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Biodiversity conservation, food security, and carbon storage potential of local agroforestry practices in the Bird's Head Region of Papua, Indonesia

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Abstract. *Hendri, Nugroho JD, Rahmadaniarti A, Nurlaela, Prabawardani S, Luhulima FDN, Gardiner C, Hematang F. 2024. Biodiversity conservation, food security, and carbon storage potential of local agroforestry practices in the Bird's Head Region of Papua, Indonesia. Biodiversitas 25: 4315-4332.* Local Agroforestry Practices (LAPs) in the Papua Region, Indonesia, which are still under-researched, play a crucial role in biodiversity conservation through sustainable crop rotation systems, intensification, and technological adaptability. This research aims to develop an improved intensification model that integrates these LAPs with sustainable agroforestry practices, biodiversity conservation, food security measures, and adaptive responses to climate change and extreme conditions. The study utilized the Focus Group Discussion (FGD) method, demonstration plot, Participatory Rural Appraisal (PRA) type selection of LAPs, and economic and allometric equations. The findings revealed a meticulous species selection process that considered biodiversity, resulting in 24 species classified as Least Concern (LC), 2 species classified as Near Threatened (NT), 1 species classified as Vulnerable (VU), and 2 species classified as Endangered (EN). The LAPs implementation achieved a Food Security (FS) score of 45,23% and 38.47% for Only Used (OU). Importantly, the total revenue generated by the LAPs design in Moswaren, Aimas, and Manokwari Village is nearly the same, with an average of Rp 16,327,231.00, Rp 16,640,731.00 and Rp 15,848,675.00 per year, respectively. This represents a significant economic impact, with the increase being 2.93-5.04 times greater than typical LAPs; this significant contribution to biodiversity conservation is a testament to their value. The aggregate carbon content across the three sites varied between 223.80 and 279.05 tC/ha.

Keywords: Agroforestry, biodiversity, carbon stock, food security, *pekarangan*, total revenue

INTRODUCTION

Maintaining a small-scale household garden, known as *pekarangan* (homegarden), is a well-established tradition in the tropical regions of Indonesia, including Papua. The minimum plot size for *pekarangan* (e.g. 400 m^2) is intended to support sustainable local agroforestry community development by incorporating crops, herbs, spices, forest trees, and Multi-Purpose Tree Species (MPTS) in a multi-layered vertical structure, fisheries, and animals (Soemarwoto and Soemarwoto 1985; Nair et al. 2021a; Achmad et al. 2022). *Pekarangan* additionally functions as a vital habitat for conserving biodiversity, specifically supporting endemic or unique plant and animal species (Nair et al. 2021b; Bagarinao 2023; Ihsan et al. 2024). In addition, it contributes to the local communities' food security, with 60-80% of it being consumed by the individual and 20-40% being sold to generate revenue (Wulandari et al. 2019; Saediman et al. 2021; Trianingsih et al. 2023).

The 22 peer-reviewed studies conducted in Indonesia on *pekarangan* agroforestry did not directly assess the FAO's concept of food security. Instead, they concentrated on food access, dietary diversity, nutrition security, and income (Duffy et al. 2021). Traditional *pekarangan* provides a 20% greater range of food options than commercial *pekarangan*, but commercial *pekarangan* can earn up to five times more. Agri-silviculture systems exhibit a compromise between the production of timber and non-timber forest products, which has consequences for both biodiversity and profitability (Muliawati et al. 2018).

Agroforestry systems are essential in the battle against climate change, as they enhance carbon storage and sequestration capabilities. The surge in CO_2 concentration in the atmosphere, leading to a rise in the earth's surface temperature and subsequent climate change, is effectively countered by agroforestry systems through increased enhancement of carbon sequestration in the total biomass (Besar et al. 2020; Das et al. 2020). The efficient management of sustainable agroforestry systems is instrumental in achieving the 31.89% emission reduction target outlined in Indonesia's Enhanced National Determined Contribution (NDC). This target can be met by adopting the Forestry and Other Land Use (FOLU) Net Sink 2030 policy, along with a strategy that focuses on increasing carbon stocks via rotational practices and simultaneously promoting various forestry-related businesses (Republic of Indonesia 2022; Ministry of Environment and Forestry Indonesia 2023).

The local food crop-based agroforestry complex systems currently in traditional use in Papua lack consideration concerning the selection of sustainable crop rotation systems, biodiversity conservation, intensification, and technological adaptability. Local people still prioritize root crops, peppers, vegetables, and fruits as sources of key nutrients and vitamins (Antoh et al. 2019; Nurhasan et al. 2022). This situation has been further exacerbated by the severe climatic conditions that have developed on the northern coast of Papua due to the interaction between the atmosphere and the sea. This phenomenon manifests as excessive precipitation or floods, as well as insufficient precipitation or drought (Hendri et al. 2016; Tuturop et al. 2022; Ampnir et al. 2024).

Therefore, to strengthen multi-forestry enterprises and support mitigation activities in the West Papua FOLU 2030 Net Sink operating plan, it is necessary to enhance the quality of the Local Agroforestry Practices (LAPs) in Bird's Head, Papua. This study aimed to improve production intensification models by integrating sustainable agroforestry practices, biodiversity conservation, food security measures, and adaptive responses to climate change and extreme conditions in new agroforestry systems. This could be achieved through (i) traditional knowledge of the Local Agroforestry Practice (LAP); (ii) developing the LAP centered on sustainable root crops as these are the local staple food while conserving the environment through the maintenance of indigenous or specific species and the adoption of climate-based technology; (iii) calculating the percentage of food security and revenue; and (iv) measuring the total biomass carbon for Local Agroforestry Practices (LAPs) in the Bird's Head Region of Papua, Indonesia.

MATERIALS AND METHODS

Study area

The study was conducted at three lowland *pekarangan* sites in the LAPs in the Bird's Head Region of Papua, Indonesia, with the coordinate point distribution detailed in Table 1 and the spatial distribution illustrated in Figure 1.

Annual rainfall averages 2,928 mm, ranging from 2,535 to 3,241 mm. The rainfall pattern is bimodal, with two rainy season peaks (December and March), known as extreme wet during the high period of typhoons (post and pre-monsoon) near the Papua Region, and a valley of the dry season (June, July, August), known as extreme dry during the period of typhoon (monsoon) outside of the region. The average annual temperature is 27.1°C (23.3°C to 31.5°C), whereas the average yearly relative humidity is 84% (82% to 85%) (Bureau of Meteorology, Climatology, and Geophysics of Manokwari, Sorong, and South Sorong 2023).

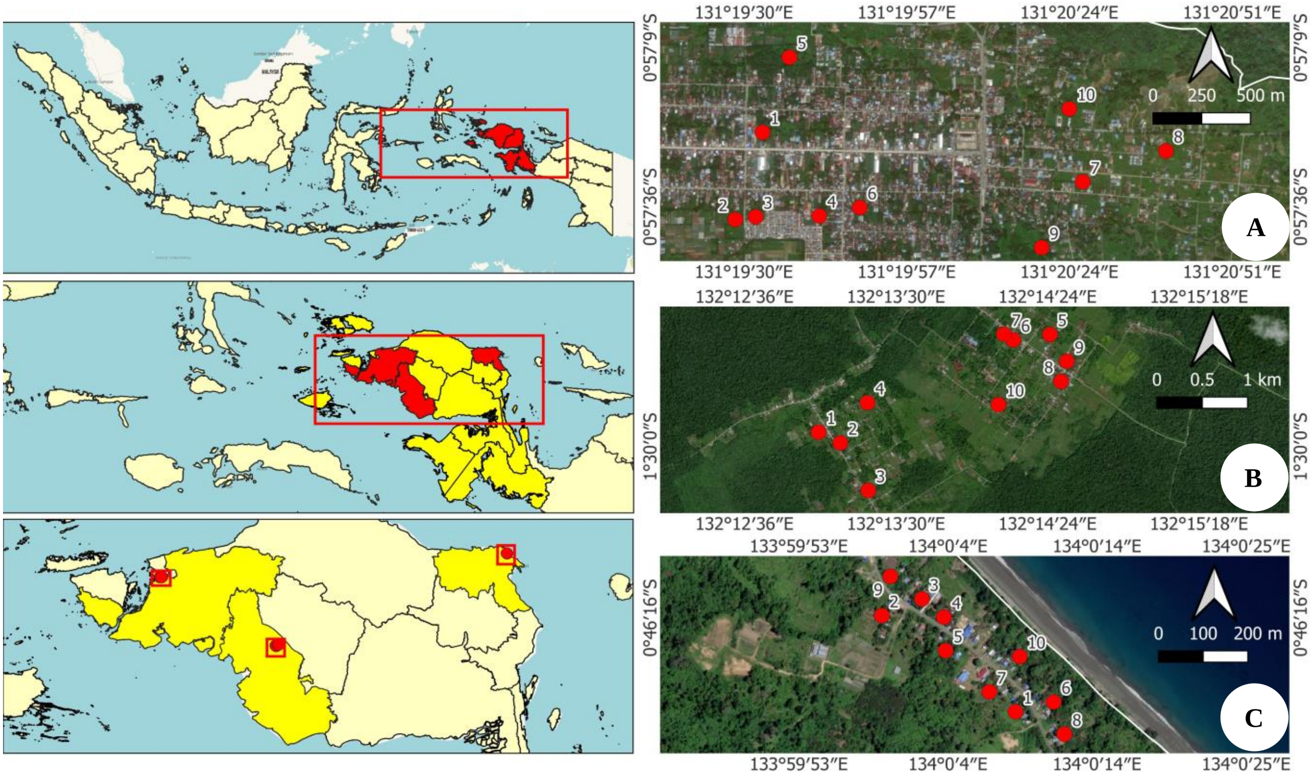

Figure 1. The location of the three LAP research sites in the Bird's Head Region of Papua, Indonesia, consists of: A. Aimas Sub-district, Sorong District; B. Moswaren Sub-district, South Sorong District; and C. Nuni Sub-district, Manokwari District

