishment. Therefore, this study is considering promoting oil palm agroforestry to improve the ecological condition of forests converted into oil palm monoculture.

We chose the CRC-990's oil palm agroforestry experimental plot and Harapan Rainforest as study sites because the two locations are close. Thus, we assume that

Jurnal Manajemen Hutan Tropika, *30*(3), 376–389, December 2024
EISSN: 2089-2063
DOI: 10.7226/jtfm.30.3.376 ISSN: 2087-0469

both locations have similar edaphic and climatic conditions, so if the oil palm agroforestry can be implemented in CRC-990's oil palm agroforestry experimental plot, it will also be possible to implement in the Harapan Rainforest. Furthermore, until now, a lot of the Harapan Rainforest area has also been heavily encroached with oil palms by local communities, so initial steps are needed to restore this forest area. The term of restoring Harapan Rainforest on this study means the effort to restore forest cover in areas that have been encroached with oil palm, so that these areas meet the requirements to be defined as forests as referred to in the Minister of Environment and Forestry Regulation Number P.14/2004.

Methods

Research framework This study compares carbon sequestration and biodiversity levels between oil palm agroforestry and monoculture patterns. We use the aboveground biomass and carbon sequestration estimation method following IPCC (2006) guidelines to measure carbon sequestration in both patterns. Then, we measure biodiversity levels in both patterns following the SNI (2014) method. The research framework is presented in Figure 4.

Study area These study sites are located in the oil palm agroforestry experimental B-11 plot of the CRC-990/EFForTS in the oil palm plantation area of PT HMS in Bungku Village and Harapan Rainforest area, specifically in Kunangan Jaya Village, Batanghari District, Jambi Province (Figure 5).

The following are several typologies of agroforestry systems in Indonesia (Arifah, 2022): a) *Yard system.* The homestead system adopts agroforestry by planting mixed crops in private homesteads, such as annuals, long-lived plants, and livestock. This type was often found on Java Island. In general, yard systems have a minimum of 2 layers of plants. The lowest layer is covered with plants up to 2 m high, such as tubers, vegetables, and bamboo. The higher plant layers are planted with fruit such as cloves, *sengon*, coconut, and other trees; b) *Garden-talun system.* The establishment of *talun*, or cultivation areas, consists of various commodities ranging from plantation crops, horticulture, and forestry crops. Once annual plants dominate and can be harvested every year, the garden will be dominated by long-term plants. At this moment, the area has entered the third stage, namely *talun*. This land is dominated by a mixture of long-lived trees, annual plants, and horticulture growing in one agroforestry area; c) *Alley-cropping system.* This type of agroforestry is mostly found in the Nusa Tenggara region. The alley-cropping system utilizes contour lines to plant legumes or plants that are a good source of protein for animal feed. The plant can be

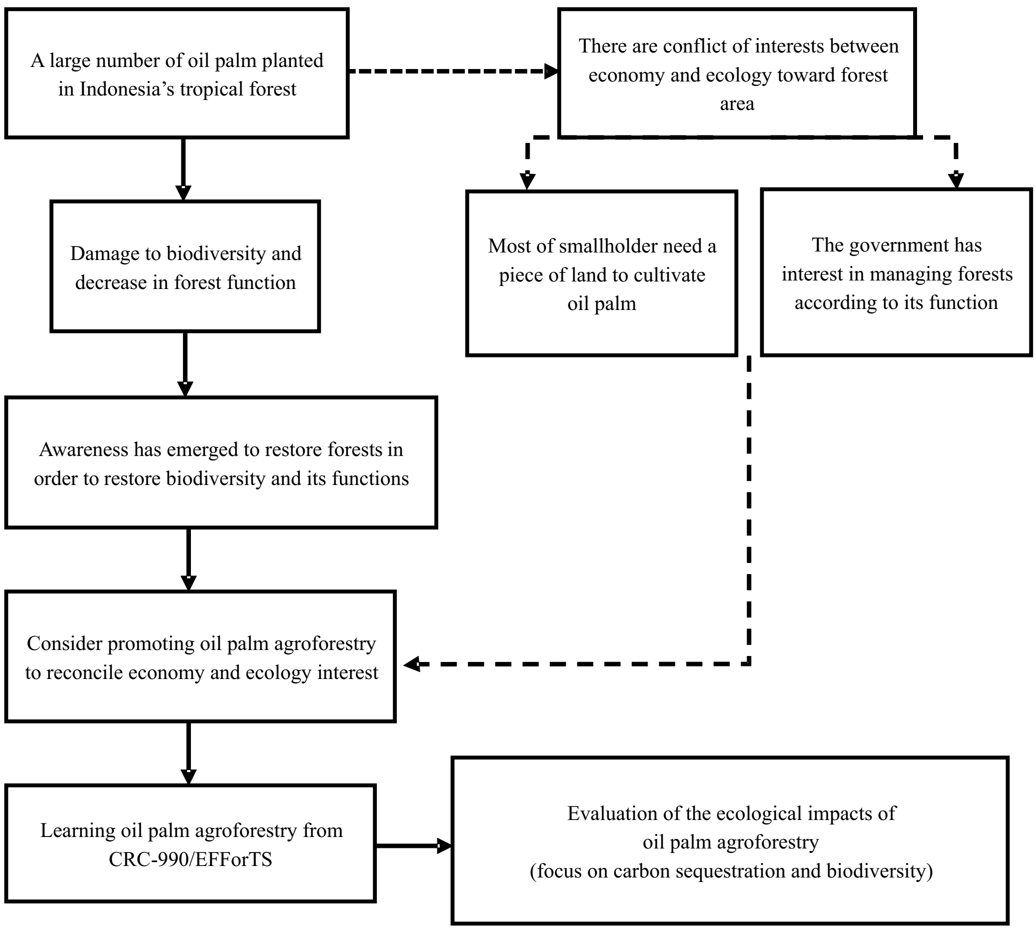

Figure 4 Research framework.

Jurnal Manajemen Hutan Tropika, *30*(3), 376–389, December 2024
EISSN: 2089-2063
DOI: 10.7226/jtfm.30.3.376
Scientific Article
ISSN: 2087-0469

