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Spatial distribution of mangrove health index on three genera dominated zones in Benoa Bay, Bali, Indonesia

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Abstract. *Sugiana IP, Andiani AAE, Dewi IGAIP, Karang IWGA, As-Syakur AR, Dharmawan IWE. 2022. Spatial distribution of mangrove health index on three genera dominated zones in Benoa Bay, Bali, Indonesia. Biodiversitas 23: 3407-3418.* A study of mangrove forest stratification was conducted in Benoa Bay which experienced high coastal development pressures during the last decade. The study aimed to determine mangrove health index distribution (MHI) and forest community structures along three genera-dominated zones which were *Sonneratia*, *Rhizophora* and *Bruguiera*. A non-parametric random forest classifier on the Google Earth Engine (GEE) cloud computing environment was applied to classify the areas of distributed genera along the bay. Forest structure was assessed with 54 plots. The forest was mainly composed of *Rhizophora* and *Sonneratia*-dominated zones in a respective forest area proportion at approximately 51% and 45%. Those zones were dominated by *R. mucronata* and *S. alba* with an importance value index (IVI) at 266.35% and 145.57%, respectively. A narrow *Bruguiera* zone composed of *B. gymnorrhiza* domination was found in the most landward area, only covering 4% of the mangrove area. Overall accuracy and a *kappa* coefficient indicated high accuracy of forest classification at 97% and 0.94 respectively. We found that 47.44% of mangrove areas could be classified into the highest healthiness category indicating that the mangrove forest in Benoa Bay is in excellent condition. The *Rhizophora* zone made a significant contribution to the entire forest state since the excellent category coverage in this zone was approximately 73.80%.

Keywords: Community structure, mangrove forest, mangrove health index, zonation

INTRODUCTION

Mangrove species live in tidal environments and are highly adapted to a wide range of salinity gradients and anoxic substrates (Srikanth et al. 2015; Naido 2016). Their distribution depends on various estuarine profiles, i.e., coastal geomorphological type (Darmadi et al. 2012), salinity gradient (Ball, 1998; Yang et al. 2013) and nutrient content (Lovelock et al. 2009; Frederika et al. 2021). The salinity gradient formed through tidal and freshwater mixing in estuarine areas has contributed to plant diversity due to an optimum salinity range preference among mangrove species (Barik et al. 2018). The gradients of environmental conditions are responsible for forest structure from the sea to the landward area in a distribution perpendicular to the coastline (Sreelekshmi et al. 2018).

The mangrove ecosystem has significant role in coastal areas in terms of ecological, physical and socio-economic perspectives. Ecologically, the ecosystem provides carbon storage service and preferred habitat for living marine and terrestrial organisms both as feeding and nursery grounds (Ramdhun and Appadoo 2020). Mangrove forests can reduce damage to coastal areas caused by strong waves, hurricanes and tsunamis (Setiawan 2013; Karimah 2017; Adilah et al. 2018). Coastal mangrove communities around small islands are important to cope with sea-level rise effects and control saltwater intrusion along with coastal areas (Gilman et al. 2006; Wilson 2017). Mangrove ecosystems provide ecosystem goods such as wood, food and medicinal compounds (Walters et al. 2008; Mojiol et al. 2016). On the other hand, the aesthetic value of mangrove forests has potential for ecotourism purposes which support community livelihood (Friess 2017; Singgalen 2020). In terms of climate change, mangrove has been considered one of the most effective carbon sequestration areas for reducing greenhouse gasses in the atmosphere and mitigating global warming (Heriyanto and Subiandono 2016; Maher et al. 2018).