Table 1. Coordinate point distribution

Location	Coordinate
Moswaren Sub-district, South Sorong District (Low disturbance)	132° 13' 2,489" E; 1° 29' 54,564" S
	132° 13' 10,267" E; 1° 29' 58,491" S
	132° 13' 20,209" E; 1° 30' 15,804" S
	132° 13' 19,907" E; 1° 29' 43,827" S
	132° 14' 24,939" E; 1° 29' 18,948" S
	132° 14' 11,893" E; 1° 29' 20,955" S
	132° 14' 8,560" E; 1° 29' 18,885" S
	132° 14' 28,937" E; 1° 29' 36,082" S
	132° 14' 30,999" E; 1° 29' 28,726" S
	132° 14' 6,604" E; 1° 29' 44,532" S
Aimas Sub-district, Sorong District (Moderate disturbance)	131° 19' 33,140" E; 0° 57' 23,310" S
	131° 19' 28,614" E; 0° 57' 38,114" S
	131° 19' 31,997" E; 0° 57' 37,653" S
	131° 19' 42,608" E; 0° 57' 37,510" S
	131° 19' 37,614" E; 0° 57' 10,570" S
	131° 19' 49,274" E; 0° 57' 36,072" S
	131° 20' 26,289" E; 0° 57' 31,726" S
	131° 20' 40,084" E; 0° 57' 26,478" S
	131° 20' 19,459" E; 0° 57' 42,865" S
	131° 20' 24,047" E; 0° 57' 19,289" S
Nuni Sub-district, Manokwari District (High disturbance)	134° 0' 8,513" E; 0° 46' 22,546" S
	133° 59' 58,808" E; 0° 46' 15,409" S
	134° 0' 1,736" E; 0° 46' 14,195" S
	134° 0' 3,327" E; 0° 46' 15,540" S
	134° 0' 3,455" E; 0° 46' 18,021" S
	134° 0' 11,286" E; 0° 46' 21,823" S
	134° 0' 6,613" E; 0° 46' 21,072" S
	134° 0' 12,056" E; 0° 46' 24,201" S
	133° 59' 59,451" E; 0° 46' 12,515" S
	134° 0' 8,822" E; 0° 46' 18,462" S

The research sites were chosen to investigate the impact of extreme climate conditions caused by the tails of tropical cyclones and typhoons originating in the Pacific Ocean, which are associated with storm surges and heavy rainfall. The geomorphology of Papua's north coast is primarily pliable rock, easily split and crushed (alluvial lowland). When northern coastal rainfall is severe, storm surges occur, and flood the *pekarangan* areas. Low rainfall in the region is associated with the El Niño phenomenon, and extremely high rain is associated with La Nina events due to the interactions between meteorology and the Pacific Ocean. Extreme weather conditions (wet and dry) may cause damage and decrease the output of seasonal crops in the *pekarangan*. Therefore, it was necessary to research ways to increase seasonal agricultural output in the *pekarangan*. This study examined three disturbance areas under extreme climate conditions: low disturbance (far from the Pacific Ocean, Moswaren District), moderate disturbance (near the Pacific Ocean, Aimas Sub-district), and high disturbance (close to the Pacific Ocean, Nuni Sub-district) (Figure 1).

Data collection

Primary data compares the composition of agroforestry vegetation and carbon metrics. Secondary data consists of supplemental information from reference libraries that underpin the research. Primary data were collected through Focus Group Discussions (FGDs) with representative respondents and through Benefit Index (BI), vegetation analysis, Diversity Index (H'), conservation status, and carbon stock analysis. This study involved 90 participants from three different locations: Nuni (Manokwari), Aimas (Sorong), and Moswaren (South Sorong). The variables and data, methods of data collection, and analysis procedures are completely outlined in Table 2.

Table 2. Variables and data, methods of data collection, and analysis procedure

Research objectives	Variables and data	Methods of data collection	Analysis procedure
Traditional knowledge of LAP	Status of local agroforestry practice	The Benefit Index (BI) was used in quantitative analysis, which suggests that the more useful a plant is, the higher the BI value. Conducted structured interviews	Level of satisfaction with the LAP expressed as a percentage.
Developing the LAP centered on sustainable root crops while conserving the environment by maintaining indigenous or specific species and adopting climate-based technology	Vegetation composition, conservation, diversity, and climate-based technology (species, diameter, height, density, and basal area of plants per hectare)	with 90 respondents and facilitated FGDs. The plots have rectangular portions measuring 20 m × 20 m for trees, 10 m × 10 m for poles, 5 m × 5 m for saplings, and 2 m × 2 m for seedlings (National Standardization Agency 2011)	High satisfaction with the Benefit Index, conservation status, and climate-based technology
Calculating the percentage of food security and revenue	LAP crop data sorting is used for food security and revenue	Identify what percentage of the crop is earmarked for food security and revenue	Vegetation analysis (Important Value Index (IVI), values of Relative Density (RD), Relative Frequency (RF), and Relative Dominance (RD). Percentage of food security and percentage of revenue
Measuring the total carbon for LAPs in the Bird's Head Region of Papua	Measurements include the height and diameter of trees for above-ground and below-ground biomass; dry weight for under-storey biomass and litter and ring samples for soil carbon content	The plots have rectangular portions measuring 20 m × 20 m for trees, 10 m × 10 m for poles, 5 m × 5 m for saplings, and 2 m × 2 m for seedlings/under-storey, litter and soil.	Analysis of the Diversity Index (H')-Shannon-Wiener, the amount of carbon stock is determined by employing an allometric equation for biomass carbon, and laboratorium analysis for under-storey, litter and soil.

Traditional knowledge in agroforestry involves local practices, skills, and beliefs transmitted over generations. It includes plant selection, crop management, and integrated agricultural systems that enhance biodiversity, promote food security, and sustain livelihoods. The Benefit Index results produced total benefit scores for agroforestry methods based on the responses received. The findings are presented in the following manner: (i) High Satisfaction: Participants may express considerable satisfaction with economic advantages resulting from reliable income streams generated by various crops. (ii) Moderate Satisfaction: Ecological advantages may attain slight satisfaction ratings due to difficulties performing sustainable methods. (iii) Low Satisfaction: A lack of regard for or integration of traditional knowledge into practice may result in diminished satisfaction levels.

The investigation offers significant insights into the impact of traditional knowledge on agroforestry techniques and the resulting satisfaction levels among practitioners. Comprehending these factors can assist policymakers and extension agencies improve agroforestry programs, guaranteeing alignment with community beliefs and practices.

Essential stages incorporating the Benefit Index (BI), conservation status, and climate-based technologies can enhance the composition of LAP traditional knowledge. Improving the LAP composition based on high satisfaction with the Benefit Index (BI) involves a systematic approach emphasizing environmental, economic, and social benefits. Sustainable improvements in LAP composition necessitate the preservation of biodiversity. The selection of a species can be influenced by the conservation status of the species, as indicated on the IUCN website. Plant characteristics that necessitate dry and wet environments are critical in implementing climate-based technologies to predict extreme climate situations.

A systematic methodology is necessary to assess the association between food security, revenue, and the Importance Value Index (IVI) in vegetation. IVI is a quantitative measure that indicates the significance of a species within a community. This study quantifies food security as the proportion of the harvest allocated for familial consumption. In this case, revenue could be related to financial profits obtained from LAP.

A comprehensive methodology for quantifying total carbon in LAPs within the Bird’s Head Region of Papua, utilizing allometric equations and linking findings with the Diversity Index (H’) to contribute to understanding the ecological dynamics of this unique area. The assessment of carbon potential was derived from four carbon reservoirs: total biomass, under-storey, litter, and soil over 30 demonstration plots of LAP.

Data analysis

The qualitative analysis in this study focused on the interaction level satisfaction of LAP using traditional knowledge. The analysis began with data gathering in the field, followed by data presentation and verification. While quantitative analysis used the Benefit Index (BI), the index suggests that the more useful a plant is, the higher its BI value (Indow et al. 2021). The benefit index is determined using the following equation:

$$BI = (Ji/N) \times 100\% \qquad (1)$$

Where:
BI : Benefit Index
Ji : Number of occurrences of the use of a plant
N : Total number of occurrences of the use of a plan

A score of 0-33% is classified as low BI, 34-69% as medium BI, and more than 70% as high BI.

Assessment of ecological characteristics in the composition of agroforestry for 30 sampling plots, each measuring 20 m × 20 m for trees, 10 m × 10 m for poles, 5 m × 5 m for saplings, and 2 m × 2 m for seedlings (Figure 2), was conducted through vegetation analysis to determine the Important Value Index (IVI) (Haq et al. 2023; Ali et al. 2024), which is the product of the values of Relative Density (RD), Relative Frequency (RF), and Relative Dominance (RD). The species count utilized for density calculations within the IVI is employed to compute the Shannon-Wiener Diversity Index (H') value. The assessment of the species diversity index, also known as the Shannon-Wiener Diversity Index, utilized the following criteria: a value of H index below one indicates a low level of species diversity; a value between one and three indicates a moderate level of species diversity; and a value above three indicates a high level of species diversity (English et al. 1994).

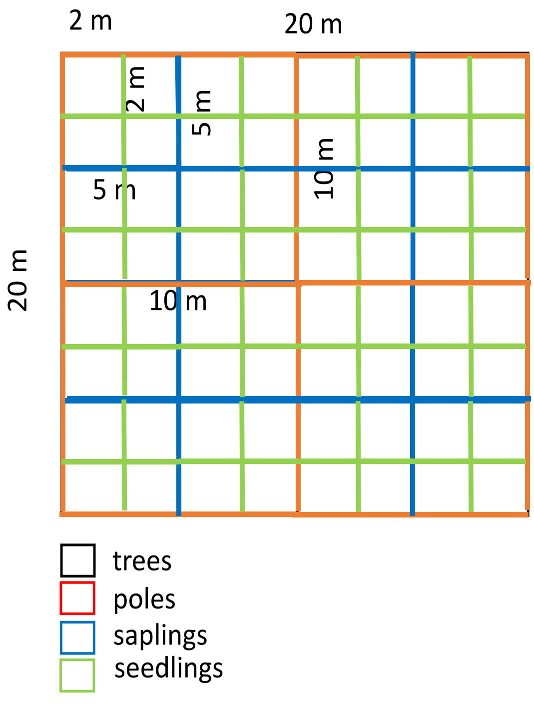

Figure 2. Sampling plots for IVI and carbon stock (modified from National Standardization Agency No. 7724, 2011)

Biodiversity conservation status was determined by utilizing the IUCN red list criteria and focusing on population trends and conservation status reported in the LAP. In contrast, climate-based technologies prioritize rain harvesting methods to mitigate the impact of damage caused by wet conditions (La Nina). They can also be applied to dry conditions (El Nino). The developed technology includes the construction of terrace beds, biopores, and mycorrhizal fertilizers.