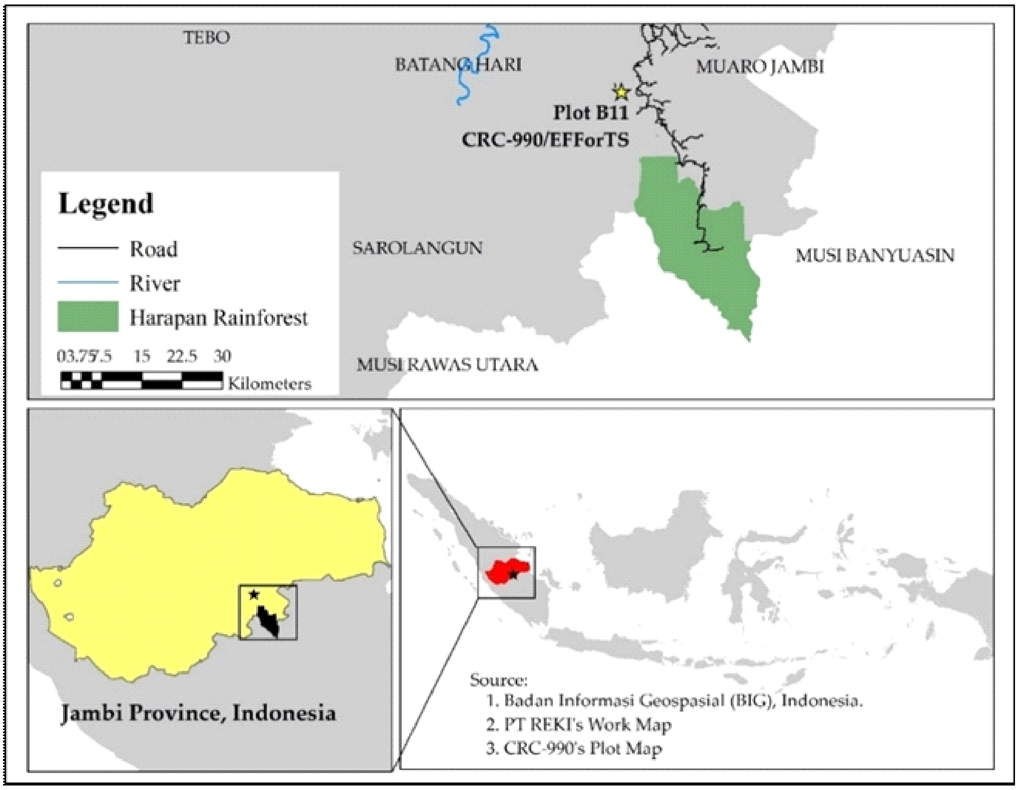

Figure 5 Study area.

lamtoro gung (*Leucaena leucocephala*), planted in the array. Between the rows, annual plants, long-lived plants, and grass will be planted; d) *Fallow system*. The fallow system restores soil fertility by planting plants that can do this, such as *Pueraria javanica*, because the conventional farming system usually hurts the ecosystem, particularly soil quality. After planting and the soil recovering, 34 months later, food crops can begin to be cultivated. Food plants that can be used include cassava, rice, peanuts, and ginger. Also, *melinjo* (*Gnetum gnemon*) can be a long-term crop choice; e) *Stratified agroforestry garden system***.** This system's main characteristic is combining forest plants and agricultural plants to form forest land with layers of strata. Agricultural crops can be plants with high selling value on the market to provide income for the household, such as chilies, eggplant, corn, beans, and cucumbers in the second layer, and understory of the woody plants such as *durian*, cinnamon, nutmeg, and coffee is the first layer. This type of agroforestry is often found in North Sumatra; and f) *Intercropping system***.** The intercropping system temporarily utilizes forest land by planting agricultural crops between hardwood plants. Its advantage is that it optimizes existing land as much as possible and for the multipurpose of forest land. This type of agroforestry is widely applied in Java.

This research complies with the intercropping agroforestry system by combining palm oil and other valuable plants for community income to bridge the economic, social, and ecosystem conflict. The data collected in this study was obtained from the CRC-990 experimental plots. We collected data on the CRC-990 oil palm agroforestry plot in 6 plots of 40 m × 40 m and 6 plots of 20 m × 20 m.

CRC-990/EFForTS has 54 experimental plots with different plot sizes: 5 m × 5 m, 10 m × 10 m, 20 m × 20 m, and 40 m × 40 m. It has different biodiversity degrees within various trees as intercrops (Figure 6). Those plots were established in 2014, laid on an area dominated by a soil type of acrisol clay and surrounded by a lowland rainforest ecosystem (Allen et al., 2015). The experimental plot was developed by enriching an eight-year-old oil palm plantation by planting trees as intercrops (trees planted in between oil palm stands), i.e., *A. pauciflorum, P. speciosa, D. zibethinus, P. canescens, S. leprosula,* and *D. lowii.* The number of oil palms in a plot of 40 m × 40 m is around 13 trees, and the spacing between the intercrops is 2 m × 2 m (Gérard et al., 2017). It means there are about 81 oil palms in a hectare and around 2,500 trees as intercrops.

Materials and equipment This study uses primary and secondary data from surveys at the study site. The primary data needed in this study include the diameter and height of each species (plant), the number of species, and the allometric equation of each species. The equipment needed to obtain the data needed and for data analysis includes a tally sheet, tape meter, phi band, clinometer, hand tally counter, and Microsoft Excel. The secondary data needed in this study include the allometric (Chave et al., 2005; IPCC, 2006; Krisnawati et al., 2012; Khasanah et al., 2015), the general condition of the study site , and other supporting data (such as climatic condition in Jambi Province, soil condition, etc.).

Data collection and data analysis A survey for the primary data needed was conducted from November 2021 until July 2022. To collect the data needed, such as the diameter breast height of trees (dbh), trees and oil palm height, and the number of species, we conducted a field survey in CRC-990's experimental plot. Referring to the SNI (2019), we use a circle sample plot. Plot sizes for each level of vegetation (life form) are as follows: seedlings and understory is 4 m^2; stake is 25 m^2; pole is 100 m^2; tree is 400 m^2 (Figure 7). The sample plots were also selected using purposive and stratified sampling methods. We stratify the oil palm agroforestry experimental plot (B11 plot CRC-990) based on the diversity of the enrichment plant. We only chose a plot with a size of 40 m × 40 m and 20 m × 20 m as a sample plot to suit the size of our sample plot following SNI (2019). Only 25 experimental plots are suitable for our criteria. We conducted non-destructive sampling for all data samples from the field survey. We also collected data from oil palm plantations within the Harapan Rainforest. Secondary data needed to be obtained from literature studies and published scientific articles.

Biomass is the total dry weight of vegetation, expressed in units of kilograms (kg) or tonnes (Chave et al., 2005). This study estimates the aboveground biomass of each species to measure carbon stock using an allometric equation. The allometric equation is a mathematical equation showing the relationship between certain parts of living things and other parts or functions (Chave et al., 2005). The Ministry of Environment and Forestry stated that the allometric model is a regression model that states the relationship between the size or growth of one of the individual tree's components and all the individual tree's components (Chave et al., 2005). The advantage of the allometric equation is that it does not cut or destroy trees and is more efficient in terms of time and cost. The general allometric equation used in estimating tree biomass is as shown in Equation *[1]*.

$$Y = a \times dbh^b \qquad [1]$$

notes: Y = above-ground biomass (kg); a = coefficient of conversion; b = coefficient of allometric; and dbh = diameter breast high (cm).

We used an allometric equation to estimate oil palm biomass developed by Khasanah et al. (2015) (Table 1). Table 2 shows other allometric equations for estimating other species.

Carbon stock analysis of oil palm agroforestry was carried out using the IPCC's biomass content approach (IPCC, 2006). The general formulation used in estimating carbon stock is as shown in Equation *[2]*.

$$C = CF \times W \qquad [2]$$

notes: C = carbon stock (tC); CF = carbon rate coefficient of vegetation in tropical forest (0.47 tC kg^{-1}) (IPCC, 2006); and W = biomass (kg).

Then, carbon sequestration analysis was calculated using carbon stock data. The general formulation used in estimating carbon sequestration is as shown in Equation *[3]*.