Indonesia has the largest mangrove forests with 22.4% of the global mangrove area (Giri et al. 2011) and Indonesian mangrove forests contribute to regulating global climate and delivers high-value ecosystem services. However, the forest area has decreased massively to about 48,025 ha in the last two decades, predominantly caused by land-use change for aquacultures and oil palm cultivation (Richard and Friess 2012; Kusmana 2014; Arifanti et al. 2019; Tosiani et al. 2020; Arifanti et al. 2021). Mangrove degradation in Indonesia has not only resulted in declines in forest area, but also decreases in forest quality (Nordhaus et al. 2019). Mangrove health index (MHI) was developed to determine forest quality state based on three stand structure dimensions, i.e., size, distribution and coverage. The MHI provides a single metric to determine mangrove healthiness and it is classified into three categories of mangrove states such as poor, moderate and excellent (Dharmawan et al. 2020b). The index was successfully modeled in spatial scale and highly correlated to a combination of several mangrove indices based on remote sensing analysis, i.e., NBR (Normalized Burn Ratio); GCI (Green Chlorophyll Index); SIPI (Structure Insensitive Pigment Index) and ARVI (Atmospherically Resistant Vegetation Index) (Nurdiansah and Dharmawan 2021a). Since it has been newly developed, MHI functionality needs to be tested comprehensively.

This study aimed to determine the spatial distribution of MHI along forest zones focused on Benoa Bay, Bali. Mangrove forest in the bay experienced a massive threat from coastal development activities in the last decade even though it is mostly included in a national forest management area; Taman Hutan Rakyat (TAHURA) Ngurah Rai Bali Ministry of Forestry and Environment. This study assessed the range of MHI values for each zone and described a holistic interpretation of mangrove healthiness. Community structure for each zone was included to clarify species composition and stand structure for each zone.

MATERIALS AND METHODS

Study description

This study area was located in the mangrove forest in the semi-enclosed Benoa Bay, Bali (8º42'16.2"S-8º47'48.1"S, 115º14'50.8"-115º10'28.1"). Mangrove forest in the bay is in the Ngurah Rai Grand Forest Park (TAHURA) by the Ministry of Forestry and Environment, consisting of a protection and utilization area of about 1.132,00 ha (Figure 1). The rest is a settlement, open land and waterbody, approximately 16.27 ha, 49.35 ha and 144.01 ha consecutively (BPKH Wilayah VII Denpasar, 2013). Wiyanto and Faiqoh (2015), Andiani et al. (2021); Dewi et al. (2021), Sugiana et al. (2021) identified three mangrove genera which dominated in this area: *Sonneratia*, *Rhizophora* and *Bruguiera*. *Rhizophora* and *Bruguiera* tend to grow in a muddy substrate with less oxygen content and less saline water. In contrast, *S. alba* species which was majority found in *Sonneratia* zone, had a better adaptation to the sandier and more porous substrate with a higher water salinity level (Sugiana et al. 2021).

Forest classification determination

Mangrove forest was classified into three genera-dominated zones; *Rhizophora*, *Sonneratia*, and *Bruguiera* based on previous studies (Wiyanto and Faiqoh, 2015; Andiani et al. 2021; Dewi et al. 2021; Sugiana et al. 2021). The classification analysis was applied using the Random Forest supervised machine learning algorithm on the Google Earth Engine cloud computing platform (Ghorbanian et al. 2021). A cloud-free Sentinel-2 Level 2A surface reflectance (SR) image was produced by aggregating collected images from September 2020 to April 2021 and reducing them using the median value for each pixel in all bands. The study area was bordered through the national mangrove polygons specifically in Benoa Bay. Training and validation data were collected on each zone in difference number of pixels. As many as 1886 pixels and 1218 pixels of the Sentinel-2 SR image were used to train and validate forest classification in all zones, respectively. Genera domination for all pixels was confirmed through two approaches; ground-truth surveys and manual interpretations from a high-resolution image on Google Earth. A producer accuracy test was applied to determine the classification performance in the training area pixels, while consumer accuracy was computed along entire mangrove pixels in Benoa Bay. Those tests represented the accuracy of classified forest areas for each zone. In addition, overall accuracy (%) and a *kappa* coefficient were calculated to detect forest classification performances in all mangrove zones.