The percentage of LAP crops allocated for food security and increasing local community revenue in the three research locations is calculated, considering the disturbance areas under extreme climate conditions. These locations include low disturbance (far from the Pacific Ocean, Moswaren Sub-district), moderate disturbance (near the Pacific Ocean, Aimas Sub-district), and high disturbance (close to the Pacific Ocean, Nuni Sub-district).

The determination of the carbon stock of LAP typically employs the utilization of an allometric equation (Cairns et al. 1997; Chave et al. 2005) in the sampling plots (Figure 2) to estimate the Total Biomass (TB) considering Above-Ground Biomass (AGB) and Below-Ground Biomass (BGB) components. The equation utilized for this purpose is as follows:

$$AGB = \exp\{-2.5570 + 0.9400\ln(\rho_w D^2 H)\} \quad \ldots\ldots\ldots\ldots (2)$$
$$BGB = \exp\{-1.0587 + 0.8836\ln(AGB)\} \quad \ldots\ldots\ldots\ldots (3)$$
$$TB = AGB.\rho_{f.}c + B\,GB.\rho_{f.}c \quad \ldots\ldots\ldots\ldots (4)$$

Where:
AGB: Estimated Above-Ground Biomass (kg per tree, including stem and branch wood and leaf biomass)
ρ_w : Wood density ($g \cdot cm^{-3}$)
D : Trunk diameter (DBH in cm)
H : Total tree height (m)
BGB : Below-Ground Biomass (kg)
ln : Natural logarithm is a data transform that normalizes data that is not regularly distributed
TB : Total Biomass ($t \cdot ha^{-1}$)
ρ_f : Population per unit area ($trees \cdot ha^{-1}$)
c : Non-dimensional conversion factor from kg to ton

Additionally, carbon assessments for understorey, litter, and soil are represented in the subsequent formula (Pearson et al. 2005):

$$B_u = (cf).B(u).A \quad \ldots\ldots\ldots\ldots (5)$$
$$L = (cf).B(l).A \quad \ldots\ldots\ldots\ldots (6)$$
$$S = (cf).\rho_{s.}d \times 100 \quad \ldots\ldots\ldots\ldots (7)$$

Where:
B_u : Estimated under-storey biomass carbon stock ($t \cdot ha^{-1}$)
L : Estimated litter carbon stock ($t \cdot ha^{-1}$)
S : Carbon stock of soil ($tC \cdot ha^{-1}$)
B(u) and B(l) : Weight biomass ($t \cdot m^{-2}$) inside a basal area A ($m^2 \cdot ha^{-1}$)
ρ_s : Soil density ($t \cdot m^{-3}$)
cf : Non-dimensional conversion factor from carbon content in the laboratory analysis using the Walkley-Black (WB) procedure
d : Vertical distance below the surface of the litter or soil (cm)
100 : Conversion factor

A computation for necromass is required for the carbon pool. Nonetheless, due to the community's agroforestry management, it is absent from the *pekarangan*. Consequently, the total carbon potential is derived as follows:

$$TC = TB + B_u + L + S \quad \ldots\ldots\ldots\ldots (8)$$

Where:
TC : Total Carbon
TB : Total Biomass carbon
B_u : Under-storey carbon
L : Litter carbon
S : Soil carbon

RESULTS AND DISCUSSION

Traditional knowledge of the Local Agroforestry Practice (LAP)

Local agroforestry practices are the traditional knowledge practice of incorporating trees, MPTS plants, and shrubs into agricultural landscapes. Local populations have been using this traditional technique for many generations. It provides many ecological and economic advantages, including promoting biodiversity, enhancing soil quality, and generating extra money through varied agricultural products. In Sub-Saharan Africa and Southeast Asia, traditional agroforestry systems, such as *pekarangan* and parklands, have played a crucial role in preserving biodiversity and ensuring food security. These systems are distinguished by planting native tree species alongside staple crops, improving ecosystem services, and promoting resilient agricultural production systems (Udawatta et al. 2019; Liu et al. 2022; Shukla and Dhyani 2023).

Staple food and other crops

The research location, characterized by a higher level of transit accessibility, facilitates the acquisition of staple food from other sources, such as rice. The Rice for the Poor (*Raskin*) government initiative supports the community's willingness and enthusiasm to switch to and consume rice. This program is part of the government's attempts to guarantee food security for its citizens by offering subsidized rice at affordable and cheap costs. This program aims to facilitate an affordable and accessible supply of energy-dense food, namely rice, to impoverished households.

On the other hand, the *Raskin* program, a government rice subsidy effort, helps to encourage staple food diversification. In addition to introducing homes to rice, this initiative promotes non-rice staple foods because sharing reduces rice per household (Utami et al. 2018). In the research area, local food remains a top concern, as evidenced by the community's continued preference for locally-grown staple foods and vegetables (Figure 2).

Traditionally, the primary food sources for most Melanesians, including those in Papua, have been taros

(*Colocasia esculenta* (L.) Schott) and various types of tubers (*Ipomoea batatas* (L.) Lam.). Nevertheless, in certain regions, sago (*Metroxylon sagu* Rottb.) starch or bananas (*Musa* spp.), particularly plantains, have served as the predominant staple food sources. Additionally, people also frequently eat coconuts (*Cocos nucifera* L.) and breadfruits (*Artocarpus altilis* (Parkinson) Fosberg). Cassava (*Manihot esculenta* Crantz) has become increasingly significant as a primary dietary energy source in recent years. Tubers have become a fundamental food source in certain areas, supplanting taros and yams (*Dioscorea* spp.). The transition is due to their higher labor productivity and security, guaranteeing that farmers seldom experience a shortage of subsistence needs (Bourke 2019).

Corn (*Zea mays* L.) is a vital staple food in Manokwari, West Papua, Indonesia, and is essential to the region's agricultural landscape and food security. Climate conditions, economic developments, and agricultural techniques all affect the production and consumption of corn (Syaranamual and Muyan 2024). The policy initiative aimed at enhancing local food commodities for sustained food security in Papua has led to a 30% surge in sago, sweet potatoes, and maize production during the last five years. This signifies a favorable influence on food production within the local area, so enhancing the region's ability to sustain itself and ensuring a long-term supply of food that meets environmental and social requirements (Saa 2024).

Indigenous Papuans have local knowledge that acknowledges peanuts as a significant contributor to soil fertility. The inclusion of peanuts (*Arachis hypogaea* L.) in intercropping systems leads to a substantial improvement of soil fertility by augmenting the levels of both Accessible Nitrogen (AN) and Total Nitrogen (TN) content. Increasing nitrogen levels is critical because it will immediately improve soil health and fertility, and essential to promote plant growth and yields. Consequently, this fertile soil increased LAP production, especially in lowland tropical climate areas where it is difficult to receive rain, as is common in Papua. The approach not only maximizes the efficient utilization of resources but also encourages the adoption of sustainable agricultural techniques, which is beneficial for farmers aiming to increase output while upholding environmental responsibility. Therefore, incorporating peanuts into the LAP system is a very efficient approach to enhance soil fertility, staple food crop, and other crops yields under these particular agroecological conditions (Aipa and Michael 2019; Rahmianna et al. 2020).

Spinach (*Amaranthus hybridus* L.) leaves are among the best vegetables commonly consumed in all three research locations, particularly in the Papua Region. Multiple researchers suggest incorporating spinach leaves into the diet of pregnant women with mild anemia to increase hemoglobin levels. This provides valuable information on successful dietary approaches for controlling anemia during pregnancy. The advantages of a nutrient-rich food like green spinach not only enhances our knowledge of nutrition and maternal health but also has the potential to influence medical procedures and guide public health recommendations for promoting wellness during pregnancy (Natalia et al. 2019; Maita and Triana 2020; Susilawati et al. 2023).

The local residents have a preference for numerous vegetables, including gedi leaves (*Abelmoschus manihot* (L.) Medik.), cayenne pepper (*Capsicum frutescens* L.), long beans (*Vigna unguiculata* (L.) Walp.), cucumbers (*Cucumis sativus* L.), tomatoes (*Solanum lycopersicum* L.), pineapples (*Ananas comosus* (L.) Merr.), mustard greens (*Brassica juncea* (L.) Czern.), red chili peppers (*Capsicum annuum* L.), red spinach (*Amaranthus tricolor* L.), mustard cabbage (*Brassica rapa* L.), ginger (*Zingiber officinale* Roscoe), eggplants (*Solanum melongena* L.), chayote (*Sechium edule* (Jacq.) Sw.), mung beans (*Vigna radiata* (L.) R.Wilczek), and adzuki beans (*V. angularis* (Willd.) Ohwi & H.Ohashi). A few vegetables, although in small quantities, are also frequently consumed in the Manokwari region. These include green fern (*Diplazium esculentum* (Retz.) Sw.), winged bean (*Psophocarpus tetragonolobus* (L.) DC.), lilin soup (*Saccharum ×edule* Hassk.), bitter melon (*Momordica charantia* L.), katuk leaves (*Sauropus androgynus* (L.) Merr.), and leek (*Allium fistulosum* L.) (Figure 3). These categories are also included in numerous research examining the sustainability of local crops in Papua (Waroy et al. 2020; Indow et al. 2021; Wahyudi et al. 2024).

Multi-Purpose Tree Species (MPTS) plants

Matoa (*Pometia pinnata* J.R.Forst. & G.Forst.) is the preferred choice among MPTS plants (Figure 4) in the three research locations as well as the Papua area. The matoa stem is valuable in the wood business, and its fruits, seeds, and leaves have medicinal properties that can be used in traditional medicine. Traditional remedies widely recognize the efficacy of the Matoa plant's leaves and bark. The Papuan people think that a concoction made from matoa leaves can alleviate hypertension. Matoa fruits are rich in flavonoids, which function as antioxidants and counteragents to free radicals. Matoa possesses bioactive substances and secondary metabolites with 96% ethanol extract from matoa leaves containing alkaloids, flavonoids, tannins, steroids, and triterpenoids, which have potential medicinal properties (Yuniastuti et al. 2023).

