Vol. 10(1): 83-106, January 2022
DOI: https://doi.org/10.23960/jsl.v10i1.575
Jurnal Sylva Lestari
P-ISSN: 2339-0913
E-ISSN: 2549-5747
Journal homepage: https://sylvalestari.fp.unila.ac.id

Full Length Research Article

The Dynamics of Secondary Mangrove Forests in Bintuni Bay, West Papua after Harvested on the First 30-Year Rotation Cycle

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ARTICLE HISTORY:

Received: 27 December 2021
Peer review completed: 5 January 2022
Received in revised form: 10 January 2022
Accepted: 12 January 2022

KEYWORDS:

Forest regeneration
Silviculture
Standing stock
Sustainable management
Timber utilization

ABSTRACT

Mangrove forests in Bintuni Bay, West Papua, Indonesia, have been managed for timber extraction since 1988 to produce wood chips using a 30-year rotation cycle. The first rotation cycle was completed, resulting in secondary mangrove forests with various stand ages (1–30 years). A large-scale forest inventory was conducted for all harvested blocks to recognize actual standing stock for the 2021–2030 management plan. A total of 434 quadrat plots (20 m x 20 m) covering 17.36 ha each were used to observe forest standing stock. The results present the dynamics of secondary mangrove forests after the initial rotation cycle. At the end of the first cycle (30-year-old stand), secondary mangrove forests provided a volume of 290.12 m^3 ha^{-1} and potential extractable biomass of 203.03 ton ha^{-1} with mean diameter, basal area, and stem density of 16.91 cm, 29.18 m^2 ha^{-1}, and 1,370 stem ha^{-1}, respectively. Annual increment of volume, biomass, and diameter were estimated to be 9.67 m^3 ha^{-1} year^{-1}, 6.77 ton ha^{-1} year^{-1}, and 0.56 cm year^{-1}, consecutively. The dynamics of secondary mangrove forests could provide significant information in the context of the management plan and implementation of the silviculture system to ensure the sustainability of utilization in managed mangrove forests.

1. Introduction

Mangroves have been recognized for their environmental benefits along tropical and sub-tropical coastlines (Aksornkoae 1993; Murdiyarso et al. 2015; Nagelkerken et al. 2008; Spalding and Leal 2021). Also, mangroves have significant economic benefits for coastal communities and industrial sectors through various sources of income such as fisheries, timber, and non-timber forest products (Ruitenbeek 1992; Salem and Mercer 2012; Suharti et al. 2016; Vo et al. 2012; Walters et al. 2008). Nevertheless, the development of coastal areas and conversion of mangroves for economic purposes into aquaculture, agriculture, and other land uses have become the main cause of degradation and deforestation on mangrove ecosystems in tropical regions, especially in Southeast Asia for recent decades (Friess 2016; Hamilton and Casey 2016; Ilman et al. 2016; Richards and Friess 2016; Romañach et al. 2018). Mangrove conversion to other land use has directly impacted biodiversity losses and increased the extinction risk for critically endangered species (Polidoro et al. 2010). The concern of mangrove loss and degradation has led to a world consensus that sustainable management and utilization must be applied to this undervalued ecosystem so that the benefits for coastal communities' livelihoods and global benefits such as blue carbon reserves will be consistently available (Feka and Morrison 2017; Herr and Landis 2016; Murdiyarso et al. 2018; Spalding and Leal 2021; UNEP 2014).

Sustainable use of mangrove forests cannot be carried out by conversion to other land uses because it will become a permanent barrier for the stand regeneration mechanism, which is an essential requirement for sustainable use of ecosystem and forest resources (Pribadi 1998; Simon 2010). One of the best approaches to use mangroves is to maintain biophysical conditions and ecosystem functions, then sell the potential carbon stored on the ecosystem as Payment for Ecosystem Services (Locatelli et al. 2014; Wylie et al. 2016), considering that mangroves are the ecosystem type with the highest carbon stock when compared to other ecosystems (Alongi 2014; Murdiyarso et al. 2015). Besides carbon trade programs which are still at the preliminary stage in most countries (Friess et al. 2020), utilization of mangrove stands could become an acceptable option by considering sustainability principles (Carter et al. 2015). The extent of mangrove areas for utilization should meet the requirements for rotation cycles as a pattern for sustainable use, which has been implemented in Thailand, India, Malaysia, and Indonesia (Aksornkoae 1993; Jusoff and Taha 2008; Saenger 2002; Wahyudi 2019). As long as the soil condition is still intact, covered by natural tidal inundation, and not converted to other land uses (e.g., ponds or palm oil), even though mangrove trees are harvested or lost to natural causes, carbon stock below ground will remain in the mangrove site while above-ground biomass is recovering and approaching a pre-disturbance condition (Adame et al. 2018; Krauss et al. 2018; Nam et al. 2016; Sasmito et al. 2020; Sillanpää et al. 2021).

The mangrove ecosystem in Bintuni Bay, Indonesia, is the third-largest in the world after Sundarbans in Bangladesh–India and Mimika in Indonesia (Gaveau et al. 2021) and provides valuable resources for social needs and environmental safeguards (Erftemeijer et al. 1991; Ruitenbeek 1992). Aside from this, Bintuni Bay's mangrove has been demonstrated to be sustainably used for timber utilization as a renewable forest resource (Sillanpää et al. 2017; Wahyudi 2019) while engaging the local community as the main partner in the management of the area (Wahyudi et al. 2014) as well as preserving wildlife and flora biodiversity within the ecosystem (Yudha et al. 2021). Recent studies in Bintuni Bay on carbon stock across different stand ages caused by logging suggest that selective logging and sustainable management on the area could maintain more than 70% mangrove carbon on harvested blocks which are stored below ground, while carbon above ground post-harvest recovers in the forest stand (Murdiyarso et al. 2021; Sasmito et al. 2020). Management of mangrove forest in Bintuni Bay has been carried out by the Forest Management Enterprise (FME) since 1988 according to a 20-year license from the Government, the Republic of Indonesia (henceforth: the Government) with a license extension in 2007 for 45 years until 2052 to manage ± 82,120 ha of mangrove forests and surrounding area in the southern part of Bintuni Bay (MoF RI 2007). The FME implemented sustainability standards in forest management according to Timber-Legality Assurance System (T-LAS) from the Government (MoEF RI 2020a), and principles and criteria in forest management from the Forest Stewardship Council (FSC 2020).

A management plan for 2021–2030 was designed using actual standing stock data as a reference to determine the target of volume which the FME will harvest during that time. To obtain information of actual standing stock, a forest inventory was carried out in the entire concession area as instructed by the MoF RI (2014a), which is conducted every ten years and is one of the important stages in terms of planning for sustainable forest management (MoEF RI 2020b). This activity was used as an opportunity to observe the dynamics of secondary mangrove forests that were harvested in the first 30-year rotation cycle. Surveys and monitoring of mangrove regeneration in Bintuni Bay have been carried out previously in several studies (Pribadi 1998; Sillanpää et al. 2017; Yudha et al. 2021). However, these studies have not presented the condition of all stand ages in secondary forests and description of forest structure in the final year of the first rotation cycle. Thus, this paper is the first to present complete dynamics and standing stock for all ages of secondary mangrove forests (1–30 years) in the first rotation cycle in Bintuni Bay. The objectives of this study were to provide an updated observation of forest dynamics and regeneration based on a concession-wide survey covering a completed harvest rotation of 30 years and to describe an overview of the potential standing stock that can be used for the next cycle. We hypothesized that secondary mangrove forests would experience significant growth after being harvested in the first 30-year cycle with sufficient standing stock for utilization in the next rotation cycle. The results of this study could provide important information to improve management planning and silvicultural practices, and could become a contribution to the national database of Indonesia (MoF RI 2011) regarding an increment of diameter and volume in managed mangrove forests.

2. Materials and Methods

2.1. Study Area

The study was conducted within the concession area of PT. Bintuni Utama Murni Wood Industries (PT. BUMWI), located in the Bird's Head of New Guinea big island, which included in the administrative area of Bintuni Bay Regency, West Papua Province, Republic of Indonesia (**Fig. 1**). Bintuni Bay is surrounded by extensive mangroves with a total area of more than 220,000 ha (Gaveau et al. 2021). Mangroves in the north part of Bintuni Bay are designated as protected areas, while the east part is declared as Nature Conservation Areas (MoF RI 2014b). PT. BUMWI concession area is located in the south part of the bay, stretches from east to west for more than 70 km, and is dominated by mangroves of 62,945.77 ha covering around 80% of the total concession area (MoEF RI 2019a). Bintuni Bay’s mangroves are categorized as Estuarine Interior, which received plenty of rich sediments from upland ecosystems (Sasmito et al. 2020). Timber harvesting conducted by the FME since 1988 has created secondary mangrove forests with the stand ages ranging from 1 to 30 years and distributed throughout the concession area where 434 sample plots of this study were established (**Fig. 2**).

The concession area is divided into 30 harvest blocks to accommodate a 30-year rotation cycle with approximately 2,000 ha per block. One block is divided into several compartments as the smallest management unit within the concession area with around 100 ha per compartment (PT. BUMWI 2021). About 25% of the total concession area is allocated as protected areas for buffer zones and High Conservation Value Forests (IDEAS Consultancy Services 2015). True mangrove observed in the concession area is composed of 28 species from 11 families, which are dominated by species from the Rhizophoraceae family (Yudha et al. 2021). The mangrove ecosystem in the area can provide habitat support for at least 103 bird species, 9 reptiles, 7 mammals, and 24 aquatic fauna. There are 34 species of bird covering 27% of total individual birds observed during the years 2009–2018 categorized as endemic species, which can only be found in New Guinea big island and surrounding satellite islands. Migratory birds from Australia, Palearctic, and Asia can also be found in Bintuni Bay's mangroves that use the area as a feeding ground during the non-breeding season (IDEAS Consultancy Services 2015; Yudha et al. 2021).

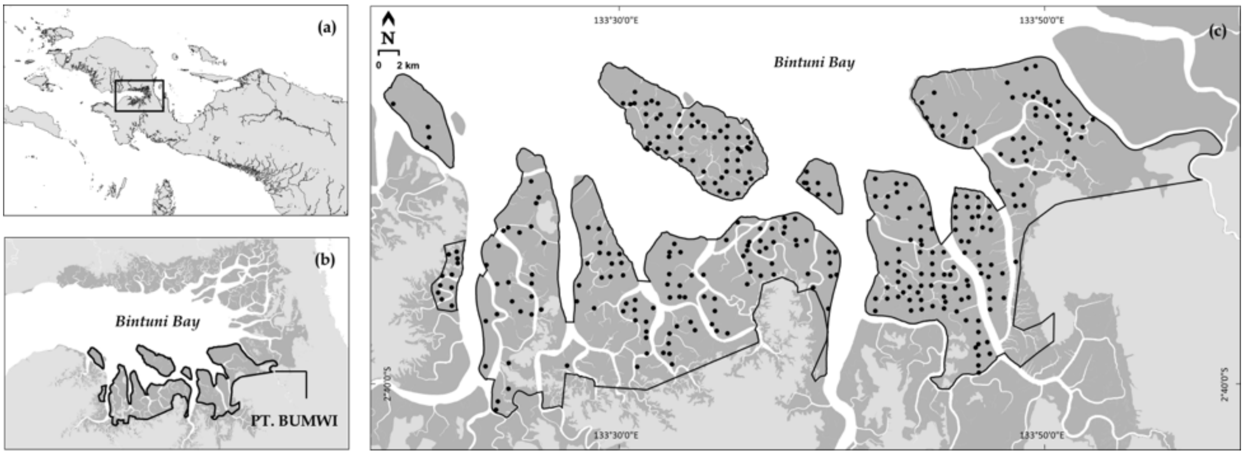

Fig. 1. Area of study. (a) Bintuni Bay is located in the Bird's Head of New Guinea big island. (b) The FME is located in the south part of Bintuni Bay. (c) Distribution of sample plot (dots) in secondary mangrove forests. The area which is not covered by plots is mostly primary forest. Dark grey is mangroves and wetlands, while light grey is dry land and terrestrial forests.

