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Research Article

The status and diversity of mangroves on the south coast of Papua Island, Indonesia, and a strategy for sustainable mangrove management

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ABSTRACT

The south coast of Papua Island, Indonesia, has one of the largest mangrove areas in the world, comprising an estimated total of 1,267,449 ha stretching from Sorong Regency in West Papua Province to Merauke Regency in Papua Province. Based on the review, the sedimentation rate, total organic carbon, and carbon storage in this area are high compared to other mangrove forests across the world. The sedimentation rates exceed the current rate of relative sea-level rise. Concerning the diversity of mangrove vegetation, 43 plant species from 27 major components and 16 minor components and belonging to 17 families have been recorded. The most common and dominant species in the area are *Rhizophora apiculata* and *Bruguiera gymnorrhiza*, with mangrove heights varying from 2.7 m to 45 m, a mangrove tree density of 372 to 1,345 stems ha^{-1}, and a basal area ranging from 24 to 90 m^2 ha^{-1}. A total of 103 crab species, 6 bivalve species, and 17 gastropod species have been found to inhabit the mangrove estuary environment of this area. Sustainable mangrove management can be implemented through mangrove diversity preservation, rehabilitation and restoration, sustainable development, local culture, and effective participative governance.

Key words: mangrove; diversity; sustainable management; Papua

INTRODUCTION

Globally, the total mangrove area has been estimated at 13.8 million ha, distributed across 118 countries and territories in tropical and subtropical regions (Giri *et al*., 2011). Approximately 75% of the world's mangroves are found in just 15 countries, and only 6.9% are protected under the existing network of protected areas (IUCN I-IV). The biggest problem for mangrove ecosystems at present is mangrove forest loss, with at least 35-50% of mangrove forests having been lost over the past half-century (Donato *et al*., 2011; Romanach, 2018). About one-quarter of the world's mangrove cover has been destroyed, and the rate of mangrove loss is still very high, estimated to be around 2 to 5 times higher than the average rate of loss for all forests (Kristian & Oktorie, 2018). The destruction of mangroves is usually related to climate change, sea-level rise, and human population grwoth (Bhomia *et al*., 2016), with major reasons for the destruction comprising urban development, aquaculture, mining, and the overexploitation of timber, fish and shellfish (Alongi, 2016).

The mangrove forests in Indonesia have very high diversity and are considered as the largest in the world, representing more than 20% of total mangrove forests (Ilman *et al*., 2011). The total area of Indonesia's mangrove forests is 3.31 million ha, based on data from Ditjen PDASHL, Ministry of Environment and Forestry, Republic of Indonesia in 2019 (Setyadi *et al*., 2021a).

One of the major pristine mangrove forests in Indonesia is on Papua Island, which accounts for about 46% of the mangrove forest in Indonesia, or about 1.5 million ha (Setyadi *et al*., 2021a). Some of the mangrove areas in Papua are classified as conserved or protected forest, such as the mangrove forest in Mimika Regency, based on the Decree of the Ministry of Forestry of the Republic of Indonesia number SK.782/Menhut-II/2012, and the mangrove forest in Mimika and Asmat Regencies as part of Lorentz National Park, based on the Decree of the Ministry of Forestry of the Republic of Indonesia Number 154.Kpts-II/1997. This vast mangrove forest on Papua Island may have a high diversity, similar to the mangrove forest in Papua New Guinea, which has been shown to contain about 29-32 mangrove flora species (Johnstone and Frodin, 1982). The high mangrove diversity and vast mangrove area on the south coast of Papua might be attributed to the high sedimentation rate from major rivers, as large mangroves are

