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Influences of zonation on water fertility and structure communities of phytoplankton and benthos in Batukaras Mangrove Forest, Pangandaran District, Indonesia

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Abstract. *Pratiwi D, Oktavia D, Sumiarsa D, Sunardi S. 2023. Influences of zonation on water fertility and structure communities of phytoplankton and benthos in Batukaras Mangrove Forest, Pangandaran District, Indonesia. Biodiversitas 24: 4978-4988.* Mangrove forests are coastal areas with several advantages, including access to natural resources that other regions do not provide. Pangandaran has mangrove forest areas, namely Batukaras mangroves, located in Batukaras Village, Pangandaran, West Java, Indonesia. This study aims to identify the primary productivity and community structure of phytoplankton and benthos as one of the natural resources in the Batukaras mangrove with different zone patterns of mangrove (seaward and landward). The purposive sampling method determined the observation stations based on the vegetation density. The obtained data of Net Primary Productivity (NPP) was analyzed with the light and dark bottle (Winkler method). In addition, the data community structure of phytoplankton and benthos was analyzed using the Shannon Wienner diversity index (H'), equitability index (E), and Simpson dominance index (D). The results show that the NPP in seaward and landward are mesotrophic with values of 105.833 mgC/m^3/h and 36.463 mgC/m^3/h. The abundance of phytoplankton and benthos in seaward is 560 ind/m^3 and 387 ind, while landward ranges from 1140 ind/m^3 and 135 ind. *Planktoniella* sp. and *Faunus ater* dominated the community structure of phytoplankton and benthos seaward, while the landward location consisted of *Oscillatoria* sp. and *Terebralia sulcata*. The community structure of phytoplankton and benthos in seaward and landward has significant differences (<0.05). The seaward and landward zone shows relatively stable and non-polluted waters.

Keywords: Diversity, landward zone, seaward zone, tropic status, vegetation

INTRODUCTION

Indonesia, the country with the most extensive coastal area, has a mangrove ecosystem of 4.5 million ha (27%) of the world's mangrove ecosystem. Mangrove ecosystems are diverse environments with a wide range of unique flora and fauna specifically adapted to the environmental characteristics of intertidal areas (Khairnar et al. 2018). Mangrove forest is an ecosystem that is very productive and valuable. It becomes a tourist attraction, withstands and protects coastal areas from waves or sea currents from erosion, helps balance the air quality, and becomes a habitat, feeding ground, spawning ground, and nursery ground for some marine organisms, reducing the devasting impact of natural disaster (Lee et al. 2015). This also explains that mangrove forests are important for ecological and economic functions. The mangrove ecosystem is divided into three zone patterns: seaward, mid, and landward.

In previous research, there has been a lot of research on the productivity and structure of biota communities in the Batukaras Mangrove Conservation. However, a recent study reported that the community structure of macrobenthos in Batukaras and Bulaksetra found nine taxa from gastropods, and diversity was classified as moderate (Nurfajrin and Rosada 2018). Water quality in Batukaras Mangrove Conservation showed a diversity of plankton, and primary productivity is higher than in the Bulaksetra area. Bacillariophyceae dominated phytoplankton, while crustaceans dominated zooplankton with eutrophic levels (Pribadi et al. 2020). Primary productivity phytoplankton in conservation mangroves in Batukaras have 300-1,600 mgC.m-3 (dry) and 100-1,400 mgC.m-3 (rainy) (Nurdiana 2020). However, previous research only focused on mangrove areas such as Batukaras and Bulaksetra. Research on community structure and water quality based on the influence of differences in zone patterns of mangroves has yet to be carried out. The zone pattern of mangroves is vital in the biodiversity of community structure. Benthos presence, phytoplankton, and fertility are indicators of quality biodiversity.

We studied mangrove forests in Batukaras, Cijulang, Pangandaran, West Java. The condition of Batukaras mangroves is quite critical because of the destruction of mangrove ecosystems due to the tsunami in 2006, but they have now been recovered and restored. The study locations were in the seaward and landward mangrove zones. The reason for choosing the seaward and landward was due to significant differences in physical and chemical conditions and vegetation composition. A tidal wave influences the seaward zone and is near an ocean with heterogeneous vegetation composition, such as Avicenna, Rhizophora, Sonneratia, and Bruguiera (mangrove trees). The Landward mangrove zone is not influenced by a tidal wave over the Cieunteung River and has a homogeneous vegetation composition (*Nypa fruticans*). The seaward area is used for ecotourism and conservation, while the landward area is used for settlement. Vegetation of mangroves is vital in the biodiversity of community structure. Benthos presence, phytoplankton, and fertility are indicators of quality biodiversity.

Therefore, we analyzed the influence of mangrove zonation on primary productivity and community structure of phytoplankton and benthos. In addition, we compare the NPP and the community structure of phytoplankton and benthos from two zone patterns. Thus, research was conducted on water fertility, benthos, and phytoplankton diversity as water quality in seaward and landward areas to provide information about the structure community and productivity of the two different zone patterns of mangrove forests. This study can be essential for studying the structure and function of aquatic ecosystems (Xiao et al. 2015) as a measure of environmental health and water resource management.