Fig. 2. Sampling locations. The figures displayed various stand ages of secondary mangrove forests; stand initiation at year 0 (condition after harvested), 5-year-old, 10-year-old, 15-year-old, and 30-year-old stands (end of one cycle).

2.2. Sampling Design

Forest inventory was carried out from December 2018 to March 2019 in all secondary forest blocks and compartments with the stand ages that ranged from 1 to 30 years. Additional plots were also established outside this period to achieve a minimum of 10 plots for each age of secondary forests. The field work is part of the Periodic Concession Forest Inventory conducted every ten years as the Government requires (MoEF RI 2015). The results of inventory in the primary forest were not included in the scope of this study because primary forest conditions have been well observed in previous studies (Sasmito et al. 2020; Sillanpää et al. 2017; Yudha et al. 2021). Furthermore, inventory in the primary forest is part of the silviculture system implementation that is always carried out in blocks of primary forest two years before harvesting to calculate available standing stock and determine volume allowance on each compartment (MoA RI 1978; MoEF RI 2016). Quadrat plot sampling (20 m x 20 m) was used to record vegetation data with 434 plots covering 17.36 ha. All trees inside the plot with Diameter at Breast High (DBH, 130 cm above ground) ≥ 10 cm were recorded since trees with this particular DBH are subject to harvesting. Trees with DBH below 10 cm and seedlings were not measured for this study. Trees with more than one stem below DBH (multi-stemmed trees) are very common in secondary mangrove forests (Goessens et al. 2014; Yudha 2021) and are included as a target for harvesting in the concession area. Therefore, the display of the secondary forest structure that was required in the management plan is an actual calculation for all existing stems. Measurement of DBH and stem count in this study was carried out for all stems in the sample plot (stem-based measurement). Thus the calculation of stem density in this paper did not represent the number of trees individually within the stands.

2.3. Data Analysis

The forest structure of secondary mangrove forests consisted of volume, stem density, basal area, and DBH, potential extractable biomass above ground, and species diversity (represented by Shannon-Wiener index), were obtained and calculated from measurement results. True mangrove species were determined according to Noor et al. (1999) and Giesen et al. (2007). Trees with a DBH ≥ 30 cm were categorized as seed trees or parent trees (since mangroves do not produce seeds) and were not included in the analysis since they could cause significant bias in the calculation. These trees did not represent regeneration in secondary forests and were only displayed in this paper to compare the distribution of stem density in different ranges of DBH between 30-year secondary forests and primary forests. Bosire et al. (2008) termed vegetation with DBH below 30 cm in reforested mangroves as potential regeneration, which becomes the main object of this study. Volume and biomass were calculated using allometry determined by Tantra et al. (2019), which developed from mangrove trees in Bintuni Bay. The allometry was determined for *Rhizophora apiculata* (RA, Equation 1 and Equation 4), *Bruguiera parviflora* (BP, Equation 2 and Equation 5), and *Bruguiera gymnorhiza* (BG, Equation 3 and Equation 6) as the most harvested species in the concession area. Based on tree diameter (Do, cm), equations for merchantable volume (V, m^3) are as follows:

$$V_{RA} = \frac{1.315 \times 10^{-3}}{1 + 4.92e^{-0.11Do}} D_0^2 \tag{1}$$

$$V_{BP} = \frac{1.181 \times 10^{-3}}{1 + 4.82e^{-0.14Do}} D_0^2 \tag{2}$$

$$V_{BG} = \frac{1.093 \times 10^{-3}}{1 + 5.40e^{-0.10Do}} D_0^2 \tag{3}$$

Allometry of biomass was developed specifically to estimate the dry weight of logs that can be utilized (excluding roots, branches, and leaves), so it did not represent total biomass above ground. Equations for potential extractable biomass (W, kg) based on tree diameter (Do, cm) are as follows:

$$W_{RA} = \frac{0.9207}{1 + 4.92e^{-0.11Do}} D_0^2 \tag{4}$$

$$W_{BP} = \frac{0.7492}{1 + 4.82e^{-0.14Do}} D_0^2 \tag{5}$$

$$W_{BG} = \frac{0.7477}{1 + 5.40e^{-0.10Do}} D_0^2 \quad (6)$$

Volume and biomass for *Rhizophora mucronata* were estimated using allometry of *R. apiculata* since these two species have a similar growth rate (Yudha 2021). *Ceriops decandra* and other species were estimated using allometry of *B. gymnorhiza* (which has the lowest rate of volume and biomass compared to *R. apiculata* and *B. parviflora*) because growth rates of other species are relatively slow and become minor composition in mangroves of Bintuni Bay (Yudha 2021; Yudha et al. 2021). Analysis of variance (ANOVA) and Kruskal-Wallis analysis was implemented to determine the variance of forest structure, biomass, and Shannon-Wiener index (H') on different stand ages of secondary forest. Regression analysis was conducted between stand ages with forest structure, biomass, and index H'. Statistical analysis was carried out using R version 3.4.4.

3. Results and Discussion

3.1. Results

3.1.1. Forest structure

Volume, stem density, basal area, and DBH at different stand ages (1–30 years) in secondary mangrove forests were significantly different (**Table 1**). At the end of the first 30-year rotation cycle (30 years stand age), mean volume was estimated to be 290.12 m^3 ha^{-1} with volume increment of 9.67 m^3 ha^{-1} $year^{-1}$, while stem density and basal area at this age were 1,370 stem ha^{-1} and 29.18 m^2 ha^{-1}, respectively. Mean DBH at the 30-year-old stand was 16.91 cm with a diameter increment of 0.56 cm $year^{-1}$ (**Table 1**, **Fig. 3**). The trend of increment in DBH could not be observed ($R^2 = 0.104$) due to the presence of unharvested trees in logged-over areas (**Table 1**, **Fig. 3.d**). The distribution of DBH was not consistent in the early years after harvest because, in some sampling plots, there was no tree at all. Thus the mean DBH in some plots was observed as zero (no data). If data of DBH for stand ages below 10-year-old were not included in regression analysis, to exclude DBH values from unharvested trees, the relationship between stand ages and mean value of DBH can be more observed ($R^2 = 0.521$) (**Fig. 4**).

3.1.2. Biodiversity

A total of 10 true mangrove species from 4 families were observed within sample plots. All of these species were not protected by the Government regulation (MoEF RI 2018) with Least Concern status according to the IUCN Red List (IUCN 2020). *Rhizophora apiculata* was the most dominant species covering 89.78% of total species composition in all ages (1–30 years) of secondary mangrove forests. Under the domination of *R. apiculata*, there were 4 codominant species from Rhizophoraceae family; *Bruguiera parviflora* (5.81%), *Bruguiera gymnorhiza* (2.15%), *Ceriops tagal* (0.81%) and *Rhizophora mucronata* (0.71%). In contrast, the other 5 species from 3 families cover only 0.74% of the total species composition (**Fig. 5**). Shannon-Wiener index (H') at different stand ages (1–30 years) of secondary mangrove forests was significantly different ($p < 0.001$) (**Table 1**). Index H' of trees was higher in the early ages of secondary forests and decreased along with the growth of the stands ($R^2 = 0.677$) due to the domination of *R. apiculata* in older forests (**Fig. 6**). Decrement in index H' of trees (DBH ≥ 10 cm) was in reverse with index H' of small stem trees (1 cm ≥ DBH < 5 cm) and seedlings (height < 1.5 m) which increase along with the time (see Discussion, **Fig. 9**).

3.1.3. Biomass

The mean of potential extractable biomass at different stand ages (1–30 years) of secondary mangrove forests was significantly different ($p < 0.001$) with consistent increment ($R^2 = 0.565$) along with the growth of the stands (**Table 1**, **Fig. 7**). Extractable biomass in 30 years stands age was in the range of 92.20–323.56 ton ha^{-1} (mean: 203.03 ton ha^{-1}), while annual increment of biomass was estimated to be 6.77 ton ha^{-1} year^{-1}. The results did not represent total biomass above ground since the allometry was only designated to describe the biomass of merchantable logs excluding roots, branches, and leaves. Biomass at the early ages of secondary forests was biomass of unharvested trees as described in the forest structure section above. Volume, basal area, and biomass have related measurements, so the linear models and coefficient correlations of these three variables were relatively similar (**Table 1**, **Fig. 3**, **Fig. 7**).

Table 1. Forest structure, extractable biomass, and Shannon-Wiener index (H') at different stand ages (1–30 years) in secondary mangrove forests of Bintuni Bay, West Papua, Indonesia