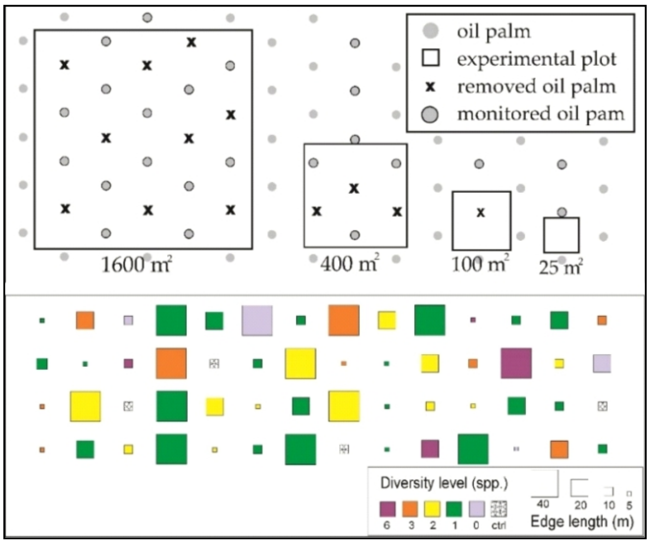

Figure 6 The experimental plots of oil palm agroforestry (adapted from Teuscher et al. (2016)).

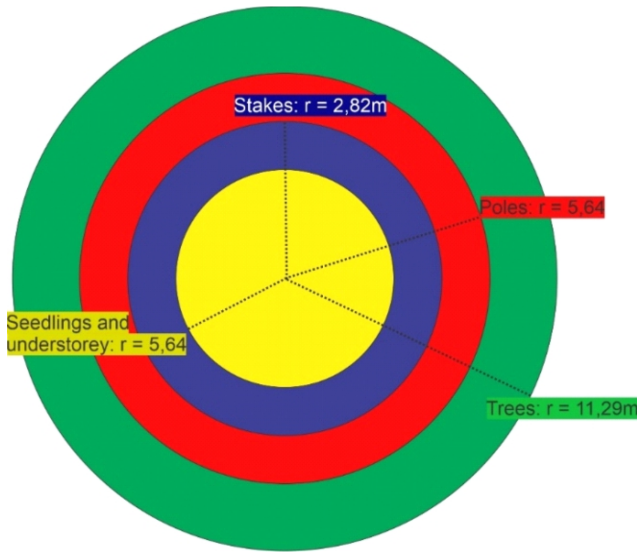

Figure 7 Shape and size of sample plot (SNI, 2019).

Table 1 Allometric equation to estimate oil palm biomass (Khasanah et al., 2015)

Growth equation	Soil type	*a*	*b*	R^2
Model I (linear): $Y = aA + b$	Mineral	0.0923	0.1333	0.8544
	Peat	0.0939	0.0951	0.9187
Model II (power): $Y = aA^b$	Mineral	0.1839	0.7660	0.9155
	Peat	0.2453	0.4933	0.9102

Annotation: Y = oil palm biomass (ton/oil palm staple)
A = oil palm height (m)

Jurnal Manajemen Hutan Tropika, *30*(3), 376–389, December 2024
EISSN: 2089-2063
DOI: 10.7226/jtfm.30.3.376 Scientific Article
ISSN: 2087-0469

Table 2 Allometric equation to estimate tree (enrichment plants) biomass

Plants	Allometric equation	Source
Shorea leprosula	$Y = 0.032D^{2.708}$	(Krisnawati et al., 2012)
Other trees *	$Y = 0.112(\pi D^2H)^{0.92}$	(Chave et al., 2005)
Other trees **	$Y = 0.051\pi D^2H$	(Chave et al., 2005)
Other trees ***	$Y = 0.0776(\pi D^2H)^{0.94}$	(Chave et al., 2005)

Annotation :
Y = oil palm biomass (kg tree^{-1})
A = diameter breast high (cm)
* Allometric equation with rainfall <1,500 mm (dry)
** Allometric equation with rainfall between 1,500–4,000 mm (humid)
*** Allometric equation with rainfall > 4,000 mm (wet)

$$EC = 3.67 \times \Delta CLC - D \quad [3]$$

notes: EC = CO_2 absorption (tCO_2); 3.67 = ratio of atomic carbon dioxide to carbon 44/12 (tCO_2e ton C^{-1}); ΔCLC–D = carbon stock.

Then, to assess the biodiversity level, we use the species community composition approach promoted by SNI 8014 (SNI, 2014). According to SNI 8014, there are three levels to estimate the composition of species communities, including alpha (α) diversity level, beta (β) diversity level, and gamma (γ) diversity level (SNI, 2014).

The indicators to estimate the diversity of the alpha (α) diversity levels are species richness and species diversity. Species richness is calculated from the number of species found in each sample unit in an ecosystem. Species diversity was calculated using the species diversity index developed by Shannon-Wiener, as shown in Equation *[4]*.

$$H' = -\sum \frac{ni}{N} ln \frac{ni}{N} \quad [4]$$

notes: H' = Shannon-Wiener biodiversity index; ni = number of species I; N = total numbers of species found. If $H' > 3$ indicates high biodiversity; if $1 \leq H' \leq 3$ indicates moderate biodiversity; if $H' < 1$ indicates low biodiversity.

Betha diversity indicators are changes in species diversity between ecosystems. The change assessment is calculated using two approaches, the Sorensen similarity index and Betha diversity index, as shown in Equation *[5]*.

$$\beta = \frac{2C}{2C+S1+S2} \text{ (Sorensen similarity index)}$$
$$\beta = (S1 - C) + (S2 - C) \text{ (Betha diversity index)} \quad [5]$$

notes: β = betha diversity; $S1$ = number of species found in ecosystems 1; $S2$ = number of species found in ecosystems 2; C = number of species found in both ecosystems. Betha diversity values range from 0 to 1, and lower values indicate that the level of similarity between ecosystems is high or the change is low.

Gamma (γ) diversity is calculated from the total species richness in all ecosystems in one study unit, calculated by the Equation *[6]*.

$$\gamma = S1 + S2 - C \quad [6]$$

notes: γ = gamma diversity; $S1$ = number of species found in ecosystems 1; $S2$ = number of species found in ecosystems 2; C = number of species found in ecosystems.

Results and Discussion

Overview of edaphic and climatic conditions between Harapan Rainforest and CRC-990's B11 plot Edaphic and climatic factors are the main factors to plant species richness. (Hofhansl et al., 2020). Moreover, edaphic and climatic factors affect plant growth (Hofhansl et al., 2020). Appropriate edaphic and climatic conditions can optimize plant growth (Hofhansl et al., 2020). Edaphic conditions are soil characteristics commonly observed in ecology (Rajakaruna & Boyd, 2019). Edaphic conditions pertain to the structure and composition of the soil in a specific area. The soil is the primary component of any plant habitat (Rahman et al., 2018; Obeng et al., 2020). Thus, the soil is viewed not only as the surface but also as a component of the Earth's crust (Rajakaruna & Boyd, 2019). Edaphic factors include soil profile, texture, nutrients, groundwater, temperature, pH, and aeration (Rajakaruna & Boyd, 2019).