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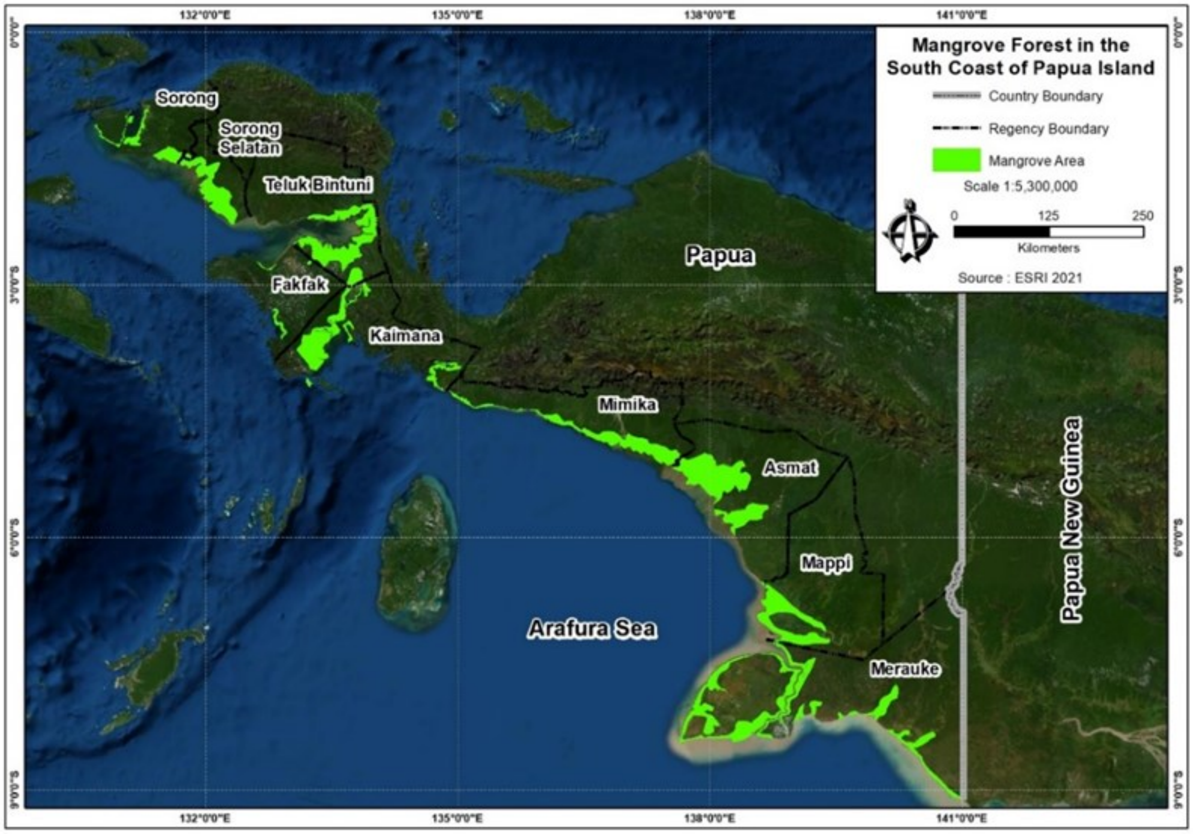

Figure 1. Map of the study area on the south coast of Papua Island, Indonesia (compiled from Murtiningsih, 2020; https://eoimages.gsfc.nasa.gov and Indonesia's One Map Mangroves)

always associated with large river systems due to high sediment accumulation (Wals & Nittrouer, 2004). Due to its size and importance, protecting the mangrove forest on the south coast of Papua is crucial to maintaining its diversity and ecosystem services.

Creating protected areas is a significant step towards conserving coastal and marine ecosystems with the objective of minimizing the effects of human activities on the environment (Almeida *et al*., 2016). It is the most effective form of mangrove management, and conducting an assessment of the status of mangrove forests is vital for good conservation planning and forest management (Schmitt and Duke, 2015). Protecting mangrove areas is also important for trapping sediment and increasing soil elevation to sustain the position in the tidal frame relative to sea-level rise (Saintilan, *et al*., 2020). This paper aims to review and compile all published and unpublished information describing the status and diversity of the mangrove ecosystem on the south coast of Papua Island. The information will be used as input to develop a strategy for the management and conservation of the mangrove forest on the south coast of Papua Island, Indonesia.

MATERIALS AND METHODS

The study methodology is a comprehensive review of the published and unpublished literature regarding the status, environmental condition, and diversity of mangroves on the south coast of Papua. The area covered in this study comprises the West Papua and Papua provinces, covering the regencies of Sorong, Sorong Selatan, Teluk Bintuni, Fak Fak, Kaimana, Mimika, Asmat, Mappi and Merauke. A map of the mangrove area covered in the study is shown in Figure 1.

RESULTS AND DISCUSSION

Environmental Condition

One of the environmental conditions affecting mangrove distribution is tide due to mangroves' ability to adapt physiologically and morphologically to habitat conditions that are affected by tidal inundation and a high salinity amplitude. Some areas on the south coast of Papua Island experience a high tidal range, such as Mimika, with a tidal range of 3.3 to 4.45 m (Aslan *et al*., 2018; Setyadi *et al*. 2021c). A study by Alifdini *et al*. (2018) using satellite altimetry data showed that the maximum tide in the Gulf of Bintuni was 4.57 m, that of South East of Papua near the Arafura Sea was 4.98, and that of South of Papua near the Arafura Sea was 4.87 m. The high tidal range might be the main factor contributing to the vast mangrove forest on the south coast of Papua.