Stand age	**Plot (*n*)**	**Volume (m^3 ha^{-1})**	**Basal area (m^2 ha^{-1})**	**Density (stem ha^{-1})**	**DBH (cm)**	**Biomass (ton ha^{-1})**	**H'**
1	10	8.00 ± 12.63	0.79 ± 1.11	30.00 ± 36.89	8.85 ± 10.12	5.57 ± 8.83	0.68
2	14	15.08 ± 22.14	1.69 ± 2.42	82.14 ± 130.25	9.12 ± 9.00	10.34 ± 15.17	1.14
3	10	14.32 ± 12.28	1.42 ± 0.95	52.50 ± 36.23	18.36 ± 5.47	9.93 ± 8.57	0.77
4	10	12.13 ± 15.55	1.39 ± 1.65	75.00 ± 83.33	11.86 ± 6.64	8.05 ± 10.21	1.38
5	12	35.47 ± 32.06	3.28 ± 2.78	122.92 ± 103.60	15.89 ± 6.33	24.07 ± 21.54	1.25
6	11	25.09 ± 31.20	2.56 ± 2.74	134.09 ± 105.64	12.71 ± 5.15	16.59 ± 20.37	1.19
7	10	21.18 ± 20.38	2.41 ± 2.07	150.00 ± 120.76	11.77 ± 4.83	14.74 ± 14.22	1.33
8	12	16.24 ± 15.40	2.06 ± 1.66	156.25 ± 107.73	11.43 ± 4.22	11.06 ± 10.36	0.92
9	10	46.94 ± 29.76	5.50 ± 3.03	385.00 ± 175.67	13.19 ± 2.31	32.37 ± 20.70	0.66
10	10	25.48 ± 38.78	3.08 ± 4.61	192.50 ± 272.60	12.54 ± 4.79	17.65 ± 26.71	0.67
11	10	37.68 ± 14.93	4.23 ± 1.60	252.50 ± 101.69	14.72 ± 2.56	26.25 ± 10.49	0.62
12	10	52.19 ± 34.65	6.07 ± 4.10	417.50 ± 317.12	12.16 ± 4.65	36.19 ± 24.16	0.76
13	17	61.67 ± 47.92	6.55 ± 4.87	370.59 ± 372.41	15.28 ± 3.15	41.85 ± 32.05	0.88
14	12	77.41 ± 35.27	9.77 ± 4.64	800.00 ± 475.30	13.24 ± 2.28	53.81 ± 24.61	0.67
15	10	97.24 ± 37.79	12.12 ± 4.34	932.50 ± 409.95	13.03 ± 2.09	67.37 ± 26.44	0.43
16	10	91.80 ± 59.10	10.32 ± 7.08	647.50 ± 574.87	15.17 ± 3.20	63.70 ± 40.77	0.55
17	17	107.84 ± 63.65	12.99 ± 6.84	926.47 ± 400.34	13.10 ± 1.39	75.27 ± 44.41	0.34
18	20	110.81 ± 61.05	12.63 ± 6.83	771.25 ± 486.89	14.17 ± 1.31	76.94 ± 42.49	0.79
19	10	147.03 ± 61.13	17.65 ± 6.41	1260.00 ± 444.28	13.20 ± 1.96	102.31 ± 42.66	0.32
20	14	158.24 ± 58.70	17.28 ± 5.77	1010.71 ± 373.87	14.84 ± 2.87	110.63 ± 40.98	0.23
21	31	217.39 ± 71.50	22.35 ± 6.95	1103.23 ± 372.03	15.83 ± 1.42	150.57 ± 50.37	0.51
22	10	276.32 ± 64.29	28.16 ± 5.56	1342.50 ± 219.55	15.88 ± 1.01	193.09 ± 45.06	0.17
23	36	252.73 ± 107.94	25.87 ± 9.87	1277.08 ± 462.54	15.67 ± 1.92	176.19 ± 76.01	0.31
24	13	227.63 ± 57.05	23.63 ± 5.88	1200.00 ± 390.51	15.67 ± 1.70	159.01 ± 40.14	0.21
25	20	279.54 ± 97.25	27.06 ± 8.52	1161.25 ± 425.46	17.06 ± 2.41	195.04 ± 68.39	0.26
26	34	169.29 ± 63.41	18.02 ± 5.88	967.65 ± 324.42	15.15 ± 1.81	118.07 ± 44.21	0.45
27	14	187.66 ± 68.85	21.40 ± 6.46	1292.86 ± 273.94	14.18 ± 0.84	131.35 ± 48.18	0.05
28	11	208.25 ± 44.59	21.15 ± 4.51	1020.45 ± 310.21	16.06 ± 2.18	144.34 ± 30.97	0.54
29	16	265.14 ± 127.34	26.79 ± 12.87	1259.38 ± 615.89	16.11 ± 1.37	185.14 ± 89.40	0.22
30	10	290.12 ± 114.02	29.18 ± 12.22	1370.00 ± 686.46	16.91 ± 2.96	203.03 ± 79.83	0.04
		$R^2 = 0.565$	$R^2 = 0.594$	$R^2 = 0.533$	$R^2 = 0.104$	$R^2 = 0.565$	$R^2 = 0.677$
		$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

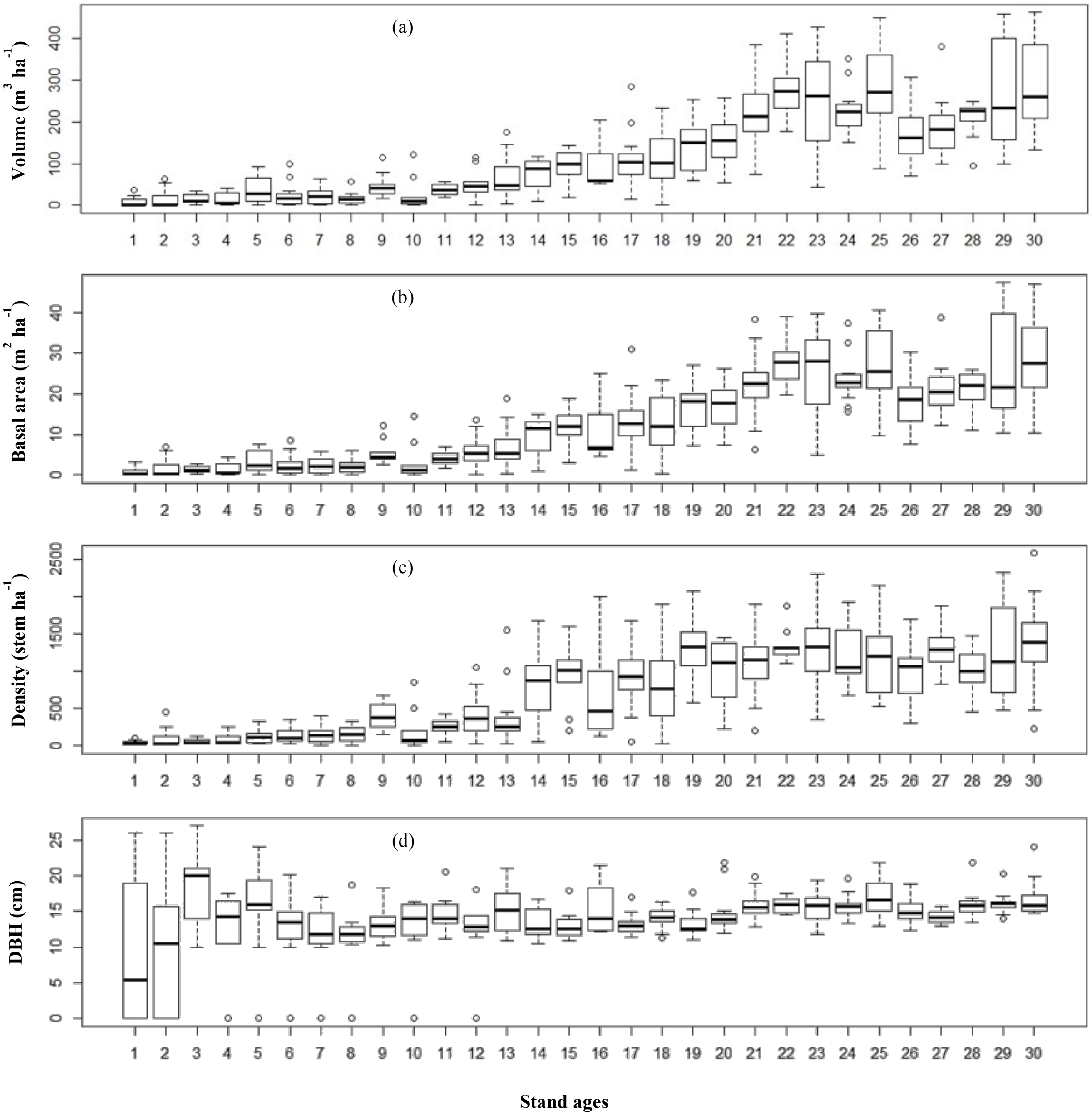

Fig. 3. Forest structure at different stand ages (1–30 years, $n = 434$) in secondary mangrove forests of Bintuni Bay, West Papua, Indonesia: (a) Volume (m^3 ha^{-1}), (b) Basal area (m^2 ha^{-1}), (c) Density (stem ha^{-1}), and (d) DBH (cm).

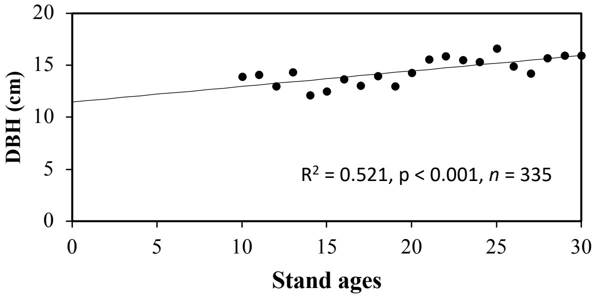

Fig. 4. Mean DBH (cm) at stand ages 10–30 years in secondary mangrove forests of Bintuni Bay, West Papua, Indonesia. The relationship between stand ages and mean DBH can be more observed in this figure when compared to **Fig. 3.d** as values from stand ages 1–9 years were eliminated to avoid bias from the diameter of remaining trees in the early years after harvest.

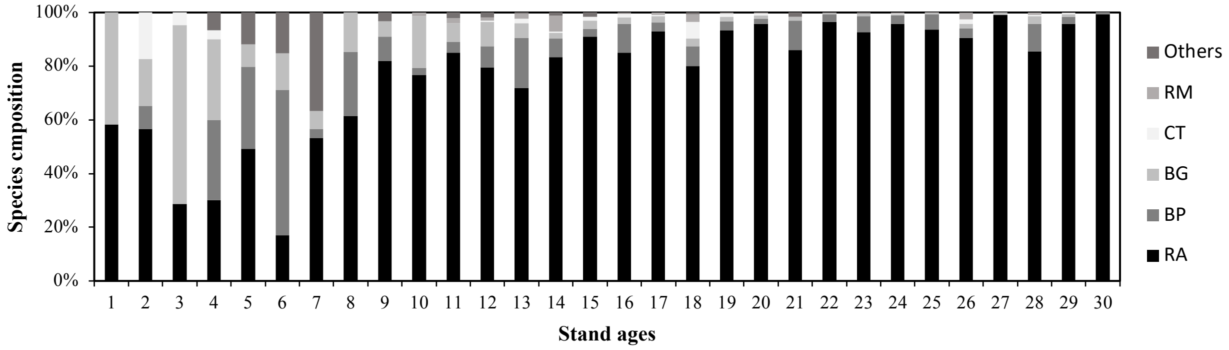

Fig. 5. Species composition (%) of trees (DBH ≥ 10 cm) at different stand ages (1–30 years, *n* = 434) in secondary mangrove forests of Bintuni Bay, West Papua, Indonesia. RA: *R. apiculata*, BP: *B. parviflora*, BG: *B. gymnorhiza*, RM: *R. mucronata*, CT: *C. tagal.*

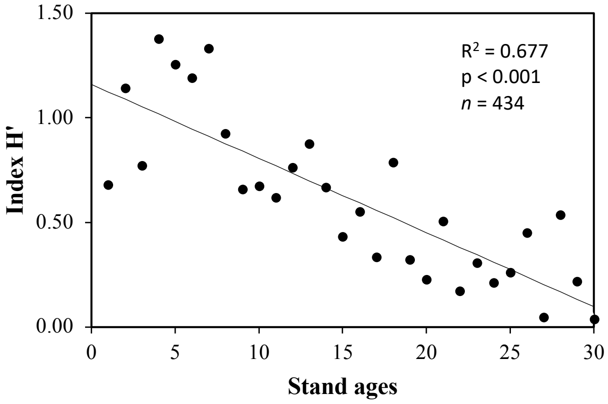

Fig. 6. Shannon Wiener index (H') of trees (DBH ≥ 10 cm) at different stand ages (1–30 years) in secondary mangrove forests of Bintuni Bay, West Papua, Indonesia.