Betel nut (*Areca catechu* L.), a popular stimulant in many Southeast Asian cultures (Gupta et al. 2020; Siregar et al. 2022), is widely chewed for its hallucinogenic properties and social rituals. On the other hand, there are health problems associated with betel nut use, including the risk of oral cancer, gum disease, and addiction. It raises awareness about the need for comprehensive health education and intervention techniques to reduce the risks associated with habitual chewing (Watopa 2019).

The coconut tree (*C. nucifera*) is highly culturally important in Papua, especially in northern and southern coastal Papua. The coconut tree plays a significant role in various sectors of life, commemorating significant events, providing a primary source of nutrition for combating starvation, and symbolizing hospitality and festivity. This underscores the profound cultural significance and purposes linked to the coconut in the area, emphasizing the value of Indigenous wisdom and the essential role of the coconut in the essence of Papuan culture (Schokkin 2022).

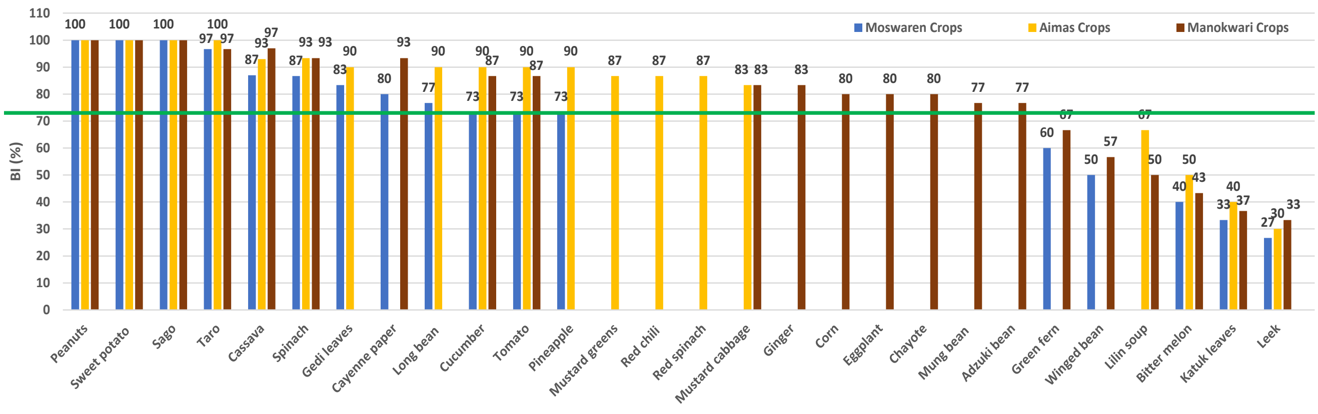

Figure 3. Benefit index of staple food and other crops

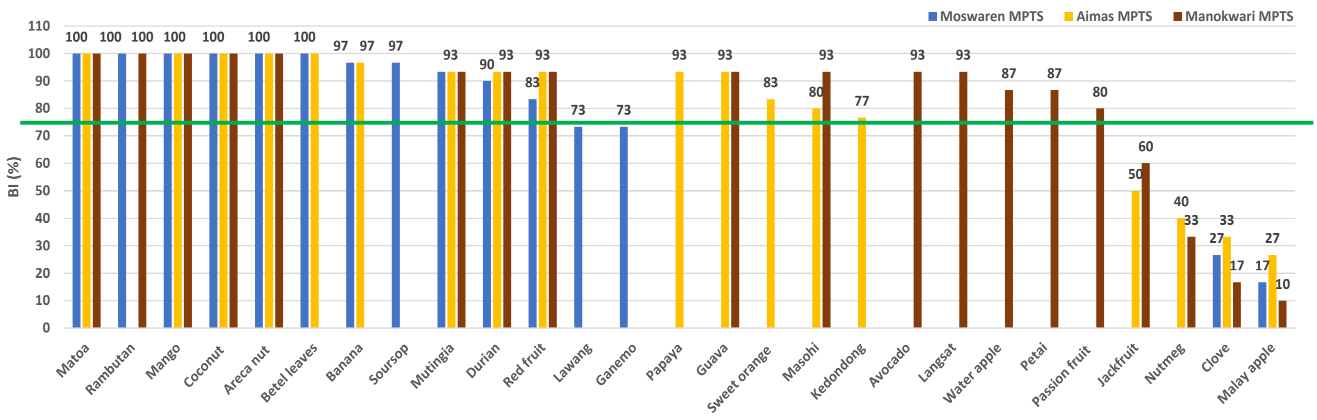

Figure 4. Benefit index of MPTS plants

The community service program in Yaugapsa Village was designed to empower the members of the family welfare program by offering them training in the production of Virgin Coconut Oil (VCO). The training successfully enhanced the participants' understanding of VCO production, which was novel. This information can be utilized as a business opportunity to enhance the family's income and ensure the family's health. Families can use this information as a business opportunity to boost their income and maintain their health. By equipping the participants with practical skills for business establishment, the initiative effectively fosters economic empowerment and self-sufficiency within the community (Kailola and Wanma 2022). In these three research locations, the production of VCO can serve as a paradigm for developing non-timber forest products (NTFPs) and a green economy.

The following fruits were discovered in the three areas of house yard (*pekarangan*), i.e: mango (*Mangifera indica* L.), rambutan (*Nephelium lappaceum* L.), betel leaves (*Piper betle* L.), banana (*Musa ×paradisiaca* L.), soursop (*Annona muricata* L.), mutingia (*Muntingia calabura* L.), durian (*Durio zibethinus* Murray), red fruit (*Pandanus conoideus* Lam.), lawang (*Cinnamomum cullilawan* (L.) Blume), ganemo (*Gnetum gnemon* L.), papaya (*Carica papaya* L.), guava (*Psidium guajava* L.), sweet orange (*Citrus ×sinensis* (L.) Osbeck), masohi (*Cryptocarya massoia* (Oken) Kosterm.), kedondong (*Spondias dulcis* Parkinson), avocado (*Persea americana* Mill.), langsat (*Lansium domesticum* Corrêa), water apple (*Syzygium jambos* (L.) Alston), petai (*Parkia speciosa* Hassk.), and passion fruit (*Passiflora edulis* Sims). Additionally, a reduced quantity of MPTS was acquired for the jackfruit (*Artocarpus heterophyllus* Lam.), nutmeg (*Myristica fragrans* Houtt.), clove (*Syzygium aromaticum* (L.) Merr. & L.M.Perry), and malay apple (*Syzygium malaccense* (L.) Merr. & L.M.Perry). These MPTS plants are frequently present in the Papua Region, as indicated by multiple research (Fonataba et al. 2022; Tuturop et al. 2022; Hendri et al. 2023).

Forestry plants

The three *pekarangan* research locations in forestry facilities prioritize Gamal (*Gliricidia sepium* (Jacq.) Kunth) leaves to produce liquid organic fertilizer rich in nutrients such as C-organic, N-total, P, and K (Figure 5). Applying Gamal leaf organic fertilizer significantly improves several crops, including pepper, lettuce, mustard, and corn. Additionally, researchers (Kusumah et al. 2019; Purwanto et al. 2021; Pratiwi and Muhsin 2023; Gomes et al. 2024; Nisa et al. 2024) suggest using the combination of Gamal leaves with animal waste as manure and Gamal leaves extract against termites.

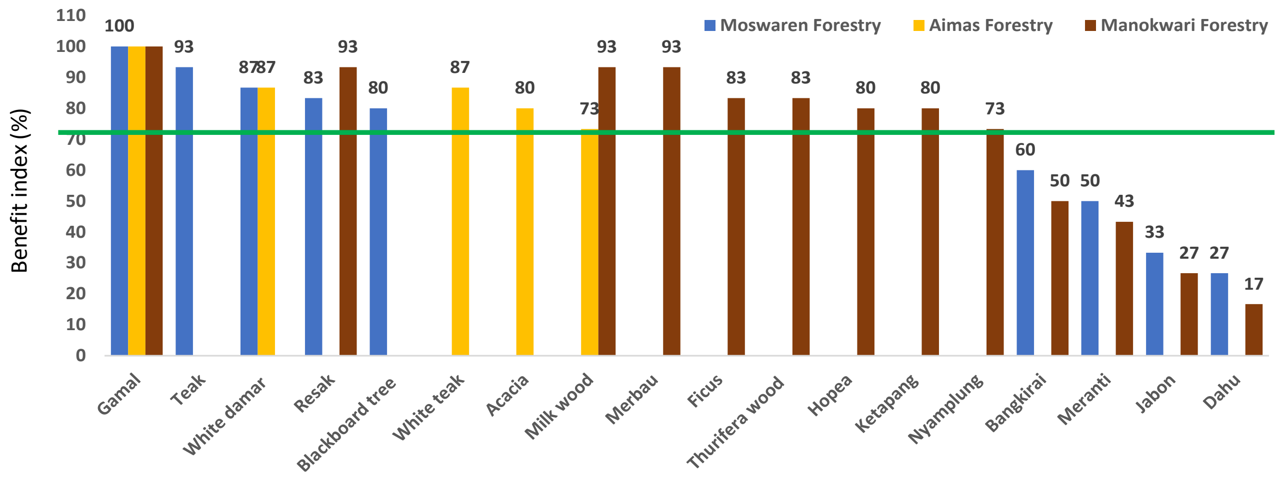

Figure 5. Benefit index of forestry plants

Various types of woody trees that dominate are deliberately planted in the yard. In Moswaren Village, teak (*Tectona grandis* L.f.) is highly valued for its quality wood, white damar (*Agathis labillardierei* Warb.) for its resin, and resak (*Vatica rassak* (Korth.) Blume), which belongs to the Meranti group, is used for building, furniture, and handicraft materials. Aimas Village has several types of trees, including gamal, white damar, and white teak (*Gmelina arborea* Roxb. ex Sm.). The white teak tree is part of a mixed forest group and has various medicinal uses. The bark and leaves of the tree are used in traditional medicine to treat dengue fever. The tree's roots have properties that can purify the blood and act as laxatives, tonics, and antidotes. The sap from the leaves can be used as a sedative to treat gonorrhea, coughs, wounds, and boils. The tree's flowers are used to treat leprosy and blood diseases. These trees are not just beautiful but also a treasure trove of health benefits. Additionally, the wood of the white teak tree is known for its strength and high economic value (Mahendru et al. 2024). Acacia trees (*Acacia mangium* Willd.) serve multiple purposes, such as providing shade, supplying raw materials for perfume production, being used in house construction, and being utilized in furniture manufacturing (Koutika and Richardson 2019). Milkwood (*Alstonia scholaris* (L.) R.Br.) has medicinal properties that effectively treat malaria, asthma, skin problems, epilepsy, and hypertension. Furthermore, it provides shade and serves as a useful material for domestic appliances (Pandey et al. 2020).