Besides edaphic factors, climatic factors are important to plant growth (Hofhansl et al., 2020). The climatic conditions are non-living conditions responsible for determining a region's climatic conditions. (Hofhansl et al., 2020). The climatic conditions include sunlight, humidity, precipitation, wind, fire, temperature, and atmosphere. Climatic factors are important in determining where particular species will grow (Hofhansl et al., 2020). On Earth, sunlight is the primary source of energy for the existence of life. Sunlight has a role in plant photosynthesis. In addition, rainfall and humidity also have a big role in plant growth (Hofhansl et al., 2020). Thus, if the climatic conditions differ between the two locations, plant growth will be affected even though the same plants are planted in both areas.

As per Table 3, the soil texture between the B11 plot and Harapan Rainforest is different. The soil in Harapan Rainforest is sandier, and the soil texture is sandy loam. On the other hand, the land texture on the B11 plot tends to be clay loam. Generally, the soil in the B11 plot has a higher cation exchange capacity (CEC) than the soil in the Harapan Rainforest area. Furthermore, soil CEC in agroforestry plots has a higher cation exchange capacity (CEC) than in oil palm monoculture. However, oil palm monoculture soil has a higher C organic and N total than soil in oil palm agroforestry. This study contrasts with Rahman et al. (2018), which states that forest soil has higher C organic than oil palm monoculture. In addition, the conversion of forests to oil palm plantations reduces both top and subsoil C organic stocks (Rahman et al., 2018).

Soil fertility is the capacity of the soil to give vital nutrients in sufficient quantities for plant growth and development (Ojomah & Joseph, 2017). According to the rating chart for soil parameters (Table 4), each location's soil fertility is lower. The low pH of the soil at both locations

Jurnal Manajemen Hutan Tropika, *30*(3), 376–389, December 2024
EISSN: 2089-2063
DOI: 10.7226/jtfm.30.3.376

ISSN: 2087-0469

Table 3 Laboratorium test results of soil composite in oil palm monoculture (Harapan Rainforest) and oil palm agroforestry (CRC-990's experimental plot)

Soil composite sample	N total (%)	C organic (%)	CEC (cmol kg^{-1})	pH	Texture (%)		
					Sand	Silt	Clay
Oil palm agroforestry with one intercrop (B11 plot)	0.10	1.34	10.58	4.51	34.72	34.34	30.94
Oil palm agroforestry with two intercrops (B11 plot)	0.16	0.93	9.80	4.01	34.78	43.97	21.25
Oil palm agroforestry with three intercrops (B11 plot)	0.09	0.96	9.84	4.19	33.41	35.64	30.95
Oil palm agroforestry with six intercrops (B11 plot)	0.14	2.25	11.88	4.25	31.83	34.61	33.56
Oil palm monoculture (Harapan Rainforest)	0.17	4.06	3.63	4.23	73.45	13.03	13.52
Kunangan Jaya's agroforestri plot (Harapan Rainforest)	0.12	0.92	4.76	4.35	60.26	23.18	15.56

implies that it is acidic. Acidic soils have low fertility and are likely toxic (Al, Mn, Fe) to plants (Ojomah & Joseph, 2017; Obeng et al., 2020). Therefore, managing the soil in both locations is necessary to improve soil fertility.

Overall, the edaphic conditions between the B11 plot and the Harapan Rainforest may be slightly the same. The big difference from soil conditions is its texture. Therefore, this study assumes that, from an ecological point of view, oil palm agroforestry can be implemented in the Harapan Rainforest area.

The Köppen climate classification states that most parts of Indonesia areas have a tropical rainforest (Af) climate category, including Sumatra, Java, and Kalimantan (Figure 8). We found the average climatic conditions in Jambi in the last four years (Table 5). This study assumes that the climatic conditions between the B11 plot and the Harapan Rainforest area might be the same. It happens because the two locations are close. B11 plot and half of Harapan Rainforest are in Bungku Village. Thus, this study assumes that from the climatic point of view, oil palm agroforestry can be implemented in the Harapan Rainforest area. The similarity of edaphic and climatic conditions between the B11 plot and the Harapan Rainforest area makes it possible to implement oil palm agroforestry in the Harapan Rainforest. However, an experimental plot within the Harapan Rainforest might be needed to ensure this assumption.

Carbon sequestration comparison between oil palm monoculture and agroforestry The increase in large-scale expansion of oil palm monoculture, particularly in Indonesia, has led to the conversion of carbon-rich land-use types to oil palm plantations with a range of negative environmental impacts (Guillaume et al., 2018), including loss of carbon from aboveground biomass, belowground, and soil organic carbon (Rahman et al., 2021). Harapan Rainforest is a tropical rainforest in Indonesia that experienced the expansion of oil palms. The local community (smallholder) owns most of the oil palm within the Harapan Rainforest. The low quality of smallholder oil palm management causes more carbon loss (Rahman et al., 2021). This study considers the oil palm agroforestry scheme as an initial step in Harapan Rainforest restoration. This study assumes that implementing oil palm agroforestry can increase carbon sequestration in the Harapan Rainforest and potentially also reduce the risk of fires (Khasanah et al., 2015; Luke et al., 2020; Rahman et al., 2021).

This study observed local communities' oil palm plantations in Harapan Rainforest and CRC-990's oil palm agroforestry plot to assess carbon sequestration. As per Table 6, this study found that oil palm agroforestry has greater carbon sequestration than oil palm monoculture. The aboveground and belowground carbon sequestration of oil palm agroforestry is greater than that of oil palm monoculture. Oil palm agroforestry with six intercrops has the highest aboveground and belowground carbon sequestration. This result aligns with the previous study that evaluated monoculture and agroforestry systems, which stated that oil palm agroforestry produced greater carbon sequestration and sequestration than oil palm monoculture (Besar et al., 2020). Furthermore, Siarudin et al. (2020) also stated that agroforestry systems produce greater carbon stock than monoculture systems in peatlands but not in the oil palm context. This study also found that the more intercropping plants led, the more carbon sequestrations increased. In other words, the more diverse intercrops in oil palm agroforestry will affect the increase of carbon sequestration both aboveground and belowground.

Most studies that evaluated monoculture and agroforestry systems showed that monoculture systems have less soil organic carbon than agroforestry systems. Negash et al. (2022) stated that agroforestry-based commercial crops retain most of the SOC and N stocks of converted native forests lost due to commercial monoculture crops. Furthermore, Balaba et al. (2016) stated that Robusta coffee agroforestry is more likely to benefit from soil carbon than Arabica coffee monoculture. However, this study's results are contrary to those of the previous study. As per Table 6, this study found that oil palm monoculture has greater soil organic carbon than oil palm agroforestry. Soil organic carbon has no trend like above-ground carbon stock/ sequestration.