Mangrove forests are net accumulators of sediment (Alongi *et al*., 2005) and play a major role as sediment traps (Kathiresan, 2003), thereby not only promoting the formation of new habitat suitable for natural mangrove colonization and the continuous development of existing mangrove forest but also providing coastal zone stabilization (Phan *et al*., 2015). Mangroves can also facilitate sediment deposition during high tides, resulting in an increase in the coastal surface area (Willemsen *et al*., 2016) and nutrient concentrations that increase the productivity of flora and fauna (Ewel *et al*., 2008). Sediment accretion was measured by Setyadi *et al*. (2021c) in Mimika Regency using sediment stakes and sediment traps. The elevation changes measured using the sediment stake method were 8.4–12.3 mm year^{-1}, while the sediment accretion measured

Table 1. Summary of mangrove sedimentation rate in the mangrove forest

Location	Rate (mm y^{-1})	Reference
Papua, Indonesia	18.5 – 25.4	Setyadi *et al*., 2021
Vietnam	2.44	MacKenzie *et al*., 2016
Palau	0.47	MacKenzie *et al*., 2016
Everglades National Park, Florida	2.5 - 3.6	Smoak *et al*., 2013
New Zealand	17–41	Swales & Lovelock., 2020
Deep Bay, China	1.38	Li *et al*., 2016
Bangladesh	1.32 -2.16	Bomer *et al*., 2019
Papua New Guinea	15 - 44	Walsh and Nittrouer, 2004

using the sediment trap method was 18.5–25.4 mm $year^{-1}$ of elevation changes with 1.88–2.98 g cm^{-2} $year^{-1}$ of sediment accumulation. These results are higher than those for similar studies in other regions, although they are consistent with other studies in Papua New Guinea, as shown in Table 1. This high sedimentation rate may be the reason for the vast mangrove forest on the south coast of Papua as there is a correlation between areas receiving large supplies of sediment and rapid coastal progradation and the expansion of mangrove habitats (Adame *et al*., 2010). The high accretion rate in the area will increase the ability of the mangrove forest on the south coast of Papua to respond to sea-level rise, which ranges from 2.6 to 3.4 mm $year^{-1}$ (Krauss *et al*., 2017; Saintilan *et al*., 2020).

The high sedimentation rate also contributes to the high total organic carbon accumulation. The study by Setyadi *et al*. (2021c) found that total organic carbon accumulation in Mimika was 736.8 g m^2 $year^{-1}$, which is relatively high compared to the global average mangrove carbon burial of 174 g m^2 $year^{-1}$ (Alongi, 2012). Taberima *et al*. (2014), measuring total carbon storage in Teluk Bintuni, Sorong and Mimika Regencies, found that it ranged from 853 to 1,312 mg ha^{-1}. Meanwhile, Sasmito *et al*. (2020) found consistent results of 1,087 ± 584 mg C ha^{-1} in West Papua province. Based on these results, the studies concluded that the carbon storage in Papua was high compared to mangrove forests in other regions.

Mangrove Distribution

The total area of mangrove forests area in Papua – both West Papua and Papua Provinces – is 1,497,724 ha (Ditjen PDASHL, 2020). Table 2 shows the mangrove forest area in each regency on the south coast of Papua Island. The total estimated area is 1,267,449 ha, which is larger than the mangrove forest in Sundarbans, Northern Bay of Bengal, which covers approximately 1 million ha (Gosh *et al*., 2015; Payo *et al*., 2016).

Mangrove tree heights vary from 2.7 to 45 m (Pribadi, 1998; Aslan *et al*., 2018; Setyadi, 2021). The majority of taller mangrove trees are found to be *Bruguiera gymnorrhiza* and *Rhizophora apiculata*, mostly in the mid intertidal zone, whereas the shorter mangrove trees are on new land in the estuary mouth or in the new colonization area. The density of mangrove trees in Bintuni ranges from 372 to 544 stems ha^{-1} with the basal area ranging from 28.3 to 36.9 m^2 ha^{-1} (Pribadi, 1998), whereas in Mimika they range from 577 to 1,345 stems ha^{-1} and 24 to 90 m^2 ha^{-1}, respectively (Setyadi *et al*., 2021). In the new colonization area in Mimika, the density of mangrove trees ranges from 219 to 277 stems ha^{-1} (Fajri, 2012).

The majority of studies on the south coast of Papua Island conclude that *R. apiculata* and *B. gymnorrhiza* are the most dominant species. In Bintuni Bay, *R. apiculata* is the most common and is found in all zones, although it is less dense near the sea. *B. gymnorrhiza* and the more patchy *Bruguiera parviflora* are also less dense near the sea (Pribadi, 1998). The study by Lekitoo and Tambing (2018) also recorded that *B. gymnorrhiza* is the most dominant species in Sumuri, Bintuni Bay. The study by Kusmana *et al*. (1998) in the Tipuka Estuary of Mimika found two community types of mangrove, namely the *Bruguiera cylindrica – R. apiculata* community and the *B. gymnorrhiza - C. schultzii - R. apiculata* community, whereby *R. apiculata* shows the highest density. Another study by Ellison