MATERIAL AND METHODS

Study area

The research was conducted in Batukaras Mangrove Forest at Batukaras Village, Cijulang, Pangandaran, West Java, Indonesia in March 2019. The research plot was in the seaward and landward zones. The seaward zone is a mangrove conservation area used as an ecotourism place and conserved to protect the land from sea waves and tsunamis. The Landward zone is part of the mangrove land zone located in the Cieunteung River. Seaward zone wad located on Jembatan Merah Batukaras in 7°43'13.61"S 108°29'44.90"E (St.1), 7°43'14.67"S 108°29'51.22"E (St.2), and 7°43'19.20"S 108°29'50.75"E (St.3). Landward zone was located in Cieunteung River in 7°44'19.88"S 108°28'27.83"E (St.1), 7°44'16.60"S 108°28'28.99"E (St.2), and 7°44'20.64"S 108°28'31.49"E (St.3). Detailed study locations can be seen in Figure 1. The determination of sampling locations uses the purposive sampling method, where station selection is based on mangrove vegetation density, with St.1 indicating medium density, St.2 indicating high density, and St.3 indicating low density.

Sampling procedure

Sampling of NPP was carried out using the light and dark bottle method. Water samples were added in light and dark Winkler bottles and allowed to stand in water for 8 hours. Water samples must be added H_2SO_4 and $MnSO_4$ before being kept in a coolbox. Plankton samples were taken using a plankton net no. 25. A total volume of 10 liters was filtered using 1 L buckets and the filtered water was stored in a 100 mL bottle. Phytoplankton samples were preserved with 1 mL of Lugol 4% solution, stored in a bottle, then counted and identified. Benthos was sampled with a surber net. Samples were added a Lugol of 4% to increase the visibility of organisms and kept in plastic. Plankton and benthos identification is carried out at the Center of Environmental and Sustainability Science (CESS), Universitas Padjadjaran, Sumedang, Indonesia.

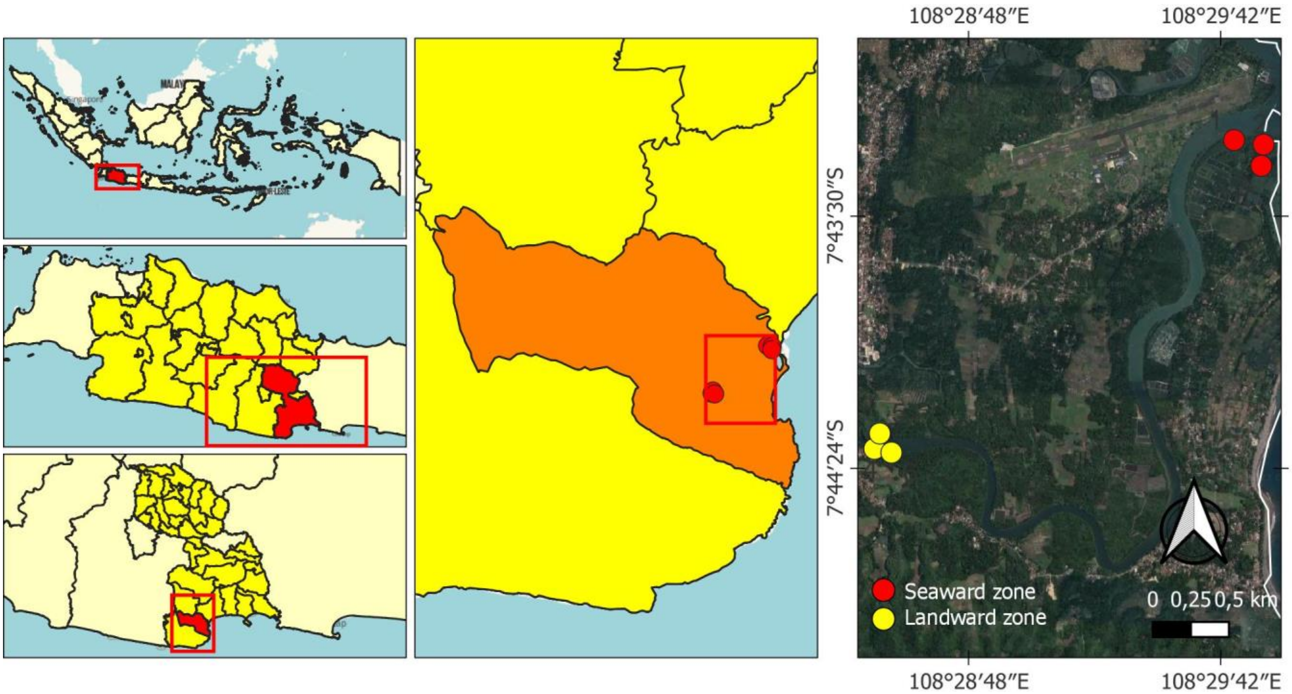

Figure 1. Plot design for sampling in seaward and landward of mangrove zone in Batukaras Village, Cijulang, Pangandaran, West Java, Indonesia

Water samples collected during dry season. The grab sampling was used at each sampling location. Physicochemical parameters were measured at the same sites where the water was sampled and analyzed. The following physico-chemical attributes were used in the study database: water temperature (WT), air temperature (AT), dissolved oxygen (DO), pH, transparency (TP), salinity (SL), carbon dioxide (CO_2), carbonate acid (HCO_3). In situ water temperature was measured with a mercury thermometer, while pH was assessed using a pH universal indicator. Salinity was measured using a refractometer, and transparency was measured using a Secci disk. Before the water samples are tested in the laboratory, the samples are bottled and transported in a cooler and stored at a temperature of approximately 4°C. The sampling, preservation, and analytical procedure for the DO, CO_2, and HCO_3 were conducted following APHA's Standard Method.

Data analysis

The water of NPP samples was analyzed using the Winkler method. NPP value was classified according to the fertility level categories by Likens (1975). Plankton observation and abundance were calculated using sedgwick rafter counting. Identification guideline uses the reference Pennak's (1989) and benthos's observation using a stereo microscope. Later, the organisms were identified to the lowest taxonomic level (up to species), according to Gaston and Marshall. The community structure of phytoplankton and benthos was analyzed using an ecological index. Shannon-Wiener Index (H'), Equitability Index (E), and Simpson Dominance Index (D) were calculated to classify their diversity, equitability, and dominance level (Odum 1993) to determine community structure. The diversity index was used in determining water pollution levels based on the criteria of Wilhm (1975). Then, all the data obtained and the environmental condition, particularly the water quality, were discussed. Statistical techniques compared this value of NPP and biota from the two locations with a T-test.