The selection of intercrops plays a pivotal role in the

Jurnal Manajemen Hutan Tropika, *30*(3), 376–389, December 2024
EISSN: 2089-2063
DOI: 10.7226/jtfm.30.3.376

Scientific Article
ISSN: 2087-0469

Table 4 Rating chart for soil parameters adapted from Ojomah and Joseph (2017)

Soil parameters	Soil reaction/Nutrient index		
	Low (I)	Medium (II)	High (III)
N total (%)	<0.08	0.08–0.25	>0.25
C organic (%)	<4	4–20	>20
CEC (cmol kg^{-1})	<6	12–18	>18
pH	<6 (acidity)	6–8 (neutrality)	>8 (alkaline)

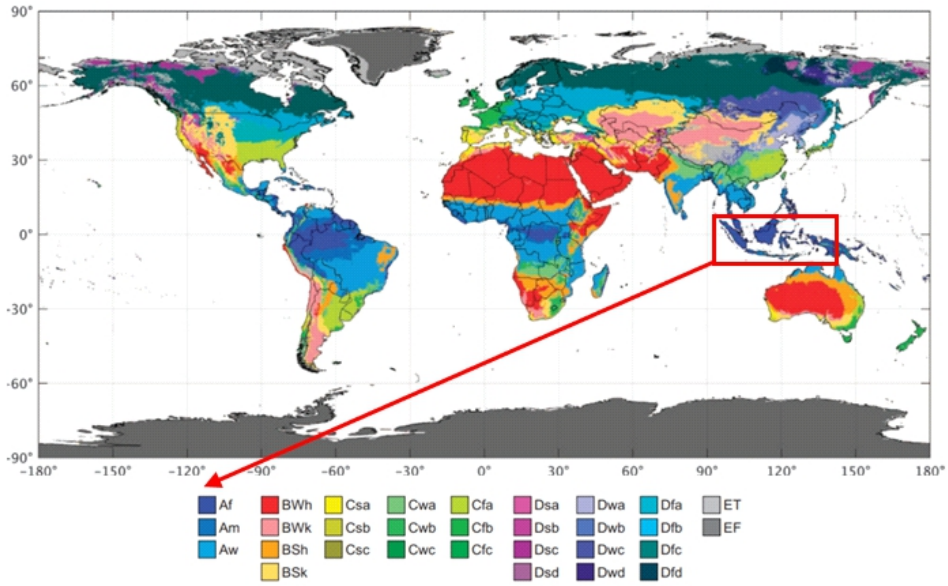

Figure 8 New and improved Köppen-Geiger classifications.

Table 5 Rating chart for soil parameters adapted from Ojomah and Joseph (2017)

Climatic factor	Observation of climate conditions Average in last 3 year		
	2019	2020	2021
Max temparature (ºC)	33.8	34.0	34.8
Min temparature (ºC)	18.1	21.6	21.6
Average temparature (ºC)	25.5	23.8	27.2
Max humidity (%)	99.7	100.0	99.0
Min humidity (%)	38.7	67.2	48.0
Average humidity (%)	83.3	58.6	85.9
Wind velocity (knot)	4.9	5.1	1.4
Rainfall (mm)	2,296.6	1,905.4	3,218.4
Sunshine time (hours day^{-1})	4.7	58.5	4.3

carbon sequestration of oil palm agroforestry. The growth rate of the intercrop directly influences the carbon stock, making it a key consideration in the implementation of the oil palm agroforestry scheme. The selection process should consider factors such as compatibility with oil palm, climatic and edaphic conditions, and economic viability. This emphasis on intercrop selection underscores its importance in the success of oil palm agroforestry.

Biodiversity level comparison between oil palm monoculture and agroforestry A previous study found that when tropical forests are turned into oil palm plantations, the habitats become less diverse, hurting biodiversity and the ecosystem's work (Luke et al., 2020). Compared to primary and secondary forests, oil palm plantations have fewer species, and the composition of species assemblages changes significantly after forest conversion to oil palm plantations (Immerzeel et al., 2014; Savilaakso et al., 2014; Lees et al., 2015). So, management strategies to increase biodiversity in agricultural landscapes have often focused on making habitats more complex. It has been suggested that agroforests and other low-impact agricultural systems can increase biodiversity and ecosystem function (Luke et al., 2020).

Agroforestry is considered capable of improving fauna habitat in oil palm monocultures. A previous study by Teuscher et al. (2016) stated that the size of the tree islands

Table 6 The amount of carbon stock and carbon sequestration between oil palm monoculture and agroforestry

Pattern	Carbon stock			Carbon sequestration
	Soil (C organic %)	Aboveground (ton ha^{-1})	Belowground (ton ha^{-1})	Above + belowground ($tCO_2\ ha^{-1}$)
Oil palm monoculture	4.06	71.74	26.54	360.6876
Oil palm agroforestry with one intercrop	1.34	107.07	39.62	538.3523
Oil palm agroforestry with two intercrops	0.93	105.88	39.18	532.3702
Oil palm agroforestry with three intercrops	0.96	161.13	59.62	810.1525
Oil palm agroforestry with six intercrops	2.25	254.31	94.10	1,278.6647

within oil palm agroforestry positively influenced the diversity and abundance of invertebrates, even on a small scale. Furthermore, the planted trees had already grown to heights of more than 4 meters, providing habitat for nesting, roosting, and foraging and possibly facilitating movement through the agricultural landscape (Teuscher et al., 2016; Gérard et al., 2017). Another previous study also stated a non-significant negative effect on oil palm yields for small oil palm agroforestry plots (Gérard et al., 2017). Thus, these findings demonstrate that oil palm agroforestry can generate synergies between economic and ecological functions under specific conditions.

This subsection of this study evaluates the biodiversity level of oil palm monoculture and agroforestry. This study compares species' biodiversity level and the change in species diversity between oil palm agroforestry and oil palm monoculture. In general, the biodiversity between oil palm monoculture was located in the Harapan Rainforest, and oil palm agroforestry was located in the CRC-990 experimental plot slightly the same. As per Table 7, the β-diversity or Sorensen similarity index that shows the change in species diversity between ecosystems oil palm agroforestry and monoculture is 0.33. Thus, the change in species diversity between oil palm agroforestry and monoculture ecosystems is quite low (SNI, 2014).

This study found that oil palm agroforestry has more species than oil palm monoculture. As per Table 8 and Table 9, oil palm agroforestry has a greater number of species. The species population of oil palm agroforestry is also greater than that of oil palm monoculture. Oil palm agroforestry has α-diversity (*H'*) bigger than oil palm monoculture (Table 7). *H'* is the Shannon-Wiener diversity index that shows species' biodiversity level (SNI, 2014). The number of oil palm agroforestry's *H'* is 2.77, which means the species diversity level of oil palm agroforestry is moderate (SNI, 2014). The number of oil palm monoculture's *H'* is 0.48, which means the species diversity level of oil palm monoculture is low (SNI, 2014).

The potential ecological impact of oil palm agroforestry as the term of improvement for restoring the Harapan Rainforest The enrichment planting scheme on oil palm monoculture within the Harapan Rainforest can encourage the increase of large trees within oil palm plantations. The large tree species can also increase the forest canopy (Walters & Sinnett, 2021). Combining oil palm and other trees such as *jengkol* or dog fruit (*A. pauciflorum*), *petai* (*P. speciosa*), *durian* (*D. zibethinus*), *sungkai* (*P. canescens*), *meranti* (*S. leprosula*), and *jelutung* (*D. lowii*) can increase forest canopy. Forest canopy provides a habitat for nesting, roosting, and foraging (Lees et al., 2015; Teuscher et al., 2016). With the availability of places to nest, root, and forage, there has been a recorded increase in the activity of insectivorous birds and bats by 556% (Zemp et al., 2023). Furthermore, it was also found that the number of bird species increased by 5 species and 2 tree species (Zemp et al., 2023).