Table 2. Mangrove area in the south coast of Papua Island, Indonesia

Regency	Province	Area (Ha)	Reference
Sorong	West Papua	55,740	Murtiningsih, 2020
Sorong Selatan	West Papua	75,170	Murtiningsih, 2020
Teluk Bintuni	West Papua	259,718	Murtiningsih, 2020
Fak-Fak	West Papua	5,850	Murtiningsih, 2020
Kaimana	West Papua	54,704	Murtiningsih, 2020
Mimika	Papua	186,291	Aslan *et al*, 2018
Asmat	Papua	305,172	Widiastuti, 2018
Mappi	Papua	30,026	Budhiman and Hasyim, 2005
Merauke	Papua	296,778	Widiastuti, 2018
Total		1,267,449	

Table 3. Major and minor components of mangrove species some regencies of South Coast of Papua Island, Indonesia using classification of Hogarth (2015): (1) Pribadi, 1998; (2) Lekitoo & Tambing, 2018; (3) Kusmana *et al*., 1998; (4) Ellison, 2005; (5) Setyadi *et al*., 2021; (6) Sunarni *et al*., 2016; (7) Rahawarin, 2005.

Family	Species	Growth Form	Category	Category	Bintuni	Mimika	Merauke
Arecaceae	*Nypa fruticans*	Palm	Major	1	4,5		7
Avicenniaceae	*Avicennia alba*	Tree	Major	1,2	5	6	7
Avicenniaceae	*Avicennia eucalyptifolia*	Tree	Major	1	4	6	
Avicenniaceae	*Avicennia lanata*	Tree	Major		5		
Avicenniaceae	*Avicennia marina*	Tree	Major	1,2	3,4,5		7
Avicenniaceae	*Avicennia officialis*	Tree	Major	1	4,5		
Combretaceae	*Lumnitzera littorea*	Tree	Major	1	5		
Combretaceae	*Lumnitzera racemosa*	Tree	Major		5		
Combretaceae	*Lumnitzera rosea*	Tree	Major		5		
Meliaceae	*Xylocarpus australiasicus*	Tree	Major		3		
Meliaceae	*Xylocarpus granatum*	Tree	Major	1,2	3,4,5		7
Meliaceae	*Xylocarpus mekongensis*	Tree	Major	1	4		
Meliaceae	*Xylocarpus molusccensis*	Tree	Major	2	5		
Rhizophoraceae	*Bruguiera cylindrica*	Tree	Major		3,4,5	6	
Rhizophoraceae	*Bruguiera gymnorrhiza*	Tree	Major	1,2	3,4,5	6	7
Rhizophoraceae	*Bruguiera hainesii*	Tree	Major			6	
Rhizophoraceae	*Bruguiera parviflora*	Tree	Major	1	4,5		
Rhizophoraceae	*Bruguiera sexangula*	Tree	Major	1,2	5	6	
Rhizophoraceae	*Ceriops decandra*	Tree	Major	1	5	6	
Rhizophoraceae	*Ceriops tagal*	Tree	Major	1,2	3,5		7
Rhizophoraceae	*Rhizophora apiculata*	Tree	Major	1,2	3,4,5		7
Rhizophoraceae	*Rhizophora mucronata*	Tree	Major	1,2	3,4,5	6	7
Rhizophoraceae	*Rhizophora stylosa*	Tree	Major	1,2	4,5	6	7
Sonneratiaceae	*Sonneratia alba*	Tree	Major	1	5	6	7
Sonneratiaceae	*Sonneratia caseolaris*	Tree	Major	1	4,5		
Sterculiaceae	*Heritiera littolaris*	Tree	Major	1	3,4		
Bignoniaceae	*Dolichandrone spathacea*	Tree	Minor	1			
Acanthaceae	*Acanthus ebracteatus*	Shrub	Minor			6	
Acanthaceae	*Acanthus ilicifolius*	Shrub	Minor	1	5	6	7
Acanthaceae	*Acanthus volubilis*	Shrub	Minor		5		
Ebenaceae	*Diospyros maritima*	Tree	Minor	1,2	3		
Ebenaceae	*Diospyros papuana*	Tree	Minor		5		
Euphorbiaceae	*Excoecaria agallocha*	Tree	Minor	1	5		
Bignoniaceae	*Dolichandrone spathacea*	Tree	Minor		5		
Bombacaceae	*Camptostemon schultzii*	Shrub/ Tree	Minor		3,5		
Myrsinaceae	*Aegiceras corniculatum*	Shrub/ Tree	Minor	1	5	6	7
Myrsinaceae	*Aegiceras floridum*	Shrub/ Tree	Minor			6	
Pteridaceae	*Acrosthicum aureum*	Fern	Minor	1	5		
Rubiceae	*Nauclea papuana*	Shrub	Minor		5		
Rubiceae	*Schyphiphora hydrophyllacea*	Shrub	Minor	1	5		