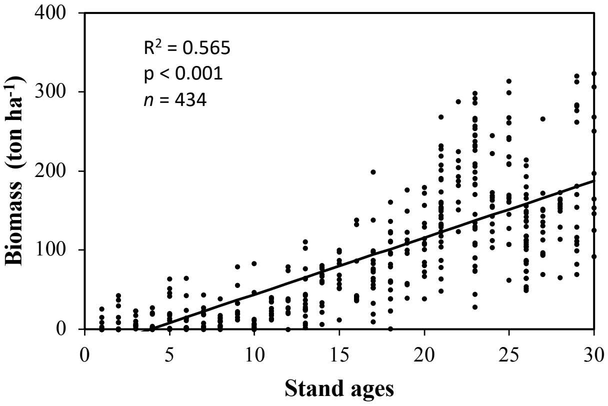

Fig. 7. Potential extractable biomass above ground (ton ha^{-1}) (excluding roots, branches, and leaves) at different stand ages (1–30 years) in secondary mangrove forests of Bintuni Bay, West Papua, Indonesia. Dots represent potential extractable biomass on each sample plot.

3.2. Discussion

3.2.1. Secondary forest dynamics

Mangrove forests in Bintuni Bay have successfully regenerated and replaced former vegetation, which was harvested in the first rotation cycle 1988–2017 as reported in the previous study (Yudha et al. 2021), with forest structure that is approaching primary forests conditions as prediction models created by Sillanpää et al. (2017). Standing stock in the last year of the first rotation cycle (30-year-old stand) is sufficient for utilization in the next cycle (**Table 1**, **Fig. 3**). These results were consistent with our hypothesis. Secondary forests below 10 years of age were still in a young stand regeneration phase which did not provide any significant standing stock. The early stand ages are struggling in various types of natural selection processes due to unfavorable environmental conditions, including propagule predation (Cannicci et al. 2008; Dahdouh-Guebas et al. 2011; Pribadi et al. 2014; Van Nedervelde et al. 2014). Success indicator of forest regeneration can be seen from stem density which is dominated by vegetation with small diameter classes. In the 30-year-old stand, the largest proportion of the stem density was found in diameter classes of 10–14 cm and 15–19 cm, covering 80% of total stem density. While according to recent standing stock inventory results (timber cruising) of a block that will be harvested in 2022 (PT. BUMWI 2020), the stem density of primary forests in diameter classes of 10–14 cm and 15–19 cm is covering only 54% of total stem density (**Fig. 8**). Timber cruising as part of silvicultural practices is conducted two years before harvest using the continuous strip sampling method (see **Table 3**). With a diameter increment of 0.56 cm year^{-1}, natural seedlings that occurred in the logged-over area one year after harvest will become trees with a diameter of 10 cm at the age of 18 years. Seedlings planted for afforestation 18 years ago have recently grown and become trees with DBH ≥ 10 cm. Therefore, the largest volume increment was found between stands ages 18 to 22 years (**Fig. 3.a**).

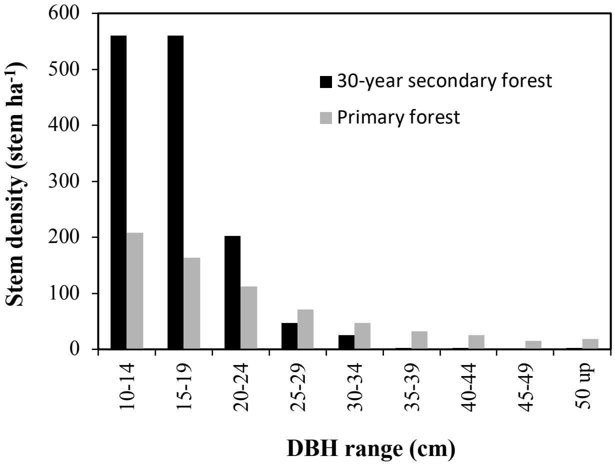

Fig. 8. Comparison of density (stem ha^{-1}) in various DBH ranges between a 30-year secondary mangrove forest (black bar) and primary mangrove forests (grey bar) of Bintuni Bay, West Papua, Indonesia.

Results of this study could become a significant contribution to the Government national data regarding an increment of diameter and volume for Indonesian natural forests. The current national data for diameter and volume increment (commercial species) in natural forests are 0.69 cm year^{-1} and 1.749 m^3 ha^{-1} year^{-1}, consecutively (MoF RI 2011). Specific increment for mangrove forests is not available in the national database because results from permanent plots in mangrove forests that could become a scientific reference have never been reported. The FME has some permanent plots within the concession area, which were established in several harvested blocks and are being measured every year as instructed by the MoF RI (2007). However, the oldest age of these permanent plots is 13-year-old, and the data of measurement has not yet reached the increment for one rotation cycle. There is a permanent plot in the concession area with a stand age of 26 years (Yudha 2021) that is purely planted without natural seedlings from parent trees, but the plot size is relatively small (1.6 ha) and the condition does not resemble natural secondary forests. Thus, this paper could become a relevant reference to describe increment in secondary mangrove forests since the sampling area covered all stand ages of the first rotation cycle with a total plot size of 17.36 ha. This study showed that the increment of diameter and volume for commercial species in secondary mangrove forests were 0.56 cm year^{-1} and 9.67 m^3 ha^{-1} year^{-1}, respectively. Another study conducted in Bintuni Bay by Yudha et al. (2021), for commercial species with DBH ≥ 10 cm and oldest sample stand of 23 years, shows that increment of diameter and volume was estimated to be 0.69 cm year^{-1} and 7.92 m^3 ha^{-1} year^{-1}, consecutively. Moreover, the result from Sillanpää et al. (2017) (DBH ≥ 5 cm, all species, oldest sample stand: 25 years) shows diameter increment of 0.46 cm year^{-1} and volume increment of 9.97 m^3 ha^{-1} year^{-1}. The differences in previous studies occurred because of different sampling methods and the oldest stand age was limited to 25 years.

When compared to forest structure in primary mangrove forests of Bintuni Bay, mean volume in a 30-year-old stand had reached 73% of mean volume in the primary forest even though mean DBH at the 30-year-old stand was only 57% of mean DBH in primary forest. The mean DBH of the 30-year-old stand is 16.91 cm, while in the primary forest is 29.64 cm (**Table 2**). It could have happened because of multi-stemmed trees; one tree individual in secondary forests can have more than one main stem because the main stem branched below DBH. About 24% of planted mangroves in Bintuni Bay are categorized as multi-stemmed trees with a maximum of 8 stems that can occur in a single tree. These multi-stemmed trees can increase the standing stock of volume in secondary mangrove forests by up to 33% (Yudha 2021). However, stem density in secondary forests can still decrease significantly due to extensive natural thinning in mangroves (Deshar et al. 2012; Gong and Ong 1995; Pranchai 2017). The mean volume of secondary mangrove forest in a 30-year-old stand in Bintuni Bay (290.12 m^3 ha^{-1}) is higher compared to other managed mangroves of the same age class. As mentioned by Kairo et al. (2002), the volume in a 30-year-old stand in Matang, Malaysia is 153 m^3 ha^{-1} (Haron 1981), while in Ranong, Thailand is 226 m^3 ha^{-1} (Aksornkoae 1993). Different allometric equations could influence these differences since they vary across regions and the global standardized framework for mangroves allometry is currently unavailable (Rovai et al. 2021; Sasmito et al. 2020). Future studies in Bintuni Bay after completion of several rotation cycles need to be carried out to observe whether the productivity of the forests is declining as has occurred in Matang, Malaysia (Gong and Ong 1995), so further research or silvicultural improvements could be conducted to prevent or reduce such decrement.

Table 2. Comparison of mean forest structure and index H' between a 30-year secondary mangrove forest and primary mangrove forests of Bintuni Bay, West Papua, Indonesia

Variable	Primary forests**	30-year secondary forest***
Volume (m^3 ha^{-1})	393.82	290.12
Basal area (m^2 ha^{-1})	26.78	29.18
Stem density (stem ha^{-1})*	474	1,370
DBH (cm)	29.64	16.91
Index H'	1.51	0.04

Notes: * Stem density in the 30-year secondary forest did not represent the density of individual trees since all stems which occurred in a single tree (multi-stemmed trees) were measured; ** Data according to Yudha et al. (2021) (*n* = 594); *** The results of this study (*n* = 10).

The Shannon-Wiener index (H') of trees was decreasing over time, with *R. apiculata* as the most dominant species. Index H' in the 30-year-old stand was 0.04 and remarkably different from primary forests of 1.51 (**Table 2**). This condition is in reverse with index H' of small stem trees and seedlings in secondary mangrove forests of Bintuni Bay that increased along with the growth of the stand. Comparison of index H' between different stratum can be seen in **Fig. 9**; trees (as the main object of this study) are vegetation with DBH ≥ 10 cm, small stem trees according to Sillanpää et al. (2017) are vegetation with 1 cm ≥ DBH < 5 cm (the below solid line is the regression of H' for small stem trees) and seedlings according to Yudha et al. (2021) are vegetation with height < 1.5 m (the above solid line is the regression of H' for seedlings). Higher index H' for small stem trees and seedlings in older forests indicate that recruitment of natural regeneration in secondary forests can occur even though the above stratum is stand dominated by *R. apiculata*. Natural recruitment of species that are not planted in monospecific stands can increase productivity and ecosystem stability, as stated by Bosire et al. (2003) and Bosire et al. (2006). However, future research in secondary mangrove forests of Bintuni Bay needs to be carried out to investigate further development of these lower stratums so that it can be observed whether high biodiversity in small stem trees and seedlings can survive and grow under monospecific stands and whether domination of *R. apiculata* in the secondary forest can decrease as the lower stratum are growing. Investigation of growth in old mature secondary forests is important in the context of ecological dynamics, considering that secondary mangrove forests have a characteristic of extensive natural thinning (Deshar et al. 2012; Gong and Ong 1995; Pranchai 2017) which can provide canopy gaps for other codominant species.

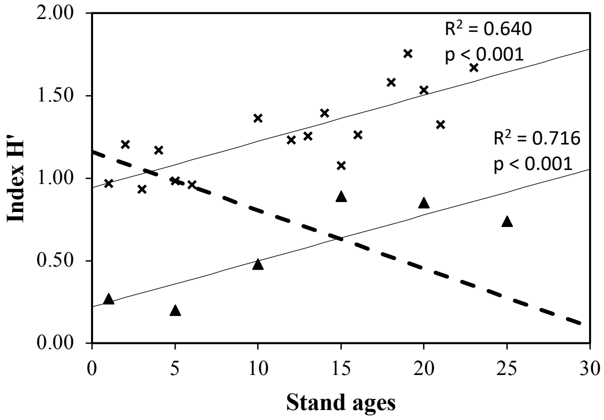

Fig. 9. Comparison of Shannon-Wiener index (H') for trees (dash line, as regression model from **Fig. 6**), small stem trees (triangle, according to Sillanpää et al. (2017), *n* = 36), and seedlings (cross, according to Yudha et al. (2021), *n* = 1,863) at different stand ages (1–30 years) in secondary mangrove forests of Bintuni Bay, West Papua, Indonesia.