Enrichment planting using *jengkol*, *petai*, *meranti*, *sungkai,* and *jelutung* also increases land productivity and economic benefits (Rahmani et al., 2021). Previous research found that the potential income of enrichment planting with *jengkol* is expected around IDR3,861,744 ha^{-1} $month^{-1}$ while the oil palm monoculture is IDR2,371,069 ha^{-1} $month^{-1}$ (Rahmani et al., 2021). Moreover, the enrichment planting also has a good impact on soil fertility, with an increase of 14% 1/soil C:N ratio (Zemp et al., 2023). The local community can benefit from the intercrop plants while reaping good ecological benefits. Therefore, intercrops are planted not only to increase ecological benefits but also to increase the community's economy. Thus, the oil palm agroforestry scheme can potentially reconcile the economic and ecological interests in the Harapan Rainforest.

It has been determined that proper management of tree canopies allows adequate transmission of photosynthetically active radiation beneath canopies (Walters & Sinnett, 2021). However, it is important to manage the canopies in an agroforestry pattern. Furthermore, it is more important for enhancing the productivity of associated arable crops (Rahman et al., 2021; Walters & Sinnett, 2021). Thus, some factors, including enrichment planting time, optimal planting space, and intercrop suitability, must be considered to optimize the application of oil palm agroforestry and achieve a good ecological impact.

Considering these results and previous studies, this study concludes that oil palm agroforestry can be considered an initial step in forest restoration of the Harapan Rainforest. Oil palm agroforestry is capable of providing a potential positive impact through the increasing of carbon sequestration and biodiversity levels. This is because oil palm agroforestry can increase litter input by around +151% leaf litter biomass

Table 7 Biodiversity level comparison between oil palm monoculture and agroforestry

Biodiversity indicators	Oil palm monoculture	Oil palm agroforestry
α-diversity (*H'*/Shannon-Wienner Index)	0.48	2.77
β-diversity (Sorensen Similarity Index)	0.33	
γ-diversity	24	

Table 8 Number of species found in oil palm agroforestry

No	Species	Number of each species (n)	Life-form
1	*Clidemia hirta*	63	Understorey
2	*Nephrolepis cordifolia*	53	Understorey
3	*Blumea lacera*	42	Understorey
4	*Digitaria ciliaris*	37	Understorey
5	*Hypolepsis punctate*	8	Understorey
6	*Eleusine indica*	40	Understorey
7	*Ageratum conyzoides*	35	Understorey
8	*Blechnum capense*	6	Understorey
9	*Histiopteris incise*	9	Understorey
10	*Eupatorium riparium*	4	Understorey
11	*Selaginella doederleinii*	13	Understorey
12	*Ocimum tenuiflorum*	4	Understorey
13	*Centella* sp.	28	Understorey
14	*Panicum montanum*	20	Understorey
15	*Mimosa pudica*	5	Understorey
16	*Archidendron pauciflorum*	16	Seedling/stake/pole/tree
17	*Shorea leprosula*	4	Seedling/stake/pole/tree
18	*Peronema canescens*	50	Seedling/stake/pole/tree
19	*Durio zibethinus*	10	Seedling/stake/pole/tree
20	*Parkia speciosa*	25	Seedling/stake/pole/tree
21	*Dyera costulata*	2	Seedling/stake/pole/tree
22	*Elaeis guineensis*	31	Seedling/stake/pole/tree
Total species (N)		505	

Table 9 Number of species found in oil palm monoculture

No	Species	Number of each species (n)	Life-form
1	*Clidemia hirta*	57	Understorey
2	*Selaginella doederleinii*	36	Understorey
3	*Nephrolepis Cordifolia*	38	Understorey
4	*Melastoma malabathricum*	48	Understorey
5	*Centella sp*	21	Understorey
6	*Ocimum tenuiflorum*	24	Understorey
7	*Ageratum conyzoides*	29	Understorey
8	*Cyperus rotundus*	7	Understorey
9	*Digitaria ciliaris*	9	Understorey
10	*Elaeis guineensis*	27	Seedling/stake/pole/tree
Total species (N)		296	

input (Zemp et al., 2023). Based on these findings, oil palm agroforestry has the potential to have a moderate improvement impact if implemented as a term improvement (*jangka benah*) in forest areas that have been encroached with oil palm, for example in Harapan Rainforest. In other words, the oil palm agroforestry scheme can be considered the improvement term (*jangka benah*) in Harapan Rainforest.

Conclusion

Oil palm agroforestry can potentially provide better ecological benefits than oil palm monoculture. It has greater carbon sequestration and biodiversity levels than oil palm monoculture. Oil palm agroforestry has a potential carbon sequestration of around two to three times greater than oil palm monoculture. The biodiversity level of oil palm agroforestry is also better than oil palm monoculture. The good ecological benefits, such as carbon sequestration and biodiversity level, of oil palm agroforestry can be considered an improvement to restore the forest that oil palm plantations have infringed on. Furthermore, oil palm agroforestry can slowly turn oil palm cover into forest cover. By increasing carbon sequestration, biodiversity level, and forest cover through the implementation of oil palm agroforestry in forest areas that have been encroached with monoculture oil palm, restoration of the function of tropical rainforests, especially in Harapan Rainforest, is becoming more possible to achieve. However, choosing suitable intercrops to implement oil palm agroforestry is necessary. The data of this study were taken from the plots of CRC 990 in Jambi. Thus, it should consider the differences in site characteristics such as soil types, temperature, precipitation, and socio-cultural to replicate this study in other places.

Recommendation

The potential ecological impact of oil palm agroforestry is quite good. We recommend conducting further research on the suitability of intercrops for mixing with oil palm. In addition, research about the optimal spacing of oil palm agroforestry with intercrops such as *jengkol* or dog fruit*, petai, durian, sungkai, meranti,* and *jelutung* is also vital to do in the future. It is also important to determine the optimal combination of oil palm agroforestry patterns to create better ecological and economic impacts, especially in the Harapan Rainforest. Moreover, developing more oil palm agroforestry experimental plots in different sites is needed to conclude the best agroforestry schemes for different places.

Acknowledgment

We would like to thank the CRC-990/EFForTS during the field research. Our sincere thanks also go to all respondents and the local community in Bungku Village for their kind support and hospitality. We gratefully acknowledge the PMDSU scholarship 2018–2022 that provided funding for this study.