Merbau wood (*Intsia bijuga* (Colebr.) Kuntze), a highly durable and superior type of wood, was also discovered in the *pekarangan* Manokwari Village and Papua Region. In addition, various other varieties of wood were discovered, including ficus (*Ficus benjamina* L.), frequently utilized by the community for its medicinal properties in treating inflammation, skin conditions, digestive disorders, leprosy, and malaria. Furthermore, ficus exhibits potential as a medicine with antibacterial, analgesic, anti-fever, and anticancer properties (Obafemi and Umahi-Ottah 2023; Khan et al. 2024). The thurifera wood (*Anisoptera thurifera* (Blanco) Blume), which bears fruit resembling green beans, is frequently discovered in Yop Meos Island and Wondama District. This wood is commonly utilized for furniture, plywood, and as raw material for ship construction. Hopea wood (*Hopea papuana* Diels) is well-suited for use as rollers in the textile industry and for poles and bridge construction. It can also serve as an alternative to wood for high shoes and as a shade tree. Additionally, the bark of hopea wood contains tannins that are valuable for tanning leather (Widiyono 2021). Ketapang (*Terminalia catappa* L.) is a canopy tree whose foliage contains inherent phytochemical compounds. The active chemicals found in saponins, triterpenoids, quinones, phenolics, tannins, and flavonoids have antioxidant, anti-inflammatory, antibacterial, antifungal, antiviral, and can also enhance water quality (Basir and Kaharuddin 2020). Nyamplung (*Calophyllum inophyllum* L.) protects against wind, preventing erosion and promoting shoreline preservation. Nyamplung oil is frequently employed for wound healing and treating various skin ailments and conditions. Nyamplung seeds are considered a viable source of biofuel (Ardhyni et al. 2022).

A variety of forestry plants, including bangkirai (*Shorea laevis* Ridl.), meranti (*Shorea* spp.), jabon (*Anthocephalus cadamba* (Roxb.) Miq.), and dahu (*Dracontomelon dao* (Blanco) Merr. & Rolfe), were discovered to be in limited demand. Various published investigations have also documented these specific varieties of forestry plants in Papua (Murdjoko et al. 2021; Sheil et al. 2021; Soenarno et al. 2023).

Improvement of the LAP plant composition

The Ayamaru Tribe in the South Sorong area has developed a system based on local knowledge to increase the cultivation of sweet potato (*I. batatas*) and taro (*C. esculenta*) in local food-based *pekarangan*. Meanwhile, the MPTS plants primarily focus on cultivating matoa (*Pometia pinnata* J.R.Forst. & G.Forst.), areca nut (*Arecha catechu* L.), banana (*Musa ×paradisiaca* L.), and soursop (*Annona muricata* L.). Forestry plants mainly focus on white damar (*Agathis labillardieri* Warb.) due to its sap, which is used for many purposes, such as building materials and firewood. Hence, it is crucial to augment the number of LAP types to enhance biodiversity and promote the green economy. The potential for crops, MPTS, and forestry plants established in Moswaren Village, Moswaren Sub-district, South Sorong District as a low disturbance area is intended for local community consumption, with a benefit index over 70% (Table 3, Figure 6.A).

Table 3. Potential types of crops, MPTS, and forestry plants in the *pekarangan* of South Sorong District, Papua, Indonesia

Group	Local name	General name	Scientific name	IUCN Status	Conditions
12 Crops	*Sagu*	Sago	*Metroxylon sagu* Rottb.	LC	W
	Betatas	Sweet potato	*Ipomoea batatas* (L.) Lam.	DD	W/D
	Talas	Taro	*Colocasia esculenta* (L.) Schott	LC	W/D
	Singkong	Cassava	*Manihot esculenta* Crantz	DD	W/D
	Kacang tanah	Peanut	*Arachis hypogaea* L.	DD	D
	Nanas	Pineapple	*Ananas comosus* (L.) Merr.	DD	D
	Cabe rawit	Cayenne paper	*Capsicum frutescens* L.	LC	D
	Bayam	Spinach	*Amaranthus* spp.	DD	W
	Daun gedi	Gedi leaves	*Abelmoschus manihot* (L.) Medik.	DD	W
	Kacang panjang	Long bean	*Vigna sinensis* (L.) Savi ex Hausskn.	DD	D
	Timun	Cucumber	*Cucumis sativus* L.	DD	D
	Tomat	Tomato	*Lycopersicon esculentum* Mill.	DD	D
13 MPTS	*Matoa*	Matoa	*Pometia pinnata* J.R.Forst. & G.Forst.	LC	
	Durian	Durian	*Durio zibethinus* Murray	DD	
	Rambutan	Rambutan	*Nephelium lappaceum* L.	LC	
	Mangga	Mango	*Mangifera indica* L.	DD	
	Kelapa	Coconut	*Cocos nucifera* L.	DD	
	Pinang	Areca nut	*Areca catechu* L.	DD	
	Pisang	Banana	*Musa acuminata* Colla	DD	
	Sirsak	Soursop	*Annona muricata* L.	LC	
	Melinjo	Ganemo	*Gnetum gnemon* L.	LC	
	Lawang	Lawang	*Cinnamomum culilaban* (L.) J.Presl	EN	
	Daun sirih	Betel leaf	*Piper betle* L.	DD	
	Kersen	Mutingia	*Muntingia calabura* L.	LC	
	Buah merah	Red fruit	*Pandanus tectorius* Parkinson ex Du Roi	LC	
5 Forestry	*Jati*	Teak	*Tectona grandis* L.f.	EN	
	Gamal	Gamal	*Gliricidia sepium* (Jacq.) Kunth	LC	
	Damar	White damar	*Agathis labillardieri* Warb.	NT	
	Resak	Resak	*Vatica rassak* (Korth.) Blume	LC	
	Pulai	Milkwood	*Alstonia scholaris* (L.) R.Br.	DD	

Note: w: wet; d: dry; DD: Data Deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; and EN: Endangered

Figure 6. A. LAPs in Papua, Indonesia: A. Moswaren; B. Aimas; and C. Manokwari

Mariat Village, located in the Aimas Sub-district of Sorong District, has a moderate level of disturbance. It has the potential for the seasonal cultivation of purple tuber sweet potato plants (*I. batatas*), which are considered superior to other colors of tubers. As a consequence, purple sweet potatoes and purple taro (*C. esculenta*) exhibit superior plant development potential. Similarly, the development of the *pekarangan* category remains basic and does not consider the biodiversity and economic status of the local community. Therefore, the primary focus is enhancing the potential of LAP forms in Sorong District, with a target benefit index exceeding 70% (Table 4, Figure 6.B).

Sairo Village, Nuni Sub-district, Manokwari District, indicates a high disturbance location with the seasonal potential to cultivate ginger (*Z. officinale*), peanut (*A. hypogaea*), sweet potato (*I. batatas*), and taro (*C. esculenta*). Typically, selecting *pekarangan* forms is straightforward; therefore, optimizing the utilization of land by incorporating potential varieties that prioritize biodiversity and the income of the local population is imperative. For the other crops, MPTS and forestry plants developed in the LAPs area of Manokwari with a benefit index of more than 70% are presented in Table 5 and Figure 6.C.

The development of different types of *pekarangan* in the three regencies demonstrates a focus on enhancing biodiversity, particularly for LC (23 species; Crops: taro (*C. esculenta*), cayenne paper (*C. frutescens*), red chilli (*C. annum*), corn (*Z. mays*), mung bean (*V. radiata*), adzuki bean (*V. angularis*); MPTS: matoa (*P. pinnata*), rambutan (*N. lappaceum*), soursop (*A. muricata*), ganemo (*G. gnemon*), guava (*P. guajava*), avocado (*P. americana*), water apple (*S. aqueu*), masohi (*C. massoia*), mutingia (*M. calabura*), petai (*P. speciosa*), red fruit (*P. tectorius*); and Forestry: white teak (*G. arborea*), gamal (*G. sepium*), resak (*V. rassak*), milk wood (*A. scholaris*), hopea (*H. papuana*), nyamplung (*C. inophyllum*)), NT (2 species; Forestry: white damar (*A. labillardieri*), merbau (*I. bijuga*)), VU (1 species; Forestry: tyhurifera wood (*A. thurifera*)), and EN (2 species; MPTS: lawang (*C. culilaban*); and Forestry: teak (*T. grandis*) which are experiencing a decline in their natural availability.