RESULTS AND DISCUSSION

Physicochemical water

The seaward zone is a conservation and ecotourism area, and the surrounding area is used as ponds. This area is close to the sea, so it is still directly affected by tidal waves, and salinity is quite high at 17‰ (Table 1). The depth is relatively shallow, and the brightness of the water is clear enough that sunlight is easy to penetrate the water. The DO value in seaward zone ranged from 5.2 to 5.36 mg/L, indicating the waters are not polluted. The CO_2 level of water in the mangrove area was 22 mg/L, which is classified as normal and does not harm the organisms in it, especially plankton.

The landward zone is nearest to the river and close to the land. The brown color of the water is suspected to be caused by the wastewater from the Green Canyon Tourism and other anthropogenic activities in the surroundings. The waters in this area have a salinity of 3‰. The waters in the landward zone were turbid and deep compared to the mangrove area. Hence, the sunlight penetration was lower than in the seaward zone. It caused a less optimal photosynthesis process in it. DO values of 3.66-5.12 mg/L are still categorized as insufficient for aquatic living organisms. According to the Ministry of Environment (2010), free CO_2 levels of more than 25 mg/L endangered fish and CO_2 concentrations of more than 100 mg/L will cause all aquatic organizations to die. The CO_2 level in landward zone waters was 28.2 mg/L, slightly harmful to aquatic biota. The high levels of CO_2 in these waters are thought to be caused by the high activity of respiration and the organic matter content of atmospheric CO_2 diffusion fibers.

Net Primary Productivity (NPP)

NPP values in seaward and landward zones were 108.833 mgC/m^3/h and 46.256 mgC/m^3/h, indicating mesotrophic (Figure 2). The NPP value of seaward zone is higher than landward zone even though both are classified as mangrove ecosystems. According to Likens (1975), trophic status with a 30-150 mgC/m^3/h is categorized as mesotrophic. This shows that the waters in the seaward and landward zone areas were in good condition and not polluted. Over primary productivity indicates that the waters are eutrophic, while too low indicates that the waters are unproductive or poor (Vallina et al. 2017). Statistical calculations of NPP samples in seaward and landward zones with independent T-tests do not differ significantly (<0.05).

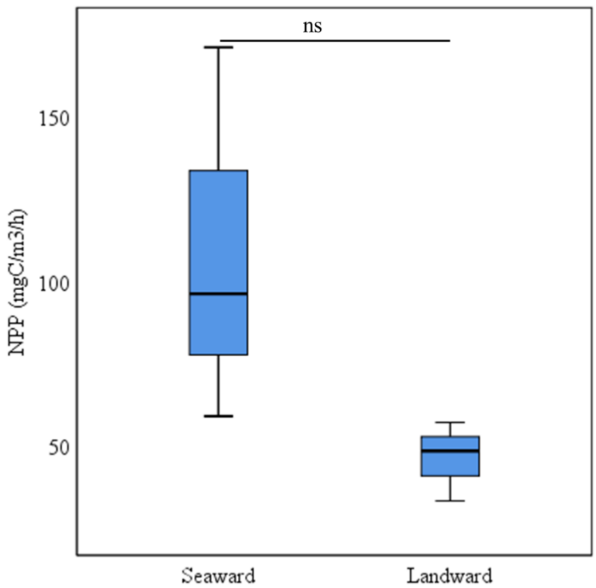

Figure 2. Comparison of NPP in seaward and landward zone of mangrove forest in Batukaras, Pangandaran District, Indonesia

Table 1. Physicochemical properties of water in seaward and landward zone of mangrove forest in Batukaras, Pangandaran District, Indonesia

Parameters	Unit	Seaward		Landward	
		Range	Mean	Range	Mean
Dp	cm	40-46	42.67±3.05	56-103	81.33±23.71
AT	°C	32.7-34	33.23±0.68	29-30.9	30±0.95
WT	°C	27	27±0	25	25±0
TP	cm	40-46	42.67±3.05	51-61	56±5
SL	‰	17	17±0	3	3±0
pH		7	7±0	7	7±0
DO	mg/L	5.2-5.36	5.31±0.09	3.66-5.12	4.29±0.75
CO_2	mg/L	17.6-26.4	22±4.4	26.4-30.8	28.6±2.2
HCO_3	mg/L	91.5-97.6	94.55±3.05	146.4-161.65	154.02±7.62

Note: Dp: Depth; AT: air temperature; WT: water temperature; TP: transparency; SL: salinity; DO: dissolved oxygen

Table 2. Composition and relative abundance (R) of phytoplankton in seaward and landward zone of mangrove forest in Batukaras, Pangandaran District, Indonesia