References

Allen, K., Corre, M. D., Tjoa, A., & Veldkamp, E. (2015). Soil nitrogen-cycling responses to conversion of lowland forests to oil palm and rubber plantations in Sumatra, Indonesia. *PLoS ONE*, *10*(7), e0133325. https://doi.org/10.1371/journal.pone.0133325

Arifah, J. R. (2022, March 31). Agroforestri: Pengertian, 6 tipe, tujuan, dan manfaatnya. *Hutanpedia.* Retrieved from https://lindungihutan.com/blog/agroforestri/

Azhar, B., Lindenmayer, D., Wood, J., Fischer, J., Manning, A., McElhinny, C., & Zakaria, M. (2014). Ecological impacts of oil palm agriculture on forest mammals in plantation estates and smallholdings. *Biodiversity and Conservation*, *23*, 1175–1191. https://doi.org/10.1007/s10531-014-0656-z

Balaba, S., Tumwebaze, & Byakagaba, P. (2016). Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda. *Agriculture, Ecosystems & Environment*, *216*, 188–193. https://doi.org/10.1016/j.agee.2015.09.037

Besar, N. A., Suardi, H., Phua, M.-H., James, D., Mokhtar, M. B., & Ahmed, M. F. (2020). Carbon stock and sequestration potential of an agroforestry system in Sabah, Malaysia. *Forests*, *11*(2), 210. https://doi.org/10.3390/f11020210

[BPS] Badan Pusat Statistik. (2023). *Statistik kelapa sawit Indonesia tahun 2022*. Jakarta: Badan Pusat Statistik.

Chave, J., Andalo, C., Brown, S., Cairns, M. A., Chambers, J. Q., Eamus, D., Fölster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.-P., Nelson, B. W., Ogawa, H., Puigh, H., Riéra, B., & Yamakura, T. (2005). Tree allometry and improved estimation of carbon stock and balance in tropical forests. *Oecologia*, *145*, 87–99. https://doi.org/10.1007/s00442-005-0100-x

Cooper, H. V., Vane, C. H., Evers, S., Paul Apline, Girkina, N. T., & Sjögersten, S. (2019). From peat swamp forest to oil palm plantations: The stability of tropical peatland carbon. *Geoderma*, *342*, 109117. https://doi.org/10.1016/j.geoderma.2019.02.021

Corley, R. H. V. (2009). How much palm oil do we need?. *Environmental Science*, *12*, 134139. https://doi.org/10.1016/j.envsci.2008.10.011

Drescher, J., Rembold, K., Allen, K., Beckschäfer, P., Buchori, D., Clough, Y., Faust, H., Fauzi, A. M., Gunawan, D., Hertel, D., Irawan, B., Jaya, I. N. S., Klarner, B., Kleinn, C., Knohl, A., Kotowska, M. M., Krashevska, V., Krishna, V., Leuschner, C., …, & Scheu, S. (2016). Ecological and socio-economic functions across tropical land use systems after rainforest conversion. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*, 20150275. https://doi.org/10.1098/rstb.2015.0275

Gérard, A., Wollni, M., Hölscher, D., Irawan, B., Sundawati, L., Teuscher, M., & Kreft, H. (2017). Oil-palm yields in diversified plantations: Initial results from a biodiversity enrichment experiment in Sumatra, Indonesia. *Agriculture, Ecosystems and Environment*, *240*, 253–260. https://doi.org/10.1016/j.agee.2017.02.026

Guillaume, T., Kotowska, M. M., Hertel, D., Knohl, A., Krashevska, V., Murtilaksono, K., Scheu, S., & Kuzyakov, Y. (2018). Carbon costs and benefits of Indonesian rainforest conversion to plantations. *Nature Communications*, *9*, 2388. https://doi.org/10.1038/s41467-018-04755-y

Harbi, J., Erbaugh, J. T., Sidiq, M., Haasler, B., & Nurrochmat, D. R. (2018). Making a bridge between livelihoods and forest conservation: Lessons from non timber forest products' utilization in South Sumatera, Indonesia. *Forest Policy and Economics*, *94*, 1–10. https://doi.org/10.1016/j.forpol.2018.05.011

Hofhansl, F., Chacón-Madrigal, E., Fuchslueger, L., Jenking, D., Morera-Beita, A., Plutzar, C., Silla, F., Andersen, K. M., Buchs, D. M., Dullinger, S., Fiedler, K., Franklin, O., Hietz, P., Huber, W., Quesada, C. A., Rammig, A., Schrodt, F., Vincent, A. G. Weissenhofer, A., & Wanek, W. (2020). Climatic and edaphic controls over tropical forest diversity and vegetation carbon storage. *Scientific Reports*, *10*, 50–66. https://doi.org/10.1038/s41598-020-61868-5

Immerzeel, D. J., Verweij, P. A., van der Hilst, F., & Faaij, A. P. C. (2014). Biodiversity impacts of bioenergy crop production: A state-of-the-art review. *GCB Bioenergy*, *6*(3), 183–209. https://doi.org/10.1111/gcbb.12067

[IPCC] Intergovernmental Panel on Climate Change. (2006). *Guidelines for national greenhouse gas inventories*. Kyoto: IPCC.

[KEHATI] Yayasan Keanekaragaman Hayati. (2019). *Hutan kita bersawit: Gagasan penyelesaian untuk perkebunan kelapa sawit dalam kawasan hutan*. Jakarta: Yayasan Keanekaragaman Hayati.

Khasanah, N., Noordwijk, M. V., & Ningsih, H. (2015). Aboveground carbon stocks in oil palm plantations and the threshold for carbon-neutral vegetation conversion on mineral soils. *Cogent Environmental Science*, *1*(1). https://doi.org/10.1080/23311843.2015.1119964

Khasanah, N., van Noordwijk, M., Slingerland, M., Sofiyudin, M., Stomph, D., Migeon, A. F., & Hairiah, K. (2020). Oil palm agroforestry can achieve economic and environmental gains as indicated by multifunctional land equivalent ratios. *Frontiers in Sustainable Food Systems*, *3*, 122. https://doi.org/10.3389/fsufs.2019.00122

Krisnawati, H., Adinugroho, W. C., & Imanuddin, R. (2012). *Model-model alometrik untuk pendugaan biomassa pohon pada berbagai tipe ekosistem hutan di Indonesia*. Bogor: Badan Penelitian dan Pengembangan Kehutanan.

Lees, A. C., Moura, N. G., Almeida, A. S. d., & Vieira, I. C. G. (2015). Poor prospects for avian biodiversity in Amazonian oil palm. *PLoS ONE*, *10*(5), e0122432. https://doi.org/10.1371/journal.pone.0122432

Luke, S. H., Advento, A. D., Aryawan, A. A. K., Adhy, D. N., Ashton-Butt, A., Barclay, H., Dewi, J. P., Drewer, J., Dumbrell, A. J., Edi, Eycott, A. E., Harianja, M. F., Hinsch, J. K., Hood, A. S. C., Kurniawan, C., Kurz, D. J., Mann, D. J., Matthews Nicholass, K. J., Naim, M., …, & Turner, E. C. (2020). Managing oil palm plantations more sustainably: Large-scale experiments within the biodiversity and ecosystem function in tropical agriculture (BEFTA) programme. *Frontiers in Forests and Global Change*, *2*, 75. https://doi.org/10.3389/ffgc.2019.00075

Margono, B. A., Potapov, P. V., Turubanova, S., Stolle, F., & Hansen, M. C. (2014). Primary forest cover loss in Indonesia over 2000–2012. *Nature Climate Change*, *4*(8), 730–735. https://doi.org/10.1038/nclimate2277

[MoA] Ministry of Agriculture. (2023). *Statistik perkebunan Indonesia 20212023.* Jakarta: Ministry of Agriculture.

[MoEF] Ministry of Environment and Forestry. (2023). *Rekalkulasi penutupan lahan Indonesia tahun 2022*. Jakarta: Ministry of Environment and Forestry.