Table 4. Potential types of crops, MPTS, and forestry plants in *pekarangan* of Sorong District, Papua, Indonesia

Group	Local name	General name	Scientific name	IUCN Status	Conditions
15 Crops	*Sagu*	Sago	*Metroxylon sagu* Rottb.	LC	W
	Betatas	Sweet potato	*Ipomoea batatas* (L.) Lam.	DD	W/D
	Talas	Taro	*Colocasia esculenta* (L.) Schott	LC	W/D
	Singkong	Cassava	*Manihot esculenta* Crantz	DD	W/D
	Nanas	Pineapple	*Ananas comosus* (L.) Merr.	DD	D
	Pakcoy	Mustard greens	*Brassica rapa* L.	DD	W
	Cabe merah	Red chili	*Capsicum annuum* L.	LC	D
	Bayam merah	Red spinach	*Amaranthus tricolor* L.	DD	D
	Daun gedi	Gedi leaves	*Abelmoschus manihot* (L.) Medik.	DD	W/D
	Kacang tanah	Peanuts	*Arachis hypogaea* L.	DD	D
	Tomat	Tomato	*Solanum lycopersicum* L.	DD	D
	Caisim	Mustard cabbage	*Brassica chinensis* L.	DD	W/D
	Kacang panjang	Long bean	*Vigna sinensis* (L.) Savi ex Hausskn.	DD	D
	Timun	Cucumber	*Cucumis sativus* L.	DD	W/D
	Sawi hijau	Mustard greens	*Brassica juncea* (L.) Czern.	DD	W/D
14 MPTS	*Matoa*	Matoa	*Pometia pinnata* J.R.Forst. & G.Forst.	LC	
	Durian	Durian	*Durio zibethinus* Murray	DD	
	Pisang	Banana	*Musa* spp.	DD	
	Mangga	Mango	*Mangifera indica* L.	DD	
	Kelapa	Coconut	*Cocos nucifera* L.	DD	
	Pinang	Areca nut	*Areca catechu* L.	DD	
	Pepaya	Papaya	*Carica papaya* L.	DD	
	Jambu biji	Guava	*Psidium guajava* L.	LC	
	Jeruk manis	Sweet orange	*Citrus ×sinensis* (L.) Osbeck	DD	
	Masohi	Masohi	*Cryptocarya massoy* (Oken) Kosterm.	LC	
	Kedodondong	Kedondong	*Spondias dulcis* Parkinson	DD	
	Daun sirih	Betel leaf	*Piper betle* L.	DD	
	Kersen	Mutingia	*Muntingia calabura* L.	LC	
	Buah merah	Red fruit	*Pandanus conoideus* Lam.	LC	
5 Forestry	*Jati putih*	White teak	*Gmelina arborea* Roxb. ex Sm.	LC	
	Gamal	Gamal	*Gliricidia sepium* (Jacq.) Kunth	LC	
	Akasia	Acacia	*Acacia mangium* Willd.	DD	
	Damar	White damar	*Agathis labillardierei* Warb.	NT	
	Pulai	Milkwood	*Alstonia scholaris* (L.) R.Br.	DD	

Note: w: wet; d: dry; DD: Data Deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; and EN: Endangered

Table 5. Potential types of crops, MPTS, and forestry plants in the *pekarangan* of Manokwari District, Papua, Indonesia

Group	Local name	General name	Scientific name	IUCN Status	Conditions
16 Crops	*Sagu*	Sago	*Metroxylon sagu* Rottb.	LC	W
	Betatas	Sweet potato	*Ipomoea batatas* (L.) Lam.	DD	W/D
	Talas	Taro	*Colocasia esculenta* (L.) Schott	LC	W/D
	Singkong	Cassava	*Manihot esculenta* Crantz	DD	W/D
	Nanas	Pineapple	*Ananas comosus* (L.) Merr.	DD	D
	Kacang tanah	Peanuts	*Arachis hypogaea* L.	DD	D
	Caisim	Mustard cabbage	*Brassica chinensis* L.	DD	W/D
	Cabe rawit	Cayenne paper	*Capsicum frutescens* L.	LC	D
	Bayam	Spinach	*Amaranthus* spp.	DD	W
	Jagung	Corn	*Zea mays* L.	LC	D
	Terong	Eggplant	*Solanum melongena* L.	DD	W/D
	Labu siam	Chayote	*Sechium edule* (Jacq.) Sw.	DD	W/D
	Tomat	Tomato	*Solanum lycopersicum* L.	DD	D
	Kacang hijau	Mung bean	*Vigna radiata* (L.) R.Wilczek	LC	D
	Melon	Melon	*Cucumis melo* L.	DD	W
	Kacang merah	Adzuki bean	*Vigna angularis* (Willd.) Ohwi & H.Ohashi	LC	D
9 Herbs	*Jahe*	Ginger	*Zingiber officinale* Roscoe	DD	D
	Daun gedi	Gedi leaves	*Abelmoschus manihot* (L.) Medik.	DD	W
	Kunyit	Turmeric	*Curcuma domestica* Valeton	DD	D
	Serai	Lemongrass	*Cymbopogon citratus* (DC.) Stapf	DD	D
	Lengkuas	Galangal	*Alpinia galanga* (L.) Willd.	DD	D
	Selasih	Basil	*Ocimum basilicum* L.	DD	D
	Labu air	Bottle guard	*Lagenaria siceraria* (Molina) Standl.	DD	D
	Daun sirih	Betel leaf	*Piper betle* L.	DD	D
	Ketimun	Cucumber	*Cucumis sativus* L.	DD	D
15 MPTS	*Matoa*	Matoa	*Pometia pinnata* J.R.Forst. & G.Forst.	LC	
	Durian	Durian	*Durio zibethinus* Murray	DD	
	Rambutan	Rambutan	*Nephelium lappaceum* L.	LC	
	Mangga	Mango	*Mangifera indica* L.	DD	
	Kelapa	Coconut	*Cocos nucifera* L.	DD	
	Pinang	Areca nut	*Areca catechu* L.	DD	
	Alpukat	Avocado	*Persea americana* Mill.	LC	
	Jambu biji	Guava	*Psidium guajava* L.	LC	
	Langsat	Langsat	*Lansium domesticum* Corrêa	DD	
	Jambu air	Water apple	*Syzygium aqueum* (Burm.fil.) Alston	LC	
	Masohi	Masohi	*Cryptocarya massoia* (Oken) Kosterm.	LC	
	Kersen	Mutingia	*Muntingia calabura* L.	LC	
	Petai	Petai	*Parkia speciosa* Hassk.	LC	
	Markisa	Passion fruit	*Passiflora edulis* Sims	DD	
	Buah merah	Red fruit	*Pandanus conoideus* Lam.	LC	
9 Forestry	*Gamal*	Gamal	*Gliricidia sepium* (Jacq.) Kunth	LC	
	Merbau	Merbau	*Intsia bijuga* (Colebr.) Kuntze	NT	
	Resak	Resak	*Vatica rassak* (Korth.) Blume	LC	
	Pulai	Milkwood	*Alstonia scholaris* (L.) R.Br.	DD	
	Beringin	Ficus	*Ficus benjamina* L.	DD	
	Mersawa	Thurifera wood	*Anisoptera thurifera* (Blanco) Blume	VU	
	Merawan	Hopea	*Hopea papuana* Diels	LC	
	Ketapang	Catappa	*Terminalia catappa* L.	DD	
	Nyamplung	Nyamplung	*Calophyllum inophyllum* L.	LC	

Note: w: wet; d: dry; DD: Data Deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; and EN: Endangered

Species data indicates that regions with high disturbance have greater ecological resilience and support a diverse range of 23 species from crops and medicine plants, as the selection of species is influenced by extreme climatic circumstances. Dry conditions favor plants adapting to limited water availability, whereas wet conditions are more suitable for plants with higher water consumption requirements. Simultaneously, technology is being utilized to enhance plant adaptability to harsh environments and climate, especially for crops, by implementing a bed system, drainage flow, bio pores, and mycorrhizal nutrients.

Much of the loss of species in nature is attributed to climate change. Lima et al. (2022) reported a significant decrease in the abundance of indigenous agroforestry species in the SSP 2-4.5 and SSP5-8.5 scenarios, with declines of 68.8% and 84.4%, respectively. According to a study conducted by Cámara-Leret et al. (2019), it is projected that by 2070, around 63% of the plant species native to New Guinea will experience a reduction in their geographic range. This is expected to result in a decline in the overall diversity of species in the ecoregion, which could lead to the extinction of up to 94 species in each linguistic area, hence affecting the accessibility of plant species that are beneficial to indigenous populations. As a result, it plays a vital role in supplementing the types of LAPs that have naturally declined in nature while also preserving indigenous communities from extinction, particularly from cultural perspectives.

Food security, uses, economic uses, and revenue of LAPs

The Local Agroforestry Practices (LAPs) implemented in Bird's Head Papua have yielded significant outcomes in three key development sectors. These practices have successfully addressed 45.23 % of the region's food security requirements, primarily through the cultivation of food crops such as tubers (*I. batatas*), taro (*C. esculenta*), cassava (*M. utilisima*), corn (*Z. mays*), and bananas (*M. textila*); 38.47% of crops and MPTS plants are used for self-consumption (Table 5). The surplus of Food Security (FS) and Only Use (OU) beyond the requirements are allocated to generate community income and fulfill daily living needs. Forestry plants are primarily utilized for residential infrastructure requirements and others for the storage demands of agroforestry maintenance equipment.

Food crops are mostly cultivated to meet carbohydrate requirements, while vegetables and fruits are grown to fulfill mineral and vitamin demands. Nuts serve as a source of protein and vitamins, while spices enhance immunity and promote overall health. On the other hand, forestry plants are primarily grown to obtain building materials and fulfill other related needs such as shade, anti-parasitic, anti-bacterial and anti-fungal, biodiesel material, feed, and nutrition. Therefore, the LAPs of the three research locations are based on agro silviculture, which involves the incorporation of more varieties of trees (MPTS and forestry) into agricultural landscapes to sustain food production, preserve natural resources and biodiversity, total revenue of the local community, and promote sustainable management practices for a healthier environment and society (Sollen-Norrlin et al. 2020; Pantera et al. 2021).

Table 6 shows the composition of annual income for each disturbance location: All at Rp. 9,187,231; High at Rp. 6,610,444; Low at Rp.7,140,000; Moderate at Rp. 7,543,500, respectively. Thus, economic optimization based on regional conditions, biodiversity, and local culture has been successfully implemented. The rise was 2.93-5.04 times from the traditional LAPs.