Biomass increment in secondary forests was remarkably observed over time along with the growth of the stands. The annual increment of biomass was estimated to be 6.77 ton ha^{-1} year^{-1} with average biomass of 203.03 ton ha^{-1} in 30-year-old secondary forest (**Table 1, Fig. 6**). Results from this study are consistent with a previous study in Bintuni Bay which discovered that biomass above ground is lost due to removal of trees in the recently logged over area and then recover when forest regeneration grows over time (Murdiyarso et al. 2021). Sasmito et al. (2020) found that live biomass in mangroves 25 years post-harvest was not significantly different from live biomass in undisturbed mangrove forests of Bintuni Bay. This could have happened because of multi-stemmed trees that can significantly increase standing stock in secondary forests (Yudha 2021); thus, live biomass in older ages of secondary forests is almost in range with primary forests' live biomass. Goessens et al. (2014) observed the same condition in managed mangrove of Matang, Malaysia that total above-ground biomass in a 30-year-old stand (372 ton ha^{-1}) is almost similar with virgin jungle reserves of 415 ton ha^{-1}. Considering that mangrove wood is one of the highest calorific values wood and steady-burned over a long period (Ahmed et al. 2012), sustainable management on mangroves could provide long-term availability of biomass for subsistence use, charcoal, and the industrial sector for renewable energy (Aksornkoae 1993; Atheull et al. 2009; Sathe et al. 2013; Thongjoo et al. 2018). Furthermore, rotational and selective logging on managed mangroves as implemented in Bintuni Bay can contribute to climate change mitigation and adaptation actions since above-ground biomass can be secured and soil carbon stocks are preserved throughout the cutting cycle (Murdiyarso et al. 2021).

3.2.2. Mangrove silvicultural practices

One of the key factors in the sustainable use of mangrove forests is the implementation of suitable silvicultural practices (Saenger 2002). The Matang Mangrove Forest Reserve (MMFR) in Malaysia is considered as the best-managed mangroves in the world that have implemented clear cut and plantation method for more than a century (Goessens et al. 2014; Jusoff and Taha 2008). Thus, a comparison of the silviculture system between the MMFR and Bintuni Bay that uses selective logging and parent trees method during the first rotation cycle is worthy of description. Implementation of silviculture system in Bintuni Bay starts three years before harvest by conducting area planning, timber cruising, and zone marking. Timber extraction is allowed on each annual block by leaving parent trees (40 trees ha^{-1}) distributed throughout the harvest area. A census of vegetation in logged-over areas is conducted two years after harvest to observe the availability of natural regeneration categorized as seedlings (height < 1.5 m) and saplings (height ≥ 1.5 m, DBH < 10 cm). Before conducting afforestation, parent trees and surrounding unharvested area are expected to contribute the maximum number of seedlings as natural regeneration in the logged-over area to achieve ecologically functional forest as in natural mangrove stand (Bosire et al. 2006, 2008) and to avoid impairments in secondary succession (Rovai et al. 2012).

There is a weak correlation between harvested area and the availability of natural regeneration in the logged-over area ($R^2 = 0.506$) with an average natural seedling of 1.021 stem ha^{-1} and saplings of 198 stem ha^{-1} that are available in logged-over area as displayed in **Fig. 10**. The dashed line in **Fig. 10** is the minimum stocking required by the Government (MoA RI 1978), while the solid line is a regression model between harvest area (ha) and the availability of natural regeneration (stem). Data according to Post-Harvest Forest Inventory results within harvest blocks of 2010 to 2014 (PT. BUMWI 2016). The activity is part of silvicultural practices, by conducting a census to count existing natural regeneration using 20 m x 20 m plots in all logged-over areas to estimate the total amount of seedlings needed for afforestation. Area with less natural regeneration then planted three years after logging by seedlings and propagules from the FME's nursery to gain minimum stocking of 2,500 stem ha^{-1} (2 m x 2 m planting distance) as required by the Government (MoA RI 1978). Seedlings and propagules that used for afforestation mostly are *R. apiculata* as the most harvested species in the concession area, covering 95% of total planted seedlings over the last 10 years (PT. BUMWI, unpublished data). In planted mangrove stands, this species can provide high standing stock for future utilization when compared to other mangrove species (Yudha 2021).

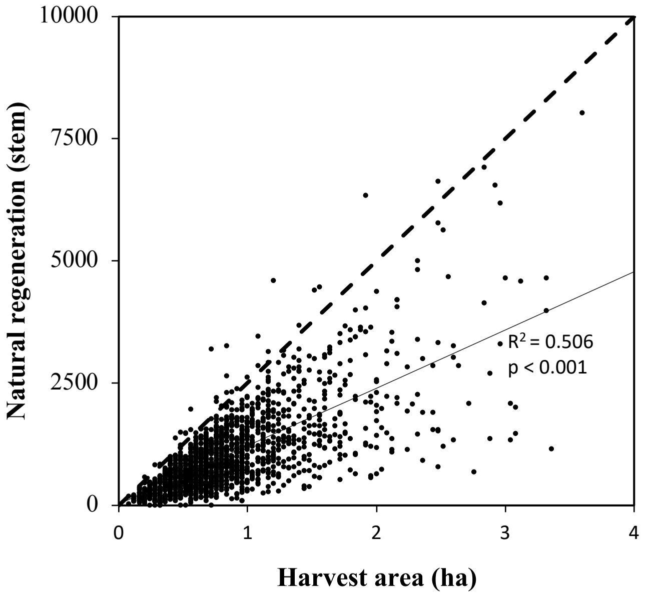

Fig. 10. The availability of natural regeneration (seedlings and saplings) two years after harvest in the logged-over mangrove area of Bintuni Bay, West Papua, Indonesia.

The density of stocking after selective logging in Bintuni Bay (2,500 stem ha^{-1}) is lower compared to density in the MMFR on the initial stocking after the clear cut that uses 1.2 m x 1.2 m for *R. apiculata* (6,944 stem ha^{-1}) and 1.8 m x 1.8 m for *R. mucronata* (3,086 stem ha^{-1}) (Goessens et al. 2014). Young stand vegetation in the MMFR that survived after natural selection (Cannicci et al. 2008) does not have sufficient space to grow and develop due to the high initial stocking density. Therefore, two periods of thinning during one rotation cycle have a significant impact on providing adequate space for secondary forests in the MMFR so that DBH increment and biomass can be optimized (Gong and Ong 1995). DBH at the end of a 30-year cycle in mangrove stands of the MMFR after two thinning is in the range of 15.0–22.5 cm (Goessens et al. 2014). While according to this study, DBH in a 30-year-old stand on Bintuni Bay was in the range of 14.76–24.11 cm. In Indonesia, artificial thinning in managed mangrove forests is allowed by the Government regulation (MoA RI 1978) between stand ages of 15 to 20 years, although the first rotation cycle in Bintuni Bay was completed without artificial thinning. Even though artificial thinning was not implemented in Bintuni Bay, the range of diameter at the same stand age (30-year-old) at the end of one rotation cycle is similar to the MMFR mangrove stands. Thus, the density of initial stocking in Bintuni Bay (2 m x 2 m) seems suitable to accommodate the growth of mangrove stands for production purposes without artificial thinning.

The purpose of mangrove utilization in the MMFR is to produce charcoal products so that trees with diameters below 10 cm can still be used through artificial thinning to obtain additional economic value and optimally use the standing stock before it is lost to natural thinning (Gong and Ong 1995). While in Bintuni Bay, mangroves are harvested to produce wood chips, and the minimum diameter that can be utilized is 10 cm (MoF RI 2007). This study showed that mangroves that grow from initial stocking in Bintuni Bay would achieve a diameter of 10 cm around 18 years stand age. If the FME implemented artificial thinning, the appropriate time would be in 18- to 20-year-old stands to compromise with the Government regulation. However, thinning in Bintuni Bay is not a priority because primary forests are still widely available for utilization (MoEF RI 2019a). In addition, the results of this study also show that even without artificial thinning, standing stock at the end of the first 30-year rotation cycle is sufficient to be harvested for the next cycle. Current regulation from the Government has accommodated clear-cut harvest method with artificial regeneration in the silviculture system of mangrove forests (MoEF RI 2016). According to the results of this study with comparison to the implementation of silvicultural practices in the MMFR Malaysia, the spacing distance of 2 m x 2 m (density of 2,500 seedlings ha^{-1}) seems appropriate to be implemented in an initial stocking if the clear cut method is used in Bintuni Bay instead of parent trees method.

3.2.3. Biodiversity conservation

R. apiculata was the most dominant in secondary forests, covering 89.78% of total species composition, which correlated with low biodiversity in the tree stratum (**Fig. 5**, **Fig. 6**). It can be explained as follows; (1) *R. apiculata* naturally is the most dominant species in primary mangrove forests of Bintuni Bay (Sasmito et al. 2020; Sillanpää et al. 2017; Yudha et al. 2021), (2) growth rate of *R. apiculata* is the highest compared to other dominant species in Bintuni Bay (Yudha 2021), (3) 63.06% of natural regeneration (seedlings and saplings) and 71.47% of the parent trees that available in the logged-over area are *R. apiculata* (PT. BUMWI 2016) and (4) more than 95% of seedlings used for afforestation in the concession area, according to data recorded over the last 10 years, are *R. apiculata* (PT. BUMWI, unpublished data). In MMFR Malaysia, species beside Rhizophora are cleared from the stands during artificial thinning at the age of 15 and 20 years. Species composition at the end of the 30-year cycle is expected to become a homogenous stand of Rhizophora (Goessens et al. 2014). In Bintuni Bay, all dominant species that appear in secondary forests can still be used for timber utilization. Therefore, the opportunity for forestry engineering to make species composition in secondary forests closer to primary forests is wide open to be applied in terms of silvicultural system implementation.

Timber cruising, which is carried out two years before logging (MoA RI 1978; MoEF RI 2016), can provide comprehensive data on the species composition in a block of primary forest. This data then can be used as a reference for afforestation post-logging so that species composition planted in the logged-over area could resemble the composition of species prior to logging. About 93% of species composition in primary mangrove forests of Bintuni Bay only consists of 5 dominant species (Yudha et al. 2021), with the variation of percentages amongst area and zonation (**Table 3**). Since mangroves are naturally given as poor biodiversity-ecosystem (Saenger 2002), the determination of species for afforestation should be focused on these 5 species according to percentages of species composition obtained from timber cruising activities in each compartment and block. If this is accommodated as part of silviculture system implementation, species composition at the end of the second rotation cycle as a result of afforestation in logged-over areas could be expected to become more diverse secondary forests without being entirely dominated by *R. apiculata*. Furthermore, the secondary forests will become more ecologically resilient from perturbation (Bosire et al. 2006) and could become habitats that offer more various niches to attract fauna from various taxa (Bosire et al. 2008; Nagelkerken et al. 2008).

Table 3. Species composition in primary mangrove forests of Bintuni Bay, West Papua, Indonesia, according to various surveys and reports

No.	Sampling design		Species composition (%)						References*
	Method	Sample size (ha)	RA	BP	BG	RM	CT	Others	
1	Quadrat plot	23.76	46.16	27.59	8.34	8.81	2.74	6.36	Yudha et al. 2021
2	Continuous strip	74.65	62.24	14.85	13.02	3.41	5.09	1.39	PT. BUMWI 2020
3	Circle plot	0.06	32.72	14.71	9.19	8.46	30.88	4.04	Sasmito et al. 2020
4	Circle plot	0.09	41.93	12.79	6.71	21.59	14.47	2.51	Sillanpää et al. 2017

Notes: * Measurement of vegetation in No. 1 and 2 was conducted for trees with DBH ≥ 10 cm, while No. 3 and 4 for DBH ≥ 5 cm; RA: *R. apiculata*, BP: *B. parviflora*, BG: *B. gymnorhiza*, RM: *R. mucronata*, CT: *C. tagal*.