Negash, M., Kaseva, J., & Kahiluoto, H. (2022). Perennial monocropping of khat decreased soil carbon and nitrogen relative to multistrata agroforestry and natural forest in southeastern Ethiopia. *Regional Environmental Change*, *22*, 38. https://doi.org/10.1007/s10113-022-01905-3

Nurrochmat, D. R., Boer, R., Ardiansyah, M., Immanuel, G., & Purwawangsa, H. (2020). Policy forum: Reconciling palm oil targets and reduced deforestation: Landswap and agrarian reform in Indonesia. *Forest Policy and Economics*, *119*, 102291. https://doi.org/10.1016/j.forpol.2020.102291

Nurrochmat, D. R., Pribadi, R., Siregar, H., Justianto, A., & Park, M. S. (2021). Transformation of agro-forest management policy under the dynamic circumstances of a two-decade regional autonomy in Indonesia. *Forests*, *12*(4), 419. https://doi.org/10.3390/f12040419

Obeng, A. S., Sadick, A., Hanyabui, E., Musah, M., Marius, M., & Acheampong, M. K. (2020). Evaluation of soil fertility status in oil palm plantations in the Western Region of Ghana. *Agriculture and Food*, *5*(4), 938–949. https://doi.org/10.3934/agrfood.2020.4.938

Ojomah, F. O., & Joseph, P. O. (2017). Assessment of soil fertility status in some areas of kogi east agroecological zone of Kogi State. *Journal of Agriculture and Rural Research*, *1*(2), 44–50.

Pendrill, F., Persson, U. M., Godar, J., Kastner, T., Moran, D., Schmidt, S., & Wood, R. (2019). Agricultural and forestry trade drives large share of tropical deforestation emissions. *Global Environmental Change*, *56*, 1–10. https://doi.org/10.1016/j.gloenvcha.2019.03.002

Purnomo, H., Okarda, B., Dermawan, A., Ilham, Q. P., Pacheco, P., Nurfatriani, F., & Suhendang, E. (2020). Reconciling oil palm economic development and environmental conservation in Indonesia: A value chain dynamic approach. *Forest Policy and Economics*, *111*, 102089. https://doi.org/10.1016/j.forpol.2020.102089

Rahman, N., E.Giller, K., Neergaard, A., Magid, J., Ven, G. v. d., & Bruun, T. B. (2021). The effects of management practices on soil organic carbon stocks of oil palm plantations in Sumatra, Indonesia. *Journal of Environmental Management*, *278*(2), 111446. https://doi.org/10.1016/j.jenvman.2020.111446

Rahman, N., Neergaard, A. d., Magid, J., Ven, G. W. J. v. d., Giller, K. E., & Bruun, T. B. (2018). Changes in soil organic carbon stocks after conversion from forest to oil palm plantations in Malaysian Borneo. *Environmental Research Letters*, *13*(10), 105001. https://doi.org/10.1088/1748-9326/aade0f

Rahmani, T. A., Nurrochmat, D. R., Hero, Y., Park, M. S., Boer, R., & Satria, A. (2021). Evaluating the feasibility of oil palm agroforestry in Harapan Rainforest, Jambi, Indonesia. *Forest and Society*, *5*(2), 458–477. https://doi.org/10.24259/fs.v5i2.10375

Rahmani, T. A., Nurrochmat, D. R., Park, M. S., Boer, R., Ekayani, M., & Satria, A. (2022). Reconciling conflict of interest in the management of forest restoration ecosystem: A strategy to incorporate different interests of stakeholders in the utilization of the Harapan Rainforest, Jambi, Indonesia. *Sustainability*, *14*(21), 13924. https://doi.org/10.3390/su142113924

Rajakaruna, N., & Boyd, R. S. (2019). Edaphic factor. *Encyclopedia of Ecology*, *3*, 361–367. https://doi.org/10.1016/B978-008045405-4.00484-5

Savilaakso, S., Garcia, C., Garcia-Ulloa, J., Ghazoul, J., Groom, M., Guariguata, M. R., Laumonier, Y., Nasi, R., Petrokofsky, G., Snaddon, J., & Zrust, M. (2014). Systematic review of effects on biodiversity from oil palm production. *Environmental Evidence*, *3*(1), 4. https://doi.org/10.1186/2047-2382-3-4

Siarudin, M., Indrajaya, Y., & Hani, A. (2020). Preliminary assessment on above ground carbon stock of agroforestry and monoculture crop systems in peatlands. *IOP Conference Series: Earth and Environmental Science*, *449*, 012010. https://doi.org/10.1088/1755-1315/449/1/012010

[SNI] Standar Nasional Indonesia. (2014). *Metode penilaian jasa lingkungan keanekaragaman hayati* (*Biodiversity*)-*SNI 8014*. Jakarta: Badan Standarisasi Nasional Indonesia.

[SNI] Standar Nasional Indonesia. (2019). *Pengukuran dan penghitungan cadangan karbon - SNI 7724*. Jakarta: Badan Standar Nasional Indonesia.

Sudarwanto, A. S., Karjoko, L., Handayani, I. G. A. K. R., Ma'aruf, A., & Glaser, H. (2022). The policy on illegal oil palm plantation reform in forest area during Jokowi's presidency. *Hasanudin Law Review*, *8*(2), 171–185. http://doi.org/10.20956/halrev.v8i2.3566

Sumarga, E., & Hein, L. (2016). Benefits and costs of oil palm expansion in Central Kalimantan, Indonesia, under different policy scenarios. *Regional Environmental Change*, *16*, 1011–1021. https://doi.org/10.1007/s10113-015-0815-0

Tambunan, I. (2018). Hutan Harapan di Jambi kian tertekan. Retrieved from http://perpustakaan.menlhk.go.id/pustaka/home/index.php?page=detail_news&newsid=557

Teuscher, M., Gérard, A., Brose, U., Buchori, D., Clough, Y., Ehbrecht, M., . Hölscher, D., Irawan, B., Sundawati, L., Wollni, M., & Kreft, H. (2016). Experimental biodiversity enrichment in oil-palm-dominated landscapes in Indonesia. *Frontiers in Plant Science*, *7*, 1538. https://doi.org/10.3389/fpls.2016.01538

Vijay, V., Pimm, S. L., Jenkins, C. N., & Smith, S. J. (2016). The impacts of oil palm on recent deforestation and biodiversity loss. *PLoS ONE*, *11*(7), e0159668. https://doi.org/10.1371/journal.pone.0159668

Walters, M., & Sinnett, D. (2021). Achieving tree canopy cover targets: A case study of Bristol, UK. *Urban Forestry & Urban Greening*, *65*, 127296. https://doi.org/10.1016/j.ufug.2021.127296

Zemp, D. C., Guerrero-Ramirez, N., Brambach, F., Darras, K., Grass, I., Potapov, A., Röll, A., Arimond, I., Ballauff, J., Behling, H., Berkelmann, D., Biagioni, S., Buchori, D., Craven, D., Daniel, R., Gailing, O., Ellsäßer, F., Fardiansah, R., Hennings, N., …, & Kreft, H. (2023). Tree islands enhance biodiversity and functioning in oil palm landscapes. *Nature*, *618*(7964), 316–321. https://doi.org/10.1038/s41586-023-06086-5