Particular agroforestry practices in the Bird's Head Region of Papua were identified as the most productive in enhancing biodiversity conservation and food security. The low disturbance area contains eight species namely Crops (*A. hybridus* and *A. comosus),* MPTS (*A. moricata*, *C. culilaban*, *G. gnemon*, and *M. acuminata*); and Forestry (*T. grandis* and *V. rassak*). Moderate disturbance contains 10 species, namely Crops (*B. chinensis*, *A. tricolor*, and *L. esculentum*), MPTS (*C. massoi*, *C. papaya*, *C. sinensis*, *P. guajava*, and *S. dulcis*), and Forestry (*A. mangium* and *G. arborea*). High disturbance encompasses 27 species including Crops (*C. melo*), Herbs (*A. galanga*, *C. domestica*, *C. citratus*), MPTS (*A. unipa*, *A. communis*, *A. heterophyllus*, *C. aurantifolia*), and Forestry (*A. thurifera*, *H. papuana*, *C. inophyllum*, *F. benjamina*, and *H. novoguineensis*). This study indicates that species selection for high disturbance areas primarily targets anticipating extreme climate events. All three locations have a total of 26 species. The total number of species identified in low-disturbance, moderate-disturbance, and high-disturbance environments are 34, 36, and 53, respectively. This indicates that biodiversity and conservation levels in these three locations are relatively high, as evidenced by various studies reporting 50 species in West Java (Ali et al. 2021), 33 species in Lampung (Heryandi et al. 2022), and 57 species in Bengkulu (Wiryono et al. 2023).

In Papua, at least five species of Invasive Alien Plant Species (IAPS) require attention (Figure 7). Generally, these plant species were introduced to Papua as ornamental vegetation. Each invasive species will have a distinct impact on the ecosystem due to its unique habitus form. The host plant's growth and development will be disrupted as lianas with aggressive growth ascend other types and close the host plant's support system to access sunlight. In the same way, shrub-like invasive plants will establish clusters and monopolize the region in which they thrive, rendering it impossible for other plants to compete for the same space (Yuliana and Lekitoo 2018). To prevent the disruption of the ecology in the three regions, ornamental plants are not included in the selection of LAPs. Of the five forms of IAPS, two types were identified as predominant in distribution in West Papua, namely Pohon Spuit and Bunga Tahi Ayam in local names. In addition, the family most frequently encountered is Asteraceae.

The effectiveness and long-term viability of LAPs are closely linked to the implementation of evidence-based methodologies and the proficient administration of diverse models in different geographical areas. This underscores the significance of tree-crop interactions and the harmonious interplay between soil nutrients, perennial trees, herbaceous crops, MPTS, spices, and other elements. As a result, agroforestry practices are socially acceptable, economically viable, and ecologically sound. Still, they require scientific-based management practices for long-term consistency and farmer satisfaction, including wide adoption and spreading capacity in regions such as Asia, Africa, and Europe (Plieninger et al. 2020; Raj et al. 2022).

The key difference between LAPs and commercial agricultural methods is evident in their environmental approaches, with LAPs prioritizing biodiversity protection and commercial agriculture emphasizing monoculture. LAPs prioritize food security and profit-driven commercial interests in the economic domain. In social and cultural dimensions, LAPs are integral to the community, and the selection of kinds is a product of extensive traditional experience. At the same time, commercial interests only focus on benefits, often neglecting local culture. Consequently, it is essential to assess the capacity of LAPs to promote sustainable livelihoods, advance biodiversity conservation, and improve ecosystem services throughout time. This may entail implementing varied agroforestry systems, promoting value-added agroforestry products, and integrating sustainable land management methods to guarantee the long-term economic viability of LAPs (Raj et al. 2022; Kumar et al. 2023).

Table 6. Food security, uses, economic uses, and revenue of LAPs

Species	**Family**	**Origin**	**IVI (%)**	**Uses**	**Economic use**	**FS, OU (%)**	**Revenue (Rp)**
Ipomoea batatas (All)	Convolvulaceae	Exotic	19.28	Food, vitamin	FS, sale	**79.82**	7,070,000
Artocarpus communis (High)	Moraceae	Exotic	8.99	Fruit, vitamin, food	OU, sale	65.22	**25,600,000**
Colocasia esculenta (All)	Araceae	Exotic	8.56	Food, vitamin	FS, sale	**79.61**	13,830,000
Intisa bijuga (High)	Fabaceae	Native & Endangered	8.47	Building material	OU		0
Lansium domesticum (High)	Meliaceae	Exotic	8.00	Fruit, vitamin	OU, sale	29.76	32,400,000
Zea mays saccharata Sturt (All)	Poaceae	Introduced	7.54	Food	FS, sale	**42.74**	16,080,000
Syzygium aqueum (High)	Myrtaceae	Introduced	7.56	Fruit, vitamin	OU, sale	45.45	15,000,000
Cocos nucifera (All)	Arecaceae	Introduced	7.16	Fruit, vitamin, food	OU, sale	41.24	11,400,000
Mangifera indica (All)	Anacardiaceae	Introduced	7.09	Fruit, vitamin	OU, sale	29.24	21,780,000
Nephelium lappaceum (All)	Sapindaceae	Introduced	7.01	Fruit, vitamin	OU, sale	36.59	23,400,000
Agathis labillardieri (All)	Araucariaceae	Native & Endangered	6.83	Building material	OU		0
Amaranthus hybridus (Low)	Amaranthaceae	Introduced	6.27	Vegetable, vitamin	OU, sale	32.81	5,120,000
Vatica rassak (Low)	Dipterocarpaceae	Native & Endangered	6.13	building material	OU		0
Tectona grandis (Low)	Lamiaceae	Introduced	5.54	building material	OU		0
Ficus benyamin (High)	Moraceae	Introduced	5.50	Shades and water sources	OU		0
Zea mays (All)	Poaceae	Introduced	4.95	Food, cereal	FS, sale	**40.60**	10,425,000
Caladium bicolor (All)	Araceae	Exotic	4.95	Food, vitamin	FS, sale	**32.59**	11,584,000
Solanum melongena (High)	Solanaceae	Introduced	4.94	Vegetable, vitamin	OU, sale	44.34	4,700,000
Solanum lycopersicum (Moderate)	Solanaceae	Introduced	4.95	Vegetable, fruit,vitamin	OU, sale	57.03	6,600,000
Brassica chinensis (Moderate)	Brassicaceac	Introduced	4.91	Vegetable, vitamin	OU, sale	55.30	2,325,000
Zingiber officinale (High)	Zingiberaceae	Introduced	4.79	Spice, medicine	OU, sale	69.64	1,530,000
Pometia pinnata (All)	Sapindaceae	Native & Endangered	4.83	Fruit, vitamin, building	OU, sale	35.71	9,000,000
Psidium guajava (Moderate)	Myrtaceae	Introduced	4.82	Fruit, vitamin	OU, sale	50.72	10,200,000
Persea americana (High)	Lauraceae	Exotic	4.63	Fruit, vitamin	OU, sale	20.16	37,080,000
Anisoptera thurifera (High)	Dipterocarpaceae	Native & Endangered	4.46	building material	OU		0
Durio zibethinus (All)	Malvaceae	Introduced	4.43	Fruit, vitamin	OU, sale	75.00	**42,000,000**
Areca cathecu (All)	Arecaceae	Exotic	4.41	Fruit, medicine	OU, sale	22.22	14,000,000
Carica papaya (Moderate)	Caricaceae	Introduced	4.26	Fruit, vitamin	OU, sale	13.89	5,580,000
Curcuma domestica (High)	Zingiberaceae	Introduced	4.10	Spice, medicine	OU, sale	61.32	4,095,000
Hopea papuana (High)	Dipterocarpaceae	Native & Endangered	3.89	Building material	OU		0
Areca unipa (High)	Arecaceae	Native & Endangered	3.86	Fruit, vitamin	OU		0
Citrus aurantifolia (High)	Rutaceae	Introduced	3.80	Fruit, vitamin	OU, sale	13.51	24,000,000
Musa textilis (All)	Musaceae	Introduced	3.71	Fruit, vitamin	FS, sale	**18.69**	13,050,000
Gmelina arborea (Moderate)	Lamiaceae	Introduced	3.61	Building material	OU		0
Gliricidia sepium (All)	Fabaceae	Introduced	3.44	Feed, nutrition	OU		0
Acacia mangium (Moderate)	Fabaceae	Introduced	3.41	Feed, nutrition	OU		0
Cymbopogon citratus (High)	Poaceae	Introduced	3.26	Spice, medicine	OU		0
Spondias dulcis (Moderate)	Anacardiaceae	Introduced	3.30	Fruit, vitamin	OU, sale	36.84	4,080,000
Hopea novoguineensis (High)	Dipterocarpaceae	Native & Endangered	3.20	Building material	OU		0
Annona muricata (Low)	Annonaceae	Introduced	3.17	Fruit, vitamin	OU, sale	29.27	8,700,000
Abelmoschus manihot (All)	Malvaceae	Exotic	3.12	Vegetables, vitamins, medicine	OU		0
Terminalia catappa (High)	Combretaceae	Introduced	3.13	Anti-parasitic, anti-bacterial, anti-fungal	OU		0
Musa spp.(All)	Musaceae	Introduced	3.10	Fruit, vitamin	FS, sale	**31.25**	6,600,000
Manihot utilissima (All)	Euphorbiaceae	Introduced	3.08	Food	FS, sale	**45.73**	4,450,000
Calophyllum inophyllum (High)	Clusiaceae	Native & Endangered	3.05	Industry, Biodiesel material	OU		0
Artocarpus heterophyllus (High)	Moraceae	Introduced	2.92	Fruit, vitamin	OU, sale	35.48	9,000,000
Musa acuminata (Low)	Musaceae	Introduced	2.92	Food, vitamin	FS, sale	**36.08**	8,000,000
Capsicum annuum (All)	Solanaceae	Introduced	2.85	Vegetable, vitamin	OU		0
Piper betle (All)	Piperaceae	Introduced	2.85	Spice, medicine	OU, sale	74.62	4,800,000