Family	Species	Seaward zone (ind/m^3)			R (%)	Landward zone (ind/m^3)			R (%)
		St.1	St.2	St.3		St.1	St.2	St.3	
Bacillariophyceae	*Amphora* sp.	0	0	0	0.000	12	9	19	3.509
	Anomoeneis sp.	0	0	0	0.000	7	7	6	1.754
	Cymbella sp.	10	0	10	3.571	20	28	32	7.018
	Fragillaria sp.	0	0	0	0.000	11	12	17	3.509
	Mastogloia sp.	0	0	0	0.000	9	4	7	1.754
	Navicula sp.	3	11	6	3.571	21	18	21	5.263
	Nitzschia sp.	11	18	11	7.143	46	31	43	10.526
	Synedra sp.	0	0	0	0.000	42	23	35	8.772
	Tabellaria sp.	0	0	0	0.000	6	8	6	1.754
	Gyrosigma sp.	8	8	4	3.571	0	0	0	0.000
	Planktoniella sp.	39	32	49	21.429	0	0	0	0.000
	Surirella sp.	19	1	0	3.571	0	0	0	0.000
	Thalassionema sp.	2	5	13	3.571	0	0	0	0.000
Coscinodiscophyceae	*Coscinodiscus* sp.	36	21	23	14.286	44	22	54	10.526
	Melosira sp.	47	13	0	10.714	0	0	0	0.000
Chlorophyceae	*Chlamydomonas* sp.	0	0	0	0.000	18	14	28	5.263
	Pediastrum sp.	0	0	0	0.000	9	0	11	1.754
Trebouxiophyceae	*Closteriopsis* sp.	0	0	0	0.000	0	0	20	1.754
Cyanophyceae	*Lyngbya* sp.	0	0	0	0.000	8	0	12	1.754
	Oscillatoria sp.	26	0	14	7.143	95	71	134	26.316
	Merismopedia sp.	4	0	36	7.143	0	0	0	0.000
	Plectonema sp.	20	0	0	3.571	0	0	0	0.000
	Spirulina sp.	20	0	0	3.571	0	0	0	0.000
Euglenoohyceae	*Euglena* sp.	0	0	0	0.000	16	4	0	1.754
Florideophyceae	*Lemanea* sp.	16	4	0	3.571	62	18	0	7.018
Xanthophyceae	*Tribonema* sp.	3	0	17	3.571	0	0	0	0.000
Total abundance (ind/m^3)		264	113	183	100	426	269	445	100
			560				1,140		

Phytoplankton and benthos community structure

The community structure of phytoplankton and benthos was analyzed in the sandward and landward zones to see the effect of different locations and vegetation. The phytoplankton abundance was represented as the quantity of individuals of a species per cubic meter (ind/m^3) (Table 2). Furthermore, 15 phytoplankton species were recorded in the seaward zone and 17 in the landward zone. Moreover, 8 phytoplankton taxa were found in the mangrove ecosystem in Batukaras (Table 2). The phytoplankton composition only found in landward zone are Euglenophyceae, Chlorophyceae, and Trebouxiophyceae. Xanthophyceae are only found in seaward zone.

The two zones' most dominating phytoplankton taxa are Bacillariophyceae, Cyanophyceae, and Coscidiscophyceae. Bacillariophyceae, better known as Diatoms, is a class of phytoplankton whose species are very diverse and most commonly found compared to other phytoplankton. Diatoms are a group of phytoplankton commonly found in flowing waters such as rivers and seas (Burliga and Kociolek 2016; Nurrachmi et al. 2021). Bacillariophyceae is more adaptable to existing environmental conditions, is cosmopolitan, and has a high tolerance (Veronika and Aryawati 2012). The abundance of Coscinodiscophyceae is almost equal to Bacillariophyceae in landward zone. Coscinodiscophyceae is a family of phytoplankton commonly found in Pangandaran waters (Rosada et al. 2017). In addition, the phytoplankton community is indeed dominated by species of Chlorophyceae, Cyanophyceae, and Bacillariophyceae (Ananda et al. 2019).

The total abundance of phytoplankton in seaward zone is 560 ind/m^3. Diatom (order: Bacillariophyceae) and Coscinodiscophyceae were most abundant in seaward zone, especially *Planktoniella* sp. In the seaward zone, the most abundant species was *Planktoniella* sp. (21.429%), followed by *Coscinodiscus* sp. (14.286%) and *Melosira* sp. (10.714%) as the second and third most abundant phytoplankton species, respectively. The Lanward zone has a total abundant phytoplankton of 1140 ind/m^3. In the landward zone, *Oscillatoria* sp. (26.316%) was the most abundant of the Cyanophyceae, followed by *Nitzchia* sp. (10.526%) and *Coscinodiscus* sp. (10.526%) (Figure 3). The landward zone has a greater abundance of phytoplankton than the seaward area. Abiotic conditions such as currents, light, nutrients, and variations in time of day and location are likely to influence the distribution of abundance in the seaward and landward zones (Astuti et al. 2012).

The presence of benthos is another indicator of aquatic quality (Afif et al. 2014). Moreover, 12 and 8 benthos species were recorded in the seaward and landward zones, respectively. Furthermore, 8 benthos taxa were found in the seaward zone (Table 3). In the seaward zone, *F. ater* was the most abundant species with a total number of individuals of 179 ind. In the landward zone, *T. sulcate* was the most abundant species with a total number of individuals of 89 ind. *F. ater* can be found easily in the seaward zone because there are many organic substances at the bottom of the waters so that gastropods can easily get nutrients. Benthos in the landward zone has less abundance than in the seaward zone. The reason is that the landward zone area has a solid mud substrate and is not waterlogged, so the nutrients only come from periphyton or litterfall. There is also not much litterfall in landward zone because the Nipa palm tree is a type of palm with not much litter. These conditions result in only certain benthos being able to adapt. Three species in both areas are *F. ater*, *Pagurus* sp., and *I. deschampsi*. The total abundance of benthos in sea and landward zones are 387 and 135 ind/m^3. The identification results showed that all species obtained were divided into two classes: Gastropods and Malacostraca. The comparison chart is shown in Figure 4. In the seaward zone, the highest species composition was Gastropods (91%) and Malacostraca (9%). The landward zone has fewer species and abundance except Gastropods (95%) and Malacostraca (5%). The increased distribution of gastropods in mangrove forests is likely due to their mobility characteristics (Kabir et al. 2014). Gastropods tend to feed on more abundant food sources in the mangrove zone, such as detritus and algae, while malacostraca are more vulnerable to predators due to their higher activity levels (Hendy et al. 2014). Gastropods have shells that provide protection from predators, giving them an advantage in competition. Additionally, gastropods may have specific adaptations to cope with environmental changes that frequently occur in the mangrove zone, such as fluctuations in water salinity (Meijer et al. 2021).