(2005) in the Ajkwa Estuary of Mimika classified five mangrove community distributions: *Nypa fruticans* forest and mixed mangrove forest on the freshwater margins; *Bruguiera* dominated forest at slightly higher elevations and on the inner bends of rivers; *Rhizophora stylosa – B. gymnorrhiza* dominated forest at the south of the estuary and the outer bends of rivers; and *Avicennia* and *Sonneratia* dominated forest in the seaward pioneer community of the lowest elevation. Aslan *et al*. (2016) conducted forest inventory measurement and eight mangrove association were identified: *Avicennia – Sonneratia*; *Rhizophora*; *Camptostemon - Rhizophora - Lumnitzera*; *Ceriops*; Transitional (Coastal); Transitional (landward), and Sago. The lastest study by Setyadi *et al*. (2021) recorded that the most dominant species is *R. apiculata*. The authors divided the mangrove zones into four zones, namely a high tidal zone dominated by *N. fruticans,* a medium high tidal zone dominated by *R. apiculata,* and *B. gymnorrhiza,* a medium low tidal zone dominated by *B. gymnorrhiza, R. apiculata* and *B. parviflora*, and a low tidal zone dominated by *Avicennia marina* and *Sonneratio alba*. Another study by Fajri *et al*. (2012) in Mimika also concluded that *S. alba* is the most dominant species in the new colonization area.

A study in the Sinagoi Estuary, Sorong Selatan (Rahawarin, 2005) recorded that *S. alba* is the most dominant species. Meanwhile, a study in Merauke by Sunarni *et al*. (2019) concluded that *Avicennia* dominates disturbed areas with sandy materials, while *Rhizophora* dominates more stable areas with silt substrate.

The mangrove ecology study in Bintuni (Pribadi, 1998) found 19 mangrove species from the major component and 7 species from the minor component using the classification of Hogarth (2015). Another study by Lekitoo and Tambing (2018) recorded 9 mangrove species from the major component and 2 species from the minor component. A study in Mimika by Kusmana *et al*. (1998) recorded 8 species from the major component and 2 species from the minor component, Ellison (2005) recorded 14 mangrove species from the major component, Aslan *et al*. (2016) recorded 20 mangrove species, and Setyadi *et al*. (2021) found 21 mangrove species from the major component and 10 species from the minor component. Research in the Merauke mangrove forest by Sunarni *et al*. (2019) recorded 10 species from the major component and 4 species from the minor component. The study in Sorong Selatan by Rahawarin (2005) recorded 10 species from the major component and 2 species from the minor component. In total, 42 plant species, 27 from the major component and 15 from the minor component, belonging to 16 families were recorded in the mangrove forests of the south coast of Papua Island, Indonesia (Table 3).

The number of mangrove species varies across the world. Kathiresan and Bingham (2001) recognized 65 mangrove species in 22 genera and 16 families. Hogarth (2015) classified true mangroves as 70 species belonging to 20 families, with 47 species representing the mangrove major component. In Indonesia, Rizal *et al*. (2018) recorded 89 species, 35 of which are trees. A higher number of species, namely 202 mangrove plant species, was recorded by Hanum (2014), of which 89 species are trees, with true mangroves accounting for 43 species. Mangrove studies in Papua New Guinea recorded 29 mangrove plant species, although there were only three major forest types in the delta, namely *Rhizophora -Bruguiera* forests, *Nypa* forests and *Avicennia-Sonneratia* forests (Robertson *et al*., 1991). Therefore, the mangroves in Papua Island of Indonesia have a higher number of mangrove species, with 42 plant species from 27 from the major component and 15 from the minor component.

Mangrove Crustacean

Crustaceans are among the most abundant and diverse mangrove fauna, particularly true crabs (Brachyura) (Hogarth, 2015). Monitoring the mangrove estuary of Mimika Regency, Rahayu and Setyadi (2009) recorded 103 crab species belonging to three infraorders (Anomura, Brachyura, and Thalassinidea). The two main families of crabs are Ocypodidae, which typically lives on the lower shore close to the estuary, and Sesarmidae, which is able to withstand dryer environments and lives on the upper shore, often climbing the roots and trunks of mangrove trees. The study by Setyadi *et al*. (2021b) in Mimika found 41 crustacean species, consisting of 37 crab species, 3 shrimp species, 1 hermit crab species, and 1 mud lobster species. According to Setyadi *et al*. (2021b), the number of crustacean species in Mimika is relatively higher than that of other mangrove forests in the world. The highest total abundance of crabs was found for *Parasesarma indiarum*, *Parasesarma cricotum*, *Sarmatium germaini*, *Clistocoeloma amamaparense* and *Sesarmoides borneensis*.