3.2.4. Extended rotation cycle

The unique fact about the utilization of mangrove forests in Bintuni Bay, which ecologically contributes to the conservation of wildlife habitat and economically ensures maximum increment of the stands, is regarding the extended rotation cycle. Even though the rotation cycle for harvesting is a 30-year cycle, the actual cycle of utilization in secondary forests will be carried out on a 60-year cycle. The area of mangroves that can be harvested (hereafter referred to as production zone) after respecting buffer zones and High Conservation Value Forests is approximately 1,658.28 ha year^{-1} with a total production zone that can be utilized for a 30-year cycle of 49,748.45 ha (MoEF RI 2021b). Meanwhile, the harvested area within the production zone for the first rotation cycle (30 years, 1988–2017) was 18,458.42 ha or 615 ha year^{-1} (Teo and Sillanpää 2019). The total harvested area for the last 3 years (2018–2020) was 807.33 ha (269 ha year^{-1}), with the extracted volume of 257,262.68 m^3 (318.65 m^3 ha^{-1} year^{-1}) (MoEF RI 2021a). Harvested areas have been declining over the last few years due to the limitation of worker availability, as well as the global effect of the COVID-19 pandemic. During the first 30-year cycle, harvesting activities from felling, debarking, and skidding were conducted manually by humans instead of heavy equipment. Therefore, mechanization in harvesting activities must be implemented to optimize timber products from mangrove forests utilization in Bintuni Bay, with maximum efforts to minimize the environmental impacts from mechanization (PT. BUMWI 2021).

The maximum capacity that is allowed by the MoF RI (2005a) for the wood industry owned by the FME to process mangrove logs into wood chips is 193,536 m^3 year^{-1} (volume without bark). If this volume is converted to standing trees volume with a bark portion of 13.32% from total standing volume (Tantra et al. 2019) and waste ratio of 13% (PT. BUMWI, unpublished data), then volume allowance to be harvested from the forests is 262,671 m^3 year^{-1}. If the standing volume of primary forest is 393.82 m^3 ha^{-1} (Yudha et al. 2021), then the total area which is needed for harvesting to fulfill the maximum capacity of the FME's industry is around 667 ha year^{-1}. Important to be underlined that the mean volume of primary forests varies among areas, but most studies and surveys in Bintuni Bay so far have shown the volume of primary forest around 400 m^3 ha^{-1} (PT. BUMWI 2020; Sillanpää et al. 2017; Yudha et al. 2021). By using the estimated harvest area above (667 ha year^{-1}) or the average harvested area in the first 30-year cycle of 615 ha year^{-1} (Teo and Sillanpää 2019), the total mangrove area that was harvested during the first rotation cycle was around 37–40% from the production zone. Thus, the logged-over area in the first cycle, which has recovered to be second-growth forest ready for harvest, will not be harvested in the second cycle because the primary forest is still available for utilization. To optimize the sustainability of forest products, primary forest is a priority for utilization (MoEF RI 2015). Therefore, secondary mangrove forests of Bintuni Bay, as results from harvesting in the first cycle, still have an opportunity to grow approaching the structure and composition of primary mangrove forests (Luo et al. 2010; Sillanpää et al. 2017).

Ministry of Environment and Forestry, the Republic of Indonesia, has officially introduced silvicultural intensification or *Silvikultur Intensif* (SILIN) since 2005 that aims to increase the productivity of timber forest products from natural forests (MoF RI 2005b; MoEF RI 2019b; c). This silvicultural intensification could result in remarkably progressive yield from natural forests (Pamoengkas and Prasetia 2014; Ruslandi et al. 2017; Wahyudi 2016) so that utilization of natural forests in Indonesia would be expected to provide maximum output for the national and global wood industry. Even though the silvicultural practices are not adopting SILIN, the progressive yield from mangrove forests in Bintuni Bay can be obtained by providing longer growth opportunities in secondary forests. Mangrove forests that are harvested in year one will be harvested again in year 61 (the third rotation) due to a low harvest rate of the first rotation cycle, and standing stock in the primary forest is still available for utilization in the second rotation. Therefore, a 30-year rotation cycle is appropriate for mangrove utilization in Bintuni Bay since the forests are only half harvested in one cycle, and the other half can still grow to maximize incremental growth to obtain a progressive yield from the stands while providing extension time for soil nutrients and sediment to recovery approaching pre-disturbance condition (Sillanpää et al. 2021). Unharvested mangroves on each annual block have a significant function as the source of propagules for natural seedlings recruitment in logged-over areas; thus, ecosystem productivity and stability could be increased (Bosire et al. 2003, 2006). The large extent of unharvested stands because of a low harvest rate each year also has an important function as a conservation reserve and refugee habitat for wildlife surrounding logged-over areas so the biodiversity of flora and fauna in managed mangrove forests can be optimally conserved (Yudha et al. 2021).

4. Conclusions

Mangrove forests are renewable resources that could be utilized sustainably with responsible forestry, while silvicultural practices in managed mangrove forests play a significant role in ensuring regeneration post-harvesting. At the end of the first rotation cycle (30-year-old stand), secondary mangrove forests of Bintuni Bay could provide volume and potential extractable biomass of 290.12 m^3 ha^{-1} and 203.03 ton ha^{-1}, respectively as a standing stock for the next rotation cycle. This standing stock even still has an opportunity to attain the structure and composition of primary forest since the FME will not harvest it yet due to the availability of primary forest for utilization in the second rotation cycle; thus, secondary forests could become more ecologically resilient forests. Unharvested mangroves during the first 30-year cycle are larger than the harvested area due to the low annual harvest rate, which contributed to supporting natural regeneration in logged-over areas and becoming refugee habitat for wildlife so that the biodiversity can be maintained. Results from pre-harvesting surveys (timber cruising) on forest standing stock and native species composition could become the reference for species determination in afforestation post-harvesting; thus, biodiversity of mangroves in secondary forests could be improved and resemble pre-disturbance condition although other species seem difficult to compete with the domination of *R. apiculata*. After primary mangrove forests in the production zone are completely harvested, utilization of secondary mangrove forests in Bintuni Bay on the third rotation cycle and forward is the utilization of renewable natural resources. With science- and rule-based management, managed mangrove of Bintuni Bay could resemble the success story of managed mangrove in the MMFR, Malaysia in sustaining the production function of mangrove forests and even have a greater opportunity to maintain the ecological function of the system with appropriate sustainable management. Future challenges in the area are to implement a clear-cut harvesting method sustainably with environmentally friendly mechanization, so the utilization of mangrove forests could be economically beneficial, socially responsible, and ecologically acceptable as has been carried out for more than three decades in Bintuni Bay.

Acknowledgments

The authors would like to thank Muhammad Santoso, Triyanto, Maximilianus Klau, and Saeful Muchtarom with all their team members for assistance in field work activity; they are among the best Mangrove Forester.

References

Adame, M. F., Zakaria, R. M., Fry, B., Chong, V. C., Then, Y. H. A., Brown, C. J., and Lee, S. Y. 2018. Loss and Recovery of Carbon and Nitrogen after Mangrove Clearing. *Ocean and Coastal Management* 161: 117-126. DOI: 10.1016/j.ocecoaman.2018.04.019

Ahmed, I., Jangsawang, W., and Gupta, A. K. 2012. Energy Recovery from Pyrolysis and Gasification of Mangrove. *Applied Energy* 91: 173-179. DOI: 10.1016/j.apenergy.2011.08.028

Aksornkoae, S. 1993. *Ecology and Management of Mangroves*. IUCN, Thailand.

Alongi, D. M. 2014. Carbon Cycling and Storage in Mangrove Forests. *Annual Review of Marine Science* 6: 195-219. DOI: 10.1146/annurev-marine-010213-135020

Atheull, A. N., Din, N., Longonje, S. N., Koedam, N., and Dahdouh-Guebas, F. 2009. Commercial Activities and Subsistence Utilization of Mangrove Forests around the Wouri Estuary and the Douala-Edea Reserve (Cameroon). *Journal of Ethnobiology and Ethnomedicine* 5: 35. DOI: 10.1186/1746-4269-5-35

Bosire, J. O., Dahdouh-Guebas, F., Kairo, J. G., and Koedam, N. 2003. Colonization of Non-Planted Mangrove Species into Restored Mangrove Stands in Gazi Bay, Kenya. *Aquatic Botany* 76: 267-279. DOI: 10.1016/s0304-3770(03)00054-8

Bosire, J. O., Dahdouh-Guebas F., Kairo, J. G., Wartel, S., Kazungu, J., and Koedam, N. 2006. Success Rates of Recruited Tree Species and Their Contribution to the Structural Development of Reforested Mangrove Stands. *Marine Ecology Progress Series* 325: 85-91. DOI: 10.3354/meps325085

Bosire, J. O., Dahdouh-Guebas, F., Walton, M., Crona, B. I., Lewis III, R. R., Field, C., Kairo, J. G., and Koedam, N. 2008. Functionality of Restored Mangroves: A Review. *Aquatic Botany* 89: 251-259. DOI: 10.1016/j.aquabot.2008.03.010

Cannicci, S., Burrows, D., Fratini, S., Smith, T. J. III, Offenberg, J., and Dahdouh-Guebas, F. 2008. Faunistic Impact on Vegetation Structure and Ecosystem Function in Mangrove Forests: A Review. *Aquatic Botany* 89: 186-200. DOI: 10.1016/j.aquabot.2008.01.009

Carter, H. N., Schmidt, S. W., and Hirons, A. C. 2015. An International Assessment of Mangrove Management: Incorporation in Integrated Coastal Zone Management. *Diversity* 7: 74-104. DOI: 10.3390/d7020074

Dahdouh-Guebas, F., Koedam, N., Satyanarayana, B., and Cannicci, S. 2011. Human Hydrographical Changes Interact with Propagule Predation Behaviour in Sri Lankan Mangrove Forests. *Journal of Experimental Marine Biology and Ecology* 399: 188-200. DOI: 10.1016/j.jembe.2010.11.012

Deshar, R., Sharma, S., Hoque, A. T. M. R., Mouctara, K., and Hagihara, A. 2012. Self-Thinning of Leaf, Wood and Above-Ground in Overcrowded Mangrove *Bruguiera gymnorhiza* Stands in Okinawa Island, Japan. *Procedia Environmental Sciences* 13: 982-993. DOI: 10.1016/j.proenv.2012.01.091

Erftemeijer, P., Alien, G., Zuwendra, and Kosamah, S. 1991. Birds of the Bintuni Bay Region, Irian Jaya. *KUKILA* 5 (2): 85-98.