Table 3. Composition and relative abundance (R) of benthos in seaward and landward zone of mangrove forest in Batukaras, Pangandaran District, Indonesia

Family	Species	Seaward zone (ind/m^3)			R%	Landward zone (ind/m^3)			R%
		St.1	St.2	St.3		St.1	St.2	St.3	
Potamididae	*Terebralia palustris*	15	0	0	3.876	0	0	0	0.000
	Cerithidea cingulate	44	0	1	11.628	0	0	0	0.000
	Telescopium telescopium	0	0	1	0.258	0	0	0	0.000
	Terebralia sulcate	0	0	0	0.000	37	38	14	65.926
Neritidae	*Nerita costata*	1	1	6	2.067	0	0	0	0.000
	Pictoneritina oualaniensis	0	1	4	1.292	0	0	0	0.000
	Neritodryas cornea	0	0	0	0.000	5	5	8	13.333
	Neritodryas dubia	0	0	0	0.000	8	3	0	8.148
Ellobiidae	*Cassidula vespertilionis*	16	0	0	4.134	0	0	0	0.000
	Melampus fasciatus	8	0	3	2.842	0	0	0	0.000
	Ellobium aurisjudae	0	0	0	0.000	2	2	0	2.963
	Pythia imperforate	0	0	0	0.000	4	0	0	2.963
Pachychilidae	*Faunus ater*	46	59	72	45.736	0	0	2	1.481
Littorinidae	*Littoraria pallescens*	33	21	18	18.605	0	0	0	0.000
Ampullariidae	*Pila polita*	0	1	0	0.258	0	0	0	0.000
Paguridae	*Pagurus* sp.	4	8	16	7.235	0	0	1	0.741
Dotilidae	*Ilyoplax deschampsi*	3	1	4	2.067	4	1	1	4.444
Total abundance (ind/m^3)		161	95	131	100	60	49	26	100
			387				135		

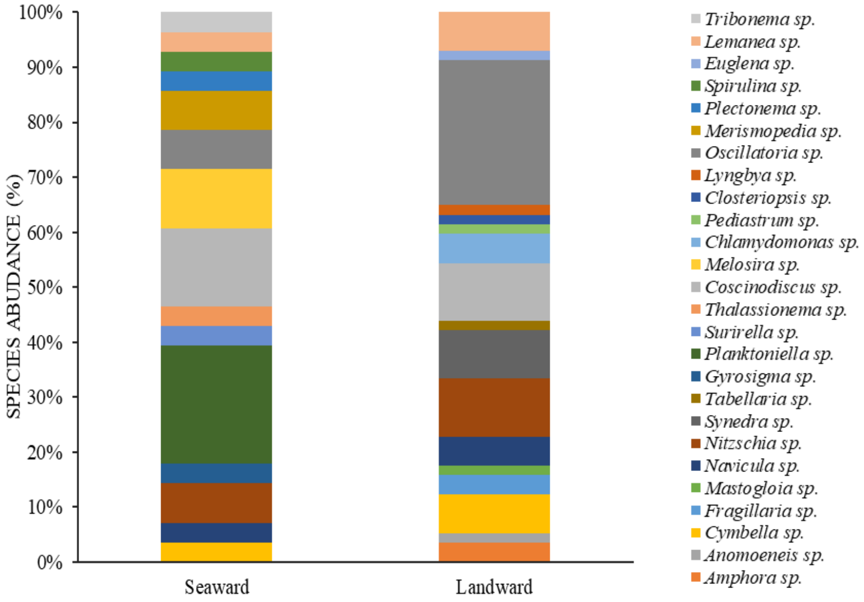

Figure 3. Pattern distribution phytoplankton in seaward and landward zones of mangrove forest in Batukaras, Pangandaran District, Indonesia

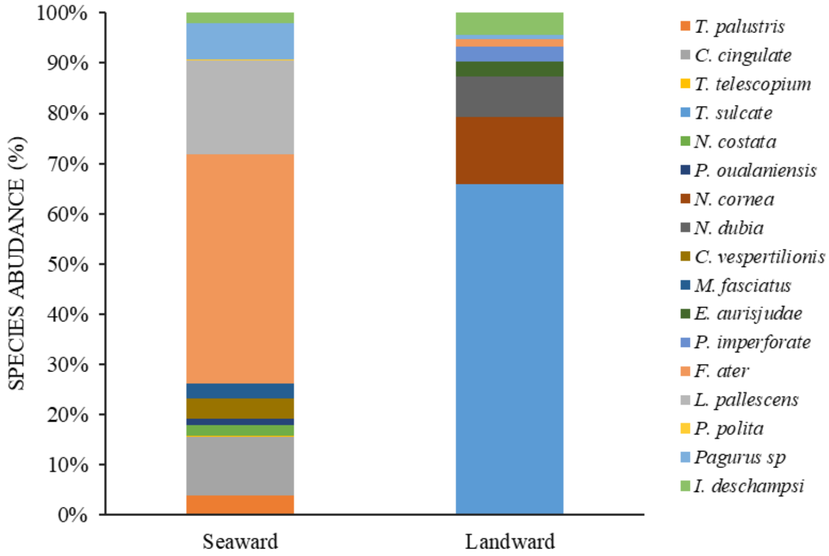

Figure 4. Pattern distribution benthos in seaward and landward zones of mangrove forest in Batukaras, Pangandaran District, Indonesia