According to Ravichandran *et al*. (2011), more than 300 species of brachyuran crabs have been reported from mangroves worldwide. This means that around 30% of known mangrove crab species are found in the mangroves on the south coast of Papua Island, Indonesia. The area has the potential for the discovery of new species, and indeed, based on intensive monitoring, a total of 20 new crab species were discovered from 2000 to 2019. The list of new species that have been published in international journals is presented in Table 4.

Table 4. New crabs species discovered in Mimika Regency, Indonesia

No	Species	Author/s	Year	Locality
1	*Clistocoeloma amamaparenase*	Rahayu & Takeda	2000	Ajkwa, Mimika Regency, Papua
2	*Neodorippe simplex*	Ng & Rahayu	2002	Otakwa, Mimika Regency, Papua
3	*Paracleistotoma laciniatum*	Rahayu & Ng,	2003	Ajkwa, Mimika Regency, Papua
4	*Paracleistotoma quadratum*	Rahayu & Ng	2003	Ajkwa, Mimika Regency, Papua
5	*Parasesarma cricotus*	Rahayu & Davie	2003	Ajkwa, Mimika Regency, Papua
6	*Parasesarma foresti*	Rahayu & Davie	2003	Kamora, Mimika Regency, Papua
7	*Amarinus pristes*	Rahayu & Ng	2004	Kamora, Mimika Regency, Papua
8	*Haberma kamora*	Rahayu & Ng	2004	Kamora, Mimika Regency, Papua
9	*Neorhyncoplax elongata*	Rahayu & Ng	2004	Kamora, Mimika Regency, Papua
10	*Parasesarma charis*	Rahayu & Ng	2004	Ajkwa, Mimika Regency, Papua
11	*Philyra bicornis*	Rahayu & Ng	2004	Kamora, Mimika Regency, Papua
12	*Neosarmatium bidentatum*	Rahayu & Davie	2006	Ajkwa, Mimika Regency, Papua
13	*Neosarmatium papuense*	Rahayu & Davie	2006	Kamora, Mimika Regency, Papua
14	*Macrophthalmus fusculatus*	Rahayu & Nugroho	2012	Ajkwa, Mimika Regency, Papua
15	*Hexapus timika*	Rahayu & Ng	2014	Otakwa, Mimika Regency, Papua,
16	*Mariaplax cyrtophallus*	Rahayu & Ng	2014	Otakwa, Mimika Regency, Papua,
17	Parasesarma gracilipes	Li, Rahayu & Ng	2018	Timika, Mimika Regency, Papua
18	Elamenopsis gracilipes	Rahayu & Ng	2019	Mimika Regency, Papua, Indonesia
19	*Clibanarius harisi*	Rahayu	2003	Timika, Mimika Regency, Papua
20	*Diogenes foresti*	Rahayu & Hortle	2003	Timika, Mimika Regency, Papua

Mangrove Mollusks

The other dominant aquatic fauna in mangrove forests is mollusks, particularly gastropods and bivalves. The distribution of gastropods is affected by several factors, such as light, tidal exposure, salinity, and substrate type, whereas bivalves are often considered to be confined to a narrow seaward zone due to feeding and larval settlement restrictions (Nagelkerken, 2008). The study by Setyadi *et al*. (2009) in Mimika Regency recorded 6 bivalve species and 17 gastropod species. The latest study by Setyadi *et al*. (2021b) in Mimika recorded 32 species of mollusks, consisting of 3 bivalves species and 29 gastropod species.

According to Setyadi *et al*. (2021b), among clams, the highest total abundance was found for *Polymesoda expansa* and *Isognomon ephippium*. For gastropods, the highest total abundance was for *Ellobium aurisjudae*, *Terebralia palustris* and *Neritina violacea*. Regarding the total number of individuals, *Nerita balteata* was the highest, followed by *E. aurisjudae, N. planospira*, and *N. violacea*. A study in Payum Coast, Merauke Regency, by Merely and Elviana (2017) identified 13 species of gastropods, namely *Cassidula angulifera, Littoraria scabra, Terebralia sulcata, Cerithidea obtusa, Neripteron violaceum, Indothais rufotincta, Nassasius unicolor, Tanea lineata, Nerita balteata, Turritella terebra, Glossaulax bicolor, Mitra sp.* and *Telescopium telescopium.* Another study in Samkai District Merauke by Masiyah and Monika (2017) recorded 1 bivalve species and 14 gastropod species.

Mangrove Birds

Mangroves provide a habitat for many bird species. The study by Cita and Budiman (2019) in Teluk Bintuni Regency found 54 bird species with 28 families, dominated by Laridae. Yudha *et al*. (2021) recorded 103 bird species representing 40 families. Eleven species were found to be the most dominant, among them *Todiramphus chloris*, *Charmosyna placentis*, *Geoffroyus geoffroyi* and *Philemon buceroides*.