Feka, Z. N., and Morrison, I. 2017. Managing Mangroves for Coastal Ecosystems Change: A Decade and Beyond of Conservation Experiences and Lessons for and from West-Central Africa. *Journal of Ecology and The Natural Environment* 9 (6): 99-123. DOI: 10.5897/jene2017.0636

Friess, D. A., Krauss, K. W., Taillardat, P., Adame, M. F., Yando, E. S., Cameron, C., Sasmito, S. D., and Sillanpää, M. 2020. Mangrove Blue Carbon in the Face of Deforestation, Climate Change, and Restoration. *Annual Plant Reviews* 3: 427-456. DOI: 10.1002/9781119312994.apr0752

FSC. 2020. *FSC-STD-IDN-02-2020: The FSC National Forest Stewardship Standard of Indonesia*. FSC (Forest Stewardship Council) International Centre, Bonn.

Gaveau, D. L. A., Santos, L., Locatelli, B., Salim, M. A., Husnayaen, H., Meijaard, E., Heatubun, C., and Sheil, D. 2021. Forest Loss in Indonesian New Guinea: Trends, Drivers, and Outlook. *BioRxiv* 2021. DOI: 10.1101/2021.02.13.431006

Giesen, W., Wulffraat, S., Zieren, M., and Scholten, L. 2007. *Mangrove Guidebook for South East Asia*. FAO and Wetlands International, Thailand.

Goessens, A., Satyanarayana, B., Van der Stocken, T., Zuniga, M. Q., Mohd-Lokman, H., Sulong, I., and Dahdouh-Guebas, F. 2014. Is Matang Forest in Malaysia Sustainably Rejuvenating after more than a Century of Conservation and Harvesting Management? *PLoS ONE* 9(8): e105069. DOI: 10.1371/journal.pone.0105069

Gong W. K., and Ong, J. E. 1995. The Use of Demographic Studies in Mangrove Silviculture. *Hydrobiologia* 295: 255-261. DOI: 10.1007/BF00029132

Hamilton, S. E., and Casey, D. 2016. Creation of a High Spatio-Temporal Resolution Global Database of Continuous Mangrove Forest Cover for the 21st Century (CGMFC-21). *Global Ecology and Biogeography* 25: 729-738. DOI: 10.1111/geb.12449

Haron, H. A. H. 1981. *A Working Plan for the Second 30 Year Rotation of the Matang Mangrove Forest Reserve*. Perak State Forestry Department, Ipoh, Malaysia.

Herr, D., and Landis, E. 2016. *Coastal Blue Carbon Ecosystems. Opportunities for Nationally Determined Contributions. Policy Brief*. IUCN, Gland and TNC, Washington.

IDEAS Consultancy Services. 2015. *Identification of High Conservation Value Area in PT. BUMWI, Bintuni Bay, West Papua*. IDEAS Consultancy Services, Bogor.

Ilman, M., Dargusch, P., and Dart, P. 2016. A Historical Analysis of the Drivers of Loss and Degradation of Indonesia's Mangroves. *Land Use Policy* 54: 448-459. DOI: 10.1002/9781119312994.apr0752

IUCN. 2020. *The IUCN Red List of Threatened Species Version 2020-2*. <http://www.iucnredlist.org> (Aug. 1, 2020).

Jusoff, K., and Taha, D. H. 2008. Managing Sustainable Mangrove Forests in Peninsular Malaysia. *Journal of Sustainable Development* 1(1): 88-96. DOI: 10.5539/jsd.v1n1p88

Kairo, J. G., Dahdouh-Guebas, F., Gwada, P. O., Ochieng, C., and Koedam, N. 2002. Regeneration Status of Mangrove Forests in Mida Creek, Kenya: A Compromised or Secured Future? *Ambio* 31: 7-8. DOI: 10.1639/0044-7447(2002)031[0562:rsomfi]2.0.co;2

Kairo, J. G., Lang'at, J. K. S., Dahdouh-Guebas, F., Bosire, J., and Karachi, M. 2008. Structural Development and Productivity of Replanted Mangrove Plantations in Kenya. *Forest Ecology and Management* 255: 2670-2677. DOI: 10.1016/j.foreco.2008.01.031

Krauss, K. W., Demopoulos, A. W., Cormier, N., et al. 2018. Ghost Forests of Marco Island: Mangrove Mortality driven by Belowground Soil Structural Shifts during Tidal Hydrological Alteration. *Estuarine, Coastal and Shelf Science* 212: 51-62. DOI: 10.1016/j.ecss.2018.06.026

Locatelli, T., Binet, T., Kairo, J. G., et al. 2014. Turning the Tide: How Blue Carbon and Payments for Ecosystem Services (PES) Might Help Save Mangrove Forests. *Ambio* 43(8): 981-995. DOI: 10.1007/s13280-014-0530-y

Luo, Z., Sun, O. J., Xu, H. 2010. A Comparison of Species Composition and Stand Structure between Planted and Natural Mangrove Forests in Shenzhen Bay, South China. *Journal of Plant Ecology* 3(3): 165-174. DOI: 10.1093/jpe/rtq004

MoA RI (Ministry of Agriculture, Republic of Indonesia). 1978. Surat Keputusan Direktur Jenderal Kehutanan No. 60/Kpts/DJ/I/1978: *Pedoman Sistem Silvikultur Hutan Payau*. Ministry of Agriculture, Republic of Indonesia, Jakarta.

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2015. Peraturan Direktur Jenderal PHPL No. P.8/PHPL-UHP/2015: *Petunjuk Teknis Inventarisasi Hutan Menyeluruh Berkala (IHMB) Pada Usaha Pemanfaatan Hasil Hutan Kayu Pada Hutan Alam Dan Hutan Tanaman Industri Dalam Hutan Produksi*. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta.

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2016. Peraturan Direktur Jenderal PHPL No. P.8/PHPL/SET/3/2016: *Pedoman Sistem Silvikultur Hutan Payau*. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta.

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2018. Peraturan Menteri Lingkungan Hidup dan Kehutanan No. P.106/MenLHK/SETJEN/KUM.1/12/2018: *Jenis Tumbuhan dan Satwa yang Dilindungi*. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta.

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2019a. Surat Direktur Inventarisasi dan Pemantauan Sumber Daya Hutan No. S.372/IPSDH/PSDH/PLA.1/7/2019: *Hasil Pemeriksaan Peta Penafsiran Citra Satelit Areal Kerja IUPHHK-HA PT. Bintuni Utama Murni Wood Industries*. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta.

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2019b. *Tingkatkan Produktivitas Hutan Alam dengan Silvikultur Intensif* (SILIN). <https://www.forda-mof.org/index.php/berita/post/5677-tingkatkan-produktivitas-hutan-alam-dengan-silvikultur-intensif-silin> (Feb. 26, 2021).

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2019c. *Silvikultur Intensif Hutan Alam Menuju 100 Tahun Kemerdekaan Indonesia*. <https://www.ppid.menlhk.go.id/siaran_pers/browse/2152> (Feb. 26, 2021).

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2020a. Keputusan Direktur Jenderal PHPL No. SK.62/PHPL/SET.5/KUM.1/12/2020: *Pedoman, Standar dan/atau Tata Cara Penilaian Kinerja Pengelolaan Hutan Produksi Lestari, Verifikasi Legalitas Kayu, Uji Kelayakan dan Penerbitan Deklarasi Kesesuaian Pemasok, serta Penerbitan Dokumen V-Legal/Lisensi FLEGT*. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta.

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2020b. *Vademecum Kehutanan Indonesia*. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta.

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2021a. *E-Monev Kinerja PHA Direktorat Usaha Hutan Produksi*. <http://monevkinerjapha.dephut.go.id/kemenhut/index.php/iuphhk/realisasi> (Mar. 12, 2021).

MoEF RI (Ministry of Environment and Forestry, Republic of Indonesia). 2021b. Keputusan Menteri Lingkungan Hidup dan Kehutanan No. 268/MenLHK-PHPL/UHP/HPL.1/1/2021: *Persetujuan Rencana Kerja Usaha Pemanfaatan Hasil Hutan Kayu dalam Hutan Alam pada Hutan Produksi Periode Tahun 2021-2030 Atas Nama PT. Bintuni Utama Murni Wood Industries Provinsi Papua Barat*. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta.

MoF RI (Ministry of Forestry, Republic of Indonesia). 2005a. Keputusan Menteri Kehutanan No. SK.4010/Menhut-VI/BPPHH/2005: *Pembaharuan Izin Usaha Industri Primer Hasil Hutan Kayu Atas Nama PT. Bintuni Utama Murni Wood Industries di Provinsi Irian Jaya Barat*. Ministry of Forestry, Republic of Indonesia, Jakarta.

MoF RI (Ministry of Forestry, Republic of Indonesia). 2005b. Keputusan Direktur Jenderal Bina Produksi Kehutanan No. 226/VI-BPHA/2005: *Pedoman Tebang Pilih Tanam Indonesia Intensif/TPTII (Silvikultur Intensif)*. Ministry of Forestry, Republic of Indonesia, Jakarta.

MoF RI (Ministry of Forestry, Republic of Indonesia). 2007. Keputusan Menteri Kehutanan No. SK.213/Menhut-II/2007: *Perpanjangan Izin Usaha Pemanfaatan Hasil Hutan Kayu Dalam Hutan Alam PT. Bintuni Utama Murni Wood Industries Atas Areal Hutan Produksi Seluas ± 82.120 Ha di Provinsi Irian Jaya Barat*. Ministry of Forestry, Republic of Indonesia, Jakarta.

MoF RI (Ministry of Forestry, Republic of Indonesia). 2011. Surat Edaran Direktur Jenderal Bina Usaha Kehutanan No. SE.10/VI-BUHA/2011: *Riap Diameter Tahunan Pada Hutan Alam Produksi*. Ministry of Forestry, Republic of Indonesia, Jakarta.

MoF RI (Ministry of Forestry, Republic of Indonesia). 2014a. Peraturan Menteri Kehutanan No. P.33/Menhut-II/2014: *Inventarisasi Hutan Menyeluruh Berkala dan Rencana Kerja Pada Izin Usaha Pemanfaatan Hasil Hutan Kayu Dalam Hutan Alam*. Ministry of Forestry, Republic of Indonesia, Jakarta.

MoF RI (Ministry of Forestry, Republic of Indonesia). 2014b. Keputusan Menteri Kehutanan No. SK.783/Menhut-II/2014: *Kawasan Hutan dan Konservasi Perairan Provinsi Papua Barat*. Ministry of Forestry, Republic of Indonesia, Jakarta.