Ecological index analysis of phytoplankton consists of the diversity index, equitability index, and dominance index in seaward and landward zones (Figure 5). Plankton diversity index (H') values obtained in seaward and landward zones were 2.363 and 2.130; those index values are categorized as moderate. According to Shannon Wienner, the value for the diversity index ranges from 1 to 3 and is classified as moderate. The diversity index in seaward zone is greater than landward zone. The equitability index (E) in landward and seaward zone are 0.886 and 0.873, which showed high phytoplankton equitability. The equitability index in seaward zone is greater than landward zone. Dominant species affect the equitability index. Dominance index (D) in landward and seaward zone are 0.143 and 0.122. Those values show no domination by a certain species of phytoplankton. Based on the Simpson Dominance Index, the value obtained at both locations shows a result close to 0. According to (Odum 1993), when the dominance index is close to 0, there is a low dominance or none. The dominance index is related to the diversity index. If the dominance index is low, the diversity index will be high. T-test diversity and phytoplankton abundance in seaward and landward zones differ significantly (<0.05).

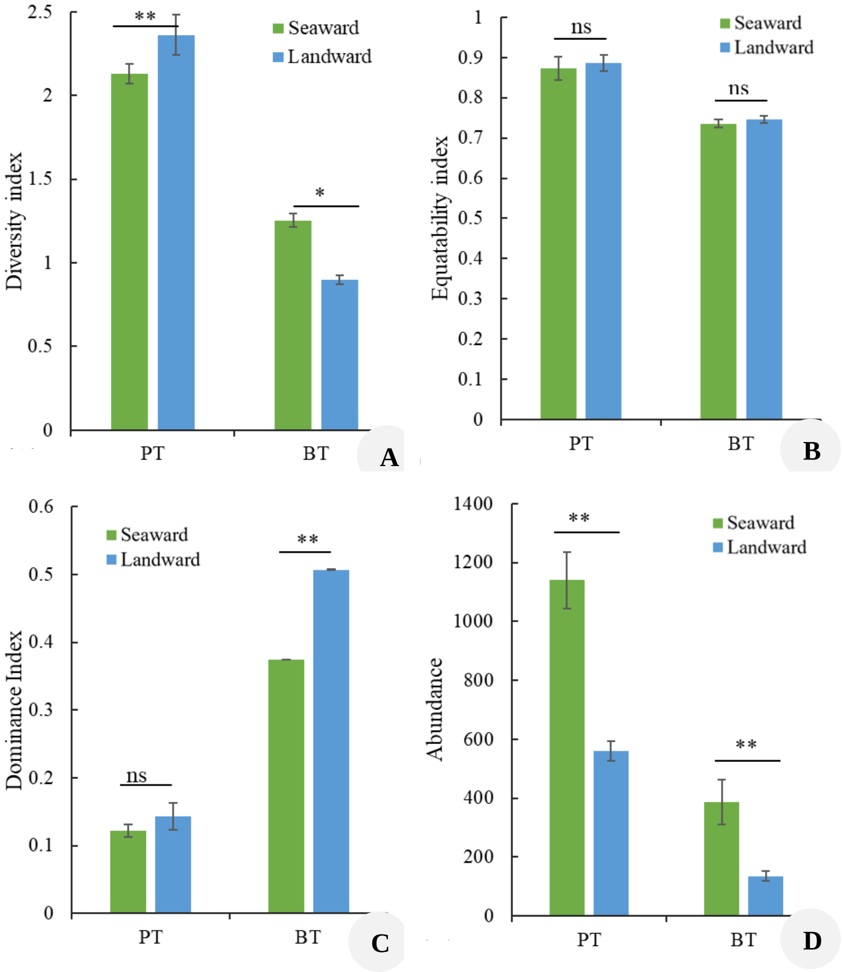

Figure 5. Ecological index analysis of phytoplankton and benthos in seaward and landward zone of mangrove forest in Batukaras, Pangandaran District, Indonesia. A. Diversity index of phytoplankton and benthos, B. Equatability index of phytoplankton and benthos, C. Dominance index of phytoplankton and benthos, D. Relative abundance of phytoplankton and benthos. Note: PT: Phytoplankton and BT: Benthos

Ecological indexes calculated are shown in Figure 5. Diversity indexes (H') in seaward and landward zone are 1.253 and 0.898, respectively. We can assume that seaward zone has a moderate diversity, but landward zone has low diversity. Equitability indexes in seaward and landward zone are 0.735 and 0.746, respectively. Those values show moderate equitability of benthos. The equitability index in the landward zone is higher than in the seaward zone. The possibility of nutrients produced from Nypa palm trees or periphytons was attached to the tree trunk to get its nutrients. Aquatic ecosystems have high organic matter, so the pattern of species distribution will be evenly distributed because nutrients are dispersed in aquatic ecosystems (Nybakken 1992). The dominance index in seaward zone is 0.375, which shows low dominance of certain benthos species. The Dominance index (D) of the benthos of landward zone was high, at 0.507, Indicates the relatively high level of *T. sulcate* (65%). This means that seaward zone has better ecosystem stability than landward zone. T-test diversity, abundance, and phytoplankton dominance in seaward and landward zones differ significantly (<0.05).