Sustainable Mangrove Management

Mangrove forests as a renewable resource must be managed on a sustainable basis to provide ecological, economic and social benefits (Kusmana, 2015). However, the management of mangroves in an ecologically and economically sustainable way requires multidisciplinary intervention, which is a challenging proposition due to the need for consistency, compounded by the often inadequate coordination among the sectors of government (Datta *et al*., 2010; Carter *et al*., 2015). Based on those facts, and also considering the diversity of flora and fauna on the south coast of Papua, the proposed concept shown in Figure 2 can be applied for sustainable mangrove management.

The majority of mangrove forests on the south coast of Papua, particularly in Mimika and Asmat Regencies, are classified as protected mangrove forests. Therefore, the conservation approach should be the main focus, with the main objective of managing the natural resources in a sustainable way to maintain and increase value and diversity. The preservation of the mangrove ecosystem as a protected forest can be ensured through high-value conservation, monitoring programs, database system development, fisheries regulation, and resource mapping (Figure 2). According to Schmitt and Duke (2015), research, economic assessment, and long-term monitoring are essential for successful conservation planning and management.

This review has demonstrated that the mangrove forest on the south coast of Papua Island is a pristine forest rich in diversity, particularly regarding mangrove crustaceans. The preservation of the mangrove forest as a habitat for crustaceans is crucial due to their roles and functions in the mangrove ecosystem, such as exporting mangrove litter, exchanging nutrients, trapping energy, and aerating the sediment (Ashton *et al*., 2003; Gillikin and Schubart, 2004; Ngo-Massou *et al*., 2018). One of the most important mangrove crustaceans on the south coast of Papua Island is *Scylla olivacea*, or mud crab, a commercially important species. Due to

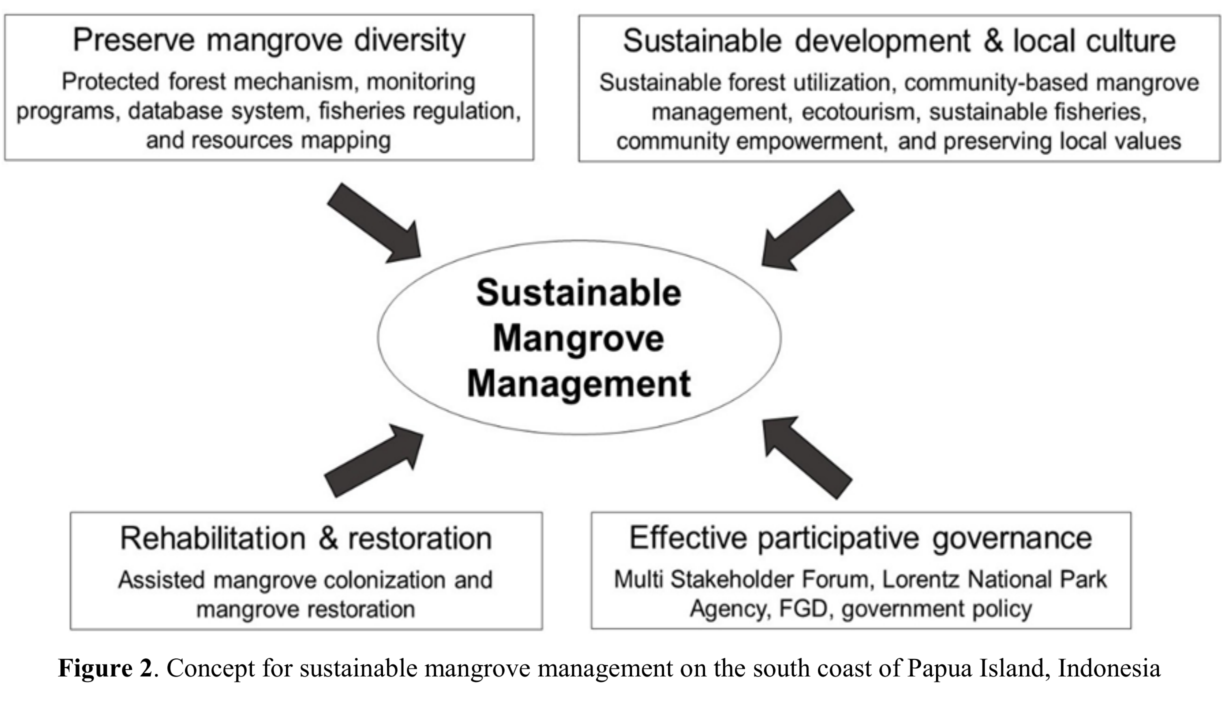

Figure 2. Concept for sustainable mangrove management on the south coast of Papua Island, Indonesia

high demand, the intense harvesting of mud crab might lead to overfishing and threaten the population. Therefore, estimating the population and exploitation levels is crucial to the implementation of proper utilization and management strategies.