Cinnamomum culilaban (Low)	Lauraceae	Native & Endangered	2.84	Spice, medicine	OU, sale	23.85	**27,500,000**
Arachis hypogaea (All)	Fabaceae	Introduced	2.80	Protein, vitamin	OU, sale	66.29	3,204,000
Alpinia galanga (High)	Zingiberaceae	Introduced	2.70	Spice, medicine	OU, sale	50.40	2,730,000
Alstonia scholaris (All)	Apocynaceae	Introduced	2.68	Building material	OU		0
Muntingia calabura (All)	Muntingiaceae	Exotic	2.63	Fruit, vitamin	OU, sale	73.18	6,150,000
Ocimum basilicum (High)	Lamiaceae	Introduced	2.62	Spice, medicine	OU, sale	21.52	3,225,000
Citrus sinensis (Moderate)	Rutaceae	Introduced	2.62	Fruit, vitamin	OU, sale	23.67	6,750,000
Cryptocarya massoia (Moderate)	Lauraceae	Native & Endangered	2.60	Spice, medicine, oil	OU, sale	33.33	**37,500,000**
Sechium edule (High)	Cucurbitaceae	Introduced	2.22	Vegetable, vitamin	OU, sale	15.82	3,458,000
Vigna sinensis (All)	Fabaceae	Introduced	2.19	Vegetable, vitamin	OU, sale	43.27	2,360,000
Parkia speciosa (High)	Fabaceae	Introduced	1.95	Fruit, vitamin, food	OU, sale	22.86	3,240,000
Ananas comosus (Low)	Bromeliaceae	Introduced	1.78	Fruit, vitamin	OU, sale	14.47	6,500,000
Cucumis sativus (All)	Cucurbitaceae	Introduced	1.64	Fruit, medicine	OU, sale	29.01	1,395,000
Amaranthus tricolor (Moderate)	Amaranthaceae	Introduced	1.61	Vegetable, vitamin	OU, sale	38.24	2,400,000
Lycopersicon esculentum (All)	Solanaceae	Introduced	1.59	Fruit, vitamin	OU, sale	44.16	3,440,000
Vigna radiata (High)	Fabaceae	Introduced	1.15	Protein, vitamin	OU, sale	31.25	924,000
Cucumis melo (High)	Cucurbitaceae	Introduced	1.10	Fruit, vitamin	OU, sale	28.85	4,440,000
Gnetum gnemon (Low)	Gnetaceae	Introduced	1.08	leaves, vitamin	OU, sale	42.76	1,300,000
Lagenaria siceraria (High)	Cucurbitaceae	Exotic	1.06	Fruit, vitamin	OU, sale	29.27	2,900,000
Vigna angularis (High)	Fabaceae	Introduced	0.95	Protein, vitamin	OU, sale	34.48	1,520,000
Passiflora edulis (High)	Passifloraceae	Exotic	0.76	Fruit, vitamin	OU, sale	19.51	2,640,000
Pandanus conoideus (All)	Pandanaceae	Exotic	0.57	Fruit, vitamin	OU, sale	29.63	2,850,000
Average							
FS						**45.23**	
OU, sale						38.47	
Average Revenue							
Three location							9,187,231
Low disturbance (Moswaren)							7,140,000
Moderate disturbance (Aimas)							7,453,500
High disturbance (Manokwari)							6,661,444
Before Modification							
Low							5,568,900
Moderate							4,384,400
High							3,143,350

Figure 7. IAPS in Papua, Indonesia required intervention: A. *Decalobanthus peltatus* (Local name *Bidara Upas* and family Convolvulaceae); B. *Spathodea campanulata* (Local name *Pohon Spuit* and family Bignoniaceae); C. *Lantana camara* (Local name *Bunga Tahi Ayam* and family Verbenaceae); D. *Mikania micrantha* (Local name *Sembung Rambat*, and family Asteraceae); E. *Chromolaena odorata* (Local name *Kenikir* and family Asteraceae)

Total biomass and total carbon stok of LAPs

The modified low and moderate disturbance zones yielded total carbon values of 105.68 $tC.ha^{-1}$ and 103.30 $tC.ha^{-1}$, respectively, with H' values ranging from moderate to high. Meanwhile, in the high disturbance area, the greatest total biomass value was 175.55 $tC.ha^{-1}$, accompanied by a moderate to high H' value (Table 7). Implementing a forestry plant and MPTS treatment, which aimed to mitigate and adapt to the climate change impacts on afflicting the area, and resulted in an increased total biomass. This treatment creates a cool microclimate in preparation for the dry season. Additionally, during heavy rain, the canopy and plant beds prevent runoff and serve as drainage, allowing for efficient watering activities.

This study discovered that high-disturbance environments exhibit greater species diversity and total carbon content. The community offers planting alternatives to enhance food security and mitigate the effects of reduced output and mortality caused by extreme climatic conditions. This is a means of community resilience in preparing for extreme weather in high-disturbance regions.

The carbon values measured in this area exceed those in other parts of Indonesia. For example, the carbon values in West Java range from 37 to 108.6 $tC.ha^{-1}$, West Sulawesi 86.09 $tC.ha^{-1}$, simple agroforestry 30 $tC.ha^{-1}$, and complex agroforestry 66.7 $tC.ha^{-1}$ (Budiastuti et al. 2021; Siarudin et al. 2021; Irundu et al. 2023). Based on the variables included in the allometric equation, the rise in density and diversity H', the wood density of the selected species, and the age of the plant positively correlate with the high total biomass carbon stock.

Table 7. Total biomass and total stock carbon of LAPs

Location	No plot	H'	Total biomass ($tB.areal^{-1}$)	Total biomas ($tC.areal^{-1}$)	Under-storey ($tC.areal^{-1}$)	Litter ($tC.areal^{-1}$)	Soil ($tC.areal^{-1}$)	Total carbon ($tC.areal^{-1}$)
	1	3.13	5.18	2.59	1.12	0.01		
Moswaren	2	4.86	48.78	24.39	1.49	0.015		
Low	3	2.94	4.02	2.01	2.65	**0.01**		
Disturbance	4	2.57	1.58	0.79	3.55	0.02		
	5	2.81	3.00	1.50	0.81	0.01		
	6	3.18	5.04	2.52	0.88	0.01		
	7	2.33	1.20	0.60	0.73	0.01		
	8	3.31	6.50	3.25	0.1	0.01		
	9	3.12	4.40	2.20	**0.25**	0.01		
	10	3.14	4.84	2.42	0.23	0.00		
		Average	8.45	4.23	1.18	0.01		
		Total ($tC.ha^{-1}$)	211.35	105.68	29.53	0.26	88.34	223.80
		Proportion		47.22	13.19	0.12	39.47	
	11	3.17	4.22	2.11	1.32	0.01		
Aimas	12	2.60	2.20	1.10	2.47	0.00		
Moderate	13	4.83	48.04	24.02	0.9	0.00		
Disturbance	14	2.42	1.48	0.74	0.87	0.005		
	15	3.68	8.66	4.33	1.81	0.00		
	16	3.04	3.18	1.59	1.4	0.01		
	17	3.07	3.46	1.73	1.04	0.00		
	18	2.63	1.64	0.82	**1.29**	0.00		
	19	3.19	4.50	2.25	1.43	0.00		
	20	3.21	5.26	2.63	1.22	0.00		
		Average	8.26	4.13	1.38	0.00		
		Total ($tC.ha^{-1}$)	206.60	103.30	34.375	0.06	88.17	225.91
		Proportion		45.73	15.22	0.03	39.03	
	21	3.62	8.24	4.12	1.22	0.00		
Manokwari	22	2.96	4.08	2.04	0.9	0.01		
High	23	3.34	6.68	3.34	1.22	0.00		
Disturbance	24	3.21	4.74	2.37	1.17	0.00		
	25	5.29	61.00	30.50	1.32	0.00		
	26	3.93	13.14	6.57	1.05	0.00		
	27	3.63	8.28	4.14	1.07	0.04		
	28	3.71	8.52	4.26	1.62	0.00		
	29	3.89	10.76	5.38	1.03	0.00		
	30	3.97	15.00	7.50	0.28	0.00		
		Average	14.04	7.02	1.09	0.01		
		Total ($tC.ha^{-1}$)	351.10	175.55	27.2	0.13	76.17	279.05
		Proportion		62.91	9.75	0.04	27.30	

Note: Areal (400 m^2)

Total carbon is calculated by adding total biomass, understory plants, necromass, and soil to a depth of 1 meter, corresponding to the depth of forestry plant roots. The total carbon ranges from 223.80 to 279.05 $tC.ha^{-1}$, with understory plants accounting for 10-15% and soil accounting for 30-40%. In North Lombok, sengon-based agroforestry, coffee, cacao, and porang generated carbon values of 371.54 $tC.ha^{-1}$, 305.33 $tC.ha^{-1}$, 166.15 $tC.ha^{-1}$, and 153.93 $tC.ha^{-1}$, respectively (Sukartono et al. 2023).

Trade-offs between carbon storage and food security in implementing LAPs must be carefully managed to ensure overall sustainability. While agroforestry systems can sequester carbon and contribute to climate change mitigation, there may be trade-offs with food production if not managed properly. Balancing land allocation for carbon sequestration and food production, promoting agroforestry practices that enhance both carbon storage and food security and integrating agroforestry with sustainable agricultural practices can help minimize these trade-offs and maximize the overall sustainability of the agroforestry system. The agroforestry system contributed 174 MgC/ha to carbon storage within agroforestry networks. Consequently, carbon offset legislation must include significant local environmental and socioeconomic issues, including community involvement and food security (Sahoo et al. 2022).

In conclusion, this research utilized the Focus Group Discussion (FGD) method, demonstration plot, Participatory Rural Appraisal (PRA) type selection of LAPs, and economic and allometric equations to model biodiversity conservation, food security, and carbon storage potential of traditional agroforestry practices by integrating sustainable agroforestry practices, biodiversity conservation, food security measures, and adaptive responses to climate change and extreme conditions in the modern agroforestry systems. The species selection process took into account biodiversity, resulting in 23 species as Least Concern (LC), two species classified as Near Threatened (NT), one species classified as Vulnerable (VU), and two species classified as Endangered (EN). The LAPs implementation achieved a food security (FS) score of 48.13% and 38.47% for Only Used (OU). The overall income obtained was 2.93-5.04 times greater than traditional LAPs, demonstrating the economic viability of the approach. Most importantly, the aggregate carbon content across the three sites varied between 223.80 and 279.05 $tC.ha^{-1}$, showing the potential for significant carbon storage and its positive impact on environmental conservation.

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