Discussion

The seaward zone is a conservation and ecotourism area of mangroves, and the surrounding area is used as a shrimp pond. This area is close to the sea and is directly affected by tidal waves. The seaward zone in Batukaras Mangrove Forest has six species of mangrove trees: *Rhizophora mucronata*, *Rhizophora apiculata*, *Avicennia alba*, *Avicennia marina*, *Bruguiera gymnorhiza* and *Sonneratia alba*. Meanwhile, many anthropogenic activities have occurred in the landward zone along the Cieunteung River, close to the settlement. The landward zone has only one species, *Nypa fruticans*. The primary productivity of water has a vital role in the carbon cycle and food chain (Xiao et al. 2015) and as a supplier of dissolved oxygen content (Zhang et al. 2014). NPP can be higher in the seaward zone of a mangrove ecosystem due to the convergence of various ecological factors that create a fertile and productive environment for plant growth. The seaward side of a mangrove zone is characterized by its proximity to the marine environment, which introduces specific conditions that influence NPP (Marchand 2017). Tidal influxes bring nutrient-rich seawater into the seaward zone, providing a continuous supply of essential elements like nitrogen and phosphorus (Taillardat et al. 2019; Wang et al. 2021). This influx supplements the nutrient pool for mangrove plants and supports the growth of phytoplankton and other aquatic primary producers (Wang et al. 2021). This strong photosynthesis and a nutrient-rich environment results in better growth rates and increased NPP (Behrenfeld et al. 2008). Mangrove litter is important as an indicator of productivity because it is the most readily quantifiable element of total NPP (Kamruzzaman et al. 2017). Litter falling from mangroves and entering the water is decomposed and mineralized, providing nutrients from carbon and nitrogen sources to the forest and surrounding waters (Zilius et al. 2020). This productivity supports the biodiversity and ecological vitality of the entire mangrove ecosystem and adjacent coastal waters.

NPP in landward zone of the mangrove ecosystem tends to be relatively lower compared to other areas due to a convergence of environmental factors that influence plant growth and ecosystem dynamics. This zone, transitioning from the more marine-influenced seaward areas to the terrestrial realm, experiences a distinctive set of conditions that shape its productivity. While the landward zone receives freshwater inputs from runoff and nearby rivers, these waters may carry fewer nutrients than the nutrient-rich seawater that influences the seaward zone (Stumpner et al. 2020). A limitation in nutrients can hinder the efficiency of this process, impacting the overall NPP of the landward zone (Chowdhury et al. 2019; Stumpner et al. 2020). Salinity fluctuations can impact water balance within plant tissues, affecting nutrient uptake and metabolic processes (Gupta and Huang 2014). Disturbances and stressors, both natural and human-induced, further influence NPP in the landward zone (Stumpner et al. 2020). The similarity in NPP between a mangrove zone's seaward and landward areas can be attributed to a combination of factors that tend to balance out the potential differences. Mangroves thrive in a unique environment that combines elements of both terrestrial and marine ecosystems. While the seaward side is exposed to saltwater and potentially higher light levels (Abdoulhalik et al. 2017), the landward side benefits from nutrient-rich freshwater inputs and a more diffused light environment due to canopy cover (Dharmawan et al. 2022). These factors may counteract each other, resulting in comparable NPP levels. Additionally, mangroves possess specialized adaptations to cope with their specific challenges, such as salt tolerance and tidal fluctuations, which could contribute to consistent productivity across zones. The intricate interconnectedness of these ecosystems also means that nutrient and energy flows can bridge the gap between the seaward and landward areas, minimizing productivity differences.

In contrast, the terrestrial zone showed an unexpected pattern where a significantly higher NPP of 36.463 mgC/m^3/h was associated with a phytoplankton abundance of 1.140 ind/m^3. This clear difference highlights the importance of considering other contributors to NPP besides phytoplankton. The terrestrial zone receives nutrient-rich detritus from mangrove litter, dynamic freshwater inputs from onshore sources, and complex interactions that drive nutrient cycling. The complex interactions between nutrient sources, ecological interactions, and environmental conditions in each zone demonstrate the intricate nature of this ecosystem and remind us of the multifaceted processes that support its productivity. While the observed antagonistic pattern challenges the expectation that high phytoplankton abundance is associated with high biomass, it underscores the multifaceted nature of NPP and the factors contributing to these different zones. In the marine zone, the NPP value of 105.83 mgC/m^3/h is not solely due to the phytoplankton abundance of 560 ind/m^3. Rather, it reflects the complex interplay of multiple ecological dynamics. The high NPP here is due to various factors, including nutrient-rich seawater from marine sources, constant light exposure, and complex nutrient exchange processes. The unique transitional nature of this zone between land and sea creates an environment where multiple influences converge, including nutrient inputs from both land and sea.

The differences in abundance and diversity of phytoplankton are different distribution patterns in both the seaward and landward zones. This variation underscores the selective nature of phytoplankton adaptation to specific salinity and mangrove conditions. It provides a critical link between phytoplankton types and the fundamental differences that characterize these two distinct regions. The Seaward zone has true mangrove plants, which are halophytic (salt-tolerant) plants that grow in intertidal zones and have several influences on phytoplankton communities in the seaward zone of a mangrove ecosystem. Mangroves can absorb nutrients from water and sediment, competing with phytoplankton for essential elements like nitrogen and phosphorus (Thatoi et al. 2013). This nutrient competition can limit the availability of resources required for phytoplankton growth, subsequently shaping their diversity and abundance (Augusta 2013). The canopy formed by mangrove vegetation casts shade over the water surface, affecting light penetration. This shading can hinder the growth of light-dependent phytoplankton species, leading to shifts in the composition of the phytoplankton community towards those better adapted to low-light conditions (Norman et al. 2022). As this organic matter decomposes, it influences nutrient availability and fosters bacterial growth (Palit et al. 2022). These bacterial communities can compete with phytoplankton for resources, playing a role in determining the makeup of the phytoplankton community (Palit et al. 2022). Consequently, these spatial variations influence the distribution and composition of phytoplankton. Additionally, some mangrove species release chemical compounds into the water that can inhibit the growth of specific phytoplankton species (Zhao et al. 2018). This allelopathic effect further contributes to the complex interactions shaping phytoplankton diversity in the seaward zone (Zhao et al. 2018).