Another important component of sustainable mangrove management is rehabilitation and restoration. Rehabilitation programs can be implemented on degraded mangrove forests or new sediment deposition areas that emerge due to natural sedimentation or human activities. The degraded mangrove forest in some areas, such as Merauke Regency (Sunarni *et al*., 2019), can be restored through rehabilitation programs involving local communities. In Merauke Regency, 43% of local communities have been involved in the mangrove rehabilitation programs (Widiastuti, 2018).

An example of an active mangrove rehabilitation program is the one implemented in Mimika Regency by PT Freeport Indonesia, which has been conducting an assisted mangrove program at new deposition areas in the Ajkwa Estuary since 2002 (Setyadi *et al*., 2006). The goal of this program is to enhance tailings retention in the estuary and assist the establishment of mangrove species on new lands. Seedlings are collected from surrounding the mangrove ecosystem, with direct planting being implemented mainly for *Rhizophora mucronata* propagules. Prior to the planting, the propagules are kept in a moist plastic bag for at least three days under natural shade to protect them from direct sunlight. This process promotes the seasoning of the propagules, thus lowering their palatability to Sesarmid crabs and increasing their chance of survival once planted. Currently, over 300 ha of new land has been planted with mangrove trees (www.ptfi.co.id).

Another strategy for sustainable mangrove management on the south coast of Papua Island is through sustainable development and local culture by implementing sustainable forest management, community-based mangrove management, eco-tourism, sustainable fisheries, community empowerment, and the preservation of local values. The sustainable utilization of mangrove forest has been implemented in Teluk Bintuni Regency, where a total mangrove area of 82,120 ha is managed by PT. Bintuni Utama Murni Wood Industries (PT. BUMWI) under a 30-year rotation cycle to produce wood chips, with strict compliance to sustainable forest management standards. The study by Sillanpää *et al*. (2017), which analyzed forest structure and biodiversity in secondary stands, concluded that the forest structure in secondary stands follows a natural regeneration process over the rotation period. However, they also found that it had not yet attained the same ecological condition as baseline forests after 25 years. Furthermore, the study suggested that the harvest rotation may need to be extended to 30–40 years for secondary stands to attain forest compositions, structures, and volumes similar to those of baseline forests. The latest study by Yuda *et al*. (2021) concluded that the impact of logging on mangrove forests can be minimized and that the ecosystem can be restored effectively to provide adequate habitat for flora and fauna through the implementation of appropriate environmental management programs.

Research to investigate a more beneficial use of mangroves by local communities is also important to improve their livelihoods. It is well known that mangrove fruits, leaves, bark and wood have beneficial uses, including as products, medicines and others, which can generate income for the local community. Community-based mangrove management through eco-tourism has also been implemented in many mangrove areas in Indonesia, such as in North Sumatra (Basuni *et al*., 2018), West Sulawesi (Malik *et al*., 2019), and East Lampung (Setiawan *et al*., 2017). In West Sulawesi, ecotourism activities include mangrove tracking, mangrove learning and rehabilitation, fishing, bird watching, spots for pre-wedding and selfie photoshoots, culinary tours, and gazebos with an ocean view for tourists. In East Lampung, the activities include boating around the mangroves, mangrove planting tourism, and bird watching. Similar eco-tourism activities can be implemented in the mangrove areas on the south coast of Papua Island to contribute to the socio-economic wellbeing of local communities. When the local community obtains direct benefit from mangrove areas, this will increase their awareness of the need to preserve and protect the local mangrove ecosystem.

The last key aspect of sustainable mangrove management is Effective Participative Governance, which can be implemented through a multi-stakeholder forum (MSF), the management of Lorentz National Park by the National Park Agency, forum group discussions, and the development and implementation of local government policies. An MSF has been established in Mimika Regency, focusing on environmental conservation issues, especially those related to the sustainable development of natural resources and the impacts of climate change (USAID IFAC, 2016). The MSF consists of representatives from the local government, civil society, and the private sector. This forum can strengthen the Regency by promoting conservation measures that support economic development while improving both spatial planning and environmental management and monitoring in order to reduce deforestation. According to Romanach *et al*. (2018), successful management, conservation, and restoration require the commitment of local and national-level governments as well as local communities.

CONCLUSION

This review has shown that the mangrove ecosystems on the south coast of Papua Island, Indonesia, have a very rich floral and faunal diversity. The conservation of the mangrove ecosystems in this area is very important to maintain this diversity while also contributing to the reduction of global warming due to carbon capture. The sedimentation rate data for the south coast of Papua demonstrate the mangroves' ability to respond to sea-level rise. Efforts are required to disseminate this information to increase awareness of the need to conserve this vast mangrove area. Other sustainable mangrove management approaches, such as the rehabilitation of critical mangrove forests, sustainable development, the promotion of local culture, and effective participative governance, should be implemented to preserve this mangrove ecosystem – one of the most pristine and diverse in the world.

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