Murdiyarso, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., Donato, D. C., Manuri, S., Krisnawati, H., Taberima, S., and Kurnianto, S. 2015. The Potential of Indonesian Mangrove Forests for Global Climate Change Mitigation. *Nature Climate Change* 5(12): 1089-1092. DOI: 10.1038/nclimate2734

Murdiyarso, D., Sukara, E., Supriatna, J., Koropitan, A., Mumbunan, S., Juliandi, B., and Jompa, J. 2018. *Creating Blue Carbon Opportunities in the Maritime Archipelago Indonesia*. CIFOR Policy Brief No. 3, November 2018. DOI: 10.17528/cifor/007058

Murdiyarso, D., Sasmito, S., Sillanpää, M., MacKenzie, R., and Gaveau, D. 2021. Mangrove Selective Logging Sustains Biomass Carbon Recovery, Soil Carbon, and Sediment. *Scientific Reports* 11: 12325. DOI: 10.1038/s41598-021-91502-x

Nagelkerken, I., Blaber, S. J. M., Bouillon, S., Green, P., Haywood, M., Kirton, L. G., Meynecke, J. O., Pawlik, J., Penrose, H. M., Sasekumar, A., and Somerfield, P. J. 2008. The Habitat Function of Mangroves for Terrestrial and Marine Fauna: A Review. *Aquatic Botany* 89: 155-185. DOI: 10.1016/j.aquabot.2007.12.007

Nam, V. N., Sasmito, S. D., Murdiyarso, D., Purbopuspito, J., and MacKenzie, R. A. 2016. Carbon Stocks in Artificially and Naturally Regenerated Mangrove Ecosystems in the Mekong Delta. *Wetlands Ecology and Management* 24: 231-244. DOI: 10.1007/s1127 3-015-9479-2

Noor, Y. R., Khazali, M., and Suryadiputra, I. N. N. 1999. *Panduan Pengenalan Mangrove di Indonesia.* Direktorat Jenderal Perlindungan dan Konservasi Alam/Wetlands International - Indonesia Programme, Bogor.

Pamoengkas, P., and Prasetia, R. 2014. Pertumbuhan Meranti Merah (*Shorea leprosula* Miq) Dalam Sistem Tebang Pilih Tanam Jalur di Areal IUPHHK-HA PT. Sarpatim, Kalimantan Tengah. *Jurnal Silvikultur Tropika* 5(3): 174-180.

Polidoro B. A., Carpenter K. E., Collins L., et al. 2010. The Loss of Species: Mangrove Extinction Risk and Geographic Areas of Global Concern. *PLoS ONE* 5(4): e10095. DOI: 10.1371/journal.pone.0010095

Pranchai, A. 2017. Regeneration and Self-Thinning Processes in a Restored *Rhizophora apiculata* Plantation in Southern Thailand. *Agriculture and Natural Resources* 51: 390-394. DOI: 10.1016/j.anres.2017.11.004

Pribadi, R. 1998. *The Ecology of Mangrove Vegetation in Bintuni Bay, Irian Jaya, Indonesia*. Ph.D. thesis, University of Stirling.

Pribadi, R., Muhajir, A., Widianingsih, and Hartati, R., 2014. Pemangsaan Propagul Mangrove Rhizophora sp. Sebagai Bukti Teori Dominance-Predation. *Ilmu Kelautan* 19 (2): 105-112.

PT. BUMWI. 2011. *Management Plan for Forest Utilization, Year of 2011-2020*. PT. BUMWI (PT. Bintuni Utama Murni Wood Industries), Jakarta.

PT. BUMWI. 2016. *Post-Harvest Forest Inventory Report, Block of 2010-2014*. PT. BUMWI (PT. Bintuni Utama Murni Wood Industries), Jakarta.

PT. BUMWI. 2020. *Timber Cruising Report, Block of 2022*. PT. BUMWI (PT. Bintuni Utama Murni Wood Industries), Jakarta.

PT. BUMWI. 2021. *Management Plan for Forest Utilization, Year of 2021-2030*. PT. BUMWI (PT. Bintuni Utama Murni Wood Industries), Jakarta.

Richards, D. R., and Friess, D. A. 2016. Rates and Drivers of Mangrove Deforestation in Southeast Asia, 2000–2012. *Proceedings of the National Academy of Sciences of the United States of America* 113: 344-349. DOI: 10.1073/pnas.1510272113

Romañach, S. S., DeAngelis, D. L., Koh, H. L., Li, Y., Teh, S. Y., Barizan, R. S. R., and Zhai, L. 2018. Conservation and Restoration of Mangroves: Global Status, Perspectives, and Prognosis. *Ocean and Coastal Management* 154: 72-82. DOI: 10.1016/j.ocecoaman.2018.01.009

Rovai, A. S., Soriano-Sierra, E. J., Pagliosa, P. R., Cintron, G., Schaeffer-Novelli, Y., Menghini, R. P., Coelho-Jr, C., Horta, P. A., Lewis III, R. R., Simonassi, J. C., Alves, J. A. A., Boscatto, F., and Dutra, S. J. 2012. Secondary Succession Impairment in Restored Mangroves. *Wetlands Ecology and Management* 20: 447-459. DOI: 10.1007/s11273-012-9269-z

Rovai, A. S., Twilley, R. R., Castañeda-Moya, E., et al. 2021. Macroecological Patterns of forest Structure and Allometric Scaling in Mangrove Forests. *Global Ecology and Biogeography* 00: 1-14. DOI: 10.1111/geb.13268

Ruitenbeek, H. J. 1992. *Mangrove Management: An Economic Analysis of Management Options with a Focus on Bintuni Bay, Irian Jaya*. EMDI Environmental Reports, 8. Dalhousie University Printing Centre, Canada.

Ruslandi, Cropper, W. P., and Putz, F. E., 2017. Effects of Silvicultural Intensification on Timber Yields, Carbon Dynamics, and Tree Species Composition in a Dipterocarp Forest in Kalimantan, Indonesia: An Individual-Tree-Based Model Simulation. *Forest Ecology and Management* 390: 104-118. DOI: 10.1016/j.foreco.2017.01.019

Saenger, P., 2002. *Mangrove Ecology, Silviculture and Conservation*. Springer, Dordrecht.

Salem, M. E., and Mercer, D. E. 2012. The Economic Value of Mangroves: A Meta-Analysis. *Sustainability* 4: 359-383. DOI: 10.3390/su4030359

Sasmito, S. D., Sillanpää, M., Hayes, M. A., Bachri, S., Saragi-Sasmito, M. F., Sidik, F., Hanggara, B. B., Mofu, W. Y., Rumbiak, V. I., Hendri, Taberima, S., Suhaemi, Nugroho, J. D., Pattiasina, T. F., Widagti, N., Barakalla, Rahajoe, J. S., Hartantri, H., Nikijuluw, V., Jowey, R. N., Heatubun, C. D., zu Ermgassen, P., Worthington, T. A., Howard, J., Lovelock, C. E., Friess, D. A., Hutley, L. B., and Murdiyarso, D. 2020. Mangrove Blue Carbon Stocks and Dynamics are Controlled by Hydrogeomorphic Settings and Land-Use Change. *Global Change Biology* 26(5): 3028–3039. DOI: 10.1111/gcb.15056

Sathe, S. S., Lavate, R. A., and Bhosale, L. J. 2013. Mangrove as Source of Energy for Rural Development with Special Reference to Ratnagiri and Sindhudarg District (MS) India. *Bioscience Discovery* 4(2): 198-201.

Sillanpää, M., Vantellingen, J., and Friess, D. A. 2017. Vegetation Regeneration in a Sustainably Harvested Mangrove Forest in West Papua, Indonesia. *Forest Ecology and Management* 390: 137-146. DOI: 10.1016/j.foreco.2017.01.022

Sillanpää, M., Lupascu, W., Yudha, R. P., Sasmito, S. D., Vulpas, S., and Teo, R. X. 2021. *Impacts of Forestry on Mangrove Sediment Dynamics.* In: Sidik, F., and Friess, D. A., (Eds.), Dynamic Sedimentary Environments of Mangrove Coasts. Elsevier, Amsterdam, pp. 583-607.

Simon, H. 2010. *Perencanaan Pembangunan Sumber Daya Hutan, Timber Management, Jilid 1A*. Pustaka Pelajar, Yogyakarta.

Spalding, M. D., and Leal, M. 2021. The State of the World's Mangroves 2021. Global Mangrove Alliance.

Suharti, S., Darusman, D., Nugroho, B., and Sundawati, L. 2016. Economic Valuation as a Basis for Sustainable Mangrove Resource Management a Case in East Sinjai, South Sulawesi. *Jurnal Manajemen Hutan Tropika* 22(3): 13-23. DOI: 10.7226/jtfm.22.1.13

Tantra, M., Sillanpää, M., and Teo, R. X. 2019. *Revisiting Mangrove Allometry for the Purpose of Sustainable Forest Management in West Papua, Indonesia*. Oral Presentation. The 5th International Mangrove, Macrobenthos and Management Meeting, Singapore.

Teo, R. X., and Sillanpää, M. 2019. *Report I – Developing a Remote Sensing Method to Delineate Harvest Area for the 2021-2030 RKU (Rencana Kerja Usaha)*. Green Forest Product & Tech. Pte. Ltd., Singapore.

Thongjoo, C., Choosak, S., and Chaichana, R. 2018. Soil Fertility Improvement from Commercial Monospecific Mangrove Forests (*Rhizophora apiculata*) at Yeesarn Village, Samut Songkram Province, Thailand. *Tropical Ecology* 59(1): 91-97.

UNEP. 2014. *The Importance of Mangroves to People: A Call to Action*. UNEP (United Nations Environment Programme) World Conservation Monitoring Centre, Cambridge.

Van Nedervelde, F., Cannicci, S., Koedam, N., Dahdouh-Guebas, F., and Bosire, J. 2015. What Regulates Crab Predation on Mangrove Propagules? *Acta Oecologica* 63: 63-70. DOI: 10.1016/j.actao.2014.11.006

Vo, Q. T., Vo, Q. M., Moder, F., and Oppelt, N. 2012. Review of Valuation Methods for Mangrove Ecosystem Services. *Ecological Indicators* 23: 431-446. DOI: 10.1016/j.ecolind.2012.04.022

Wahyudi, Tokede, M. J., Mardiyadi, Z., Tampang, A., and Mahmud. 2014. Customary Right Compensation and Forest Villages Development Programs of Mangrove Company at Bintuni Bay Papua Barat. *Jurnal Manajemen Hutan Tropika* 20(3): 187-194. DOI: 10.7226/jtfm.20.3.187

Wahyudi. 2016. *Kebangkitan Kehutanan Indonesia.* Isana Press, Bogor.

Wahyudi. 2019. *Pemanfaatan dan Pengelolaan Sumberdaya Mangrove di Teluk Bintuni, Papua Barat.* Percetakan Pohon Cahaya, Yogyakarta.

Walters, B. B., Ronnback, P., Kovacs, J. M., Crona, B., Hussain, S. A., Badola, R., Primavera, J. H., Barbier, E., and Dahdouh-Guebas, F. 2008. Ethnobiology, Socio-Economics and Management of Mangrove Forests: A Review. *Aquatic Botany* 89: 220-236. DOI: 10.1016/j.aquabot.2008.02.009

Wylie, L., Sutton-Grier, A. E., and Moore, A. 2016. Keys to Successful Blue Carbon Projects: Lessons Learned from Global Case Studies. *Marine Policy* 65: 76-84. DOI: 10.1016/j.marpol.2015.12.020

Yudha, R. P. 2021. Forest Structure of 26-Year-Old Planted Mangroves. *Journal of Sylva Indonesiana* 4(2): 61-69. DOI: 10.32734/jsi.v4i02.5680

Yudha, R. P., Sugito, Y. S., Sillanpää, M., and Nurvianto, S. 2021. Impact of Logging on the Biodiversity and Composition of Flora and Fauna in the Mangrove Forests of Bintuni Bay, West Papua, Indonesia. *Forest Ecology and Management* 488: 119038. DOI: 10.1016/j.foreco.2021.119038