Landward zone transitions from the more marine-influenced seaward areas to the terrestrial realm; it experiences unique conditions that shape the phytoplankton dynamics. Furthermore, the hydrology of the landward zone, shaped by tides and freshwater inflow, plays a role in determining phytoplankton distribution (Smits et al. 2023). One of the defining features of the landward zone is its proximity to terrestrial inputs, which can bring freshwater and nutrients into the ecosystem (Ward et al. 2020). This influx of nutrients, often carried by runoff from nearby land, can provide phytoplankton with the essential building blocks for growth, including nitrogen and phosphorus (Ward et al. 2020). Consequently, phytoplankton populations in this zone may exhibit higher growth rates and productivity due to the nutrient enrichment. Instead, phytoplankton adapted to lower light conditions might flourish in this shaded environment. Mangroves contribute to the landward zone by shedding leaves and other organic matter into the water. As this organic matter decomposes, it releases nutrients that can further support phytoplankton growth.

The abundance of benthos is higher in the seaward zone than in the landward zone. The benthic species diversity was gastropod and malacostraca classes. The Batukaras mangrove area on the seaward side is a mangrove restoration area due to the tsunami and is used for ecotourism. Increasing the area of mangrove restoration will increase biodiversity such as benthos (zu Ermgassen et al. 2016). Differences in benthic abundance, dominance, and diversity can be seen in the distribution patterns of species from both areas (Figure 5). Only certain species can survive and adapt to nutrient-poor substrates and terrestrial environments. Therefore, benthic species will determine the most fundamental differences between the two regions. True mangrove plants significantly influence benthos communities in the seaward zone of a mangrove ecosystem, creating a complex web of interactions that shape the structure and dynamics of this transitional habitat (Dharmawan et al. 2022). These interactions arise from the intricate relationships between mangroves, sediment characteristics, and the diverse array of benthic organisms that inhabit the area (Lee 2008; Kabir et al. 2014). The complex network of roots stabilizes sediment, preventing erosion and providing structural support. This stabilization directly impacts the distribution and abundance of benthos, as it creates substrates where various organisms can attach, burrow, and feed (Meijer et al. 2021). The roots also serve as shelter for small benthic organisms, offering protection from predation and creating a diverse array of microhabitats (Meijer et al. 2021). This organic matter from litterfall is a crucial food source for detritivores, microorganisms, and filter-feeding organisms among the benthos community (Ferreira et al. 2023).

The decomposition of mangrove-derived organic matter drives nutrient cycling and provides energy to the benthic food web, influencing the composition and abundance of benthos species (Schratzberger and Ingels 2018). The burrowing and bioturbation activities of benthos also facilitate the mixing of sediment layers, aiding in the distribution of nutrients and oxygen (Booth et al. 2023). Sediment serves as a basic substrate that creates distinct habitat layers for intertidal scavenging organisms. The substrate in the seaward zone is mud-flat with litterfall. Gastropods consume litterfall from mangrove plants to meet their nutritional needs. Muddy substrates are suitable habitats for most benthic animals, and sandy substrates for bivalves (Zulkifli and Setiawan 2012). Moreover, the nutrient-rich conditions associated with mangrove-influenced sediments can enhance the growth of filter-feeding bivalves and other suspension-feeding organisms (Kabir et al. 2014).

The landward zone of a mangrove ecosystem often exhibits lower abundance and diversity of benthic organisms compared to other areas within the ecosystem. Tidal inundation and varying water levels subject the area to rapid changes in salinity and moisture, which can pose challenges for benthic organisms (Luo et al. 2019). The fine sediments, often composed of silt and clay particles, can be less hospitable for benthic organisms that rely on coarser substrates for burrowing, attachment, and feeding (Das et al. 2017). This type of sediment can limit oxygen penetration and impact resource availability, thereby influencing the ability of benthic organisms to thrive (Das et al. 2017). Freshwater inputs from the land into the landward zone may carry fewer nutrients than seawater. Benthic organisms must contend for limited resources such as food and suitable substrate for attachment and burrowing. Moreover, disturbances stemming from human activities, pollution, and habitat alteration can disrupt benthic communities, exacerbating the challenges faced by these organisms (Harris 2019). In addition, the variability in salinity, though influenced by freshwater inputs, can fluctuate due to tidal and seasonal changes that can impact the distribution and tolerance of benthic species.

In conclusion, zoning differences in mangroves provide significant differences in the pattern distribution of phytoplankton and zooplankton community structure. Pattern distribution of phytoplankton and benthos in seaward and landward zones have moderate diversity. The seaward zone contributes significantly to high productivity, reflected in the NPP values, thereby impacting benthic life with a marked presence of high diversity in species and abundance. This contrasts with the diversity of phytoplankton species, where there is a low abundance. Due to the limited nutrients and biomass from terrestrial and river sources, the landward zone exhibits lower NPP values and limited benthos due to the scarcity of substrate biomass to support their survival. Conversely, this zone's relatively high abundance of phytoplankton can be attributed to its proximity to human settlements and land. This likely results in nutrient influx, providing ample nourishment for phytoplankton growth. The anticipated outcome of this research is to offer provide a fundamental basis for managing the Batukaras Mangrove Area, which serves as a protective zone against coastal waves and potential tsunami disasters in the Pangandaran, West Java.

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