Mangrove community structure measurement

Density, dominance and frequency for each species and stands level determined from measured DBH value were used to calculate relative values and then the important value index (IVI). Fifty-four quadratic-10m x 10m plots were distributed purposively in each genera-dominated zone, i.e. 25 plots in the *Sonneratia* zone, 22 plots in the *Rhizophora* zone and seven plots in *Bruguiera* zone (Figure 1). Species identification was applied for each measured stand based on Tomlinson (2016) and Kitamura et al. (1997). The DBH (diameter at breast height) of all stands was measured on each plot and then classified into tree (DBH≥5 cm) and sapling category (DBH<5 cm). Mangrove community height for each zone was estimated using a trigonometric approach by measuring several angles of the top-most forest canopy at a 10-meter distance. Hemispherical photography was applied to estimate mangrove canopy coverage in each zone (Dharmawan, 2020). As many as nine photographs were distributed on each plot. A smartphone with camera resolution of at least 3MP captured squared output hemisphere photographs from scattered positions on each plot. Each picture was analyzed using ImageJ software to count pixel numbers. Canopy coverage percentage was calculated by comparing the pixel number of vegetation objects to the total pixels on each photograph.

The MonMang 2.0 app was used to efficiently record and process the field data measurement. The Shapiro-Wilk normality test was applied to univariate data from each zone, i.e., sapling and tree density, canopy coverage percentage, estimated tree height, and measured stem diameter. One-way ANOVA was generated for normally distributed parameters followed by the Tukey HSD test. Statistical analysis was proceeded by an open-source application, R-studio (Lubis 2021).

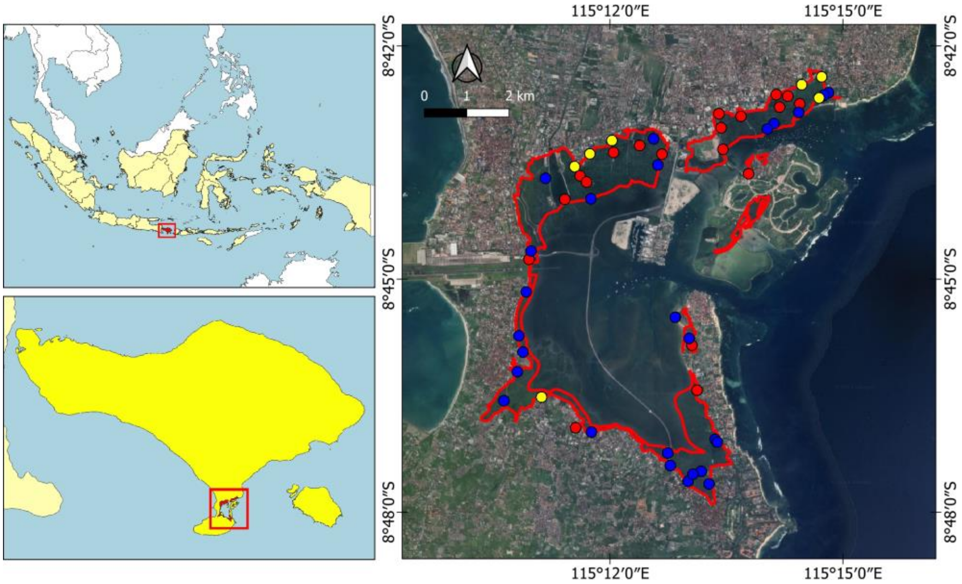

Figure 1. Distribution of forest assessment plots representing each mangrove zone i.e. *Sonneratia* (blue dots), *Rhizophora* (red dots) and *Bruguiera* (yellow dots)

Spatial distribution of MHI along forest zones

A cloud-free Sentinel-2A imagery was used to delineate forest classification in each classified zone coverage. The spatial distribution of MHI was analyzed based on high accuracy (R^2 = 0.831) model developed by Nurdiansah and Dharmawan (2021a), which combined four selected vegetation indices, i.e., NBR (Normalized Burn Ratio); GCI (Green Chlorophyll Index); SIPI (Structure Insensitive Pigment Index) and ARVI (Atmospherically Resistant Vegetation Index) and utilized several Sentinel-2 bands Near Infrared (NIR); Shortwave Infrared - (SWIR), red green and blue bands.

MHI = 102.12*NBR - 4.64*GCI +178.15*SIPI + 159.53*ARVI - 252.39

Where:

NBR = (NIR - SWIR) / (NIR + SWIR)

GCI = (NIR/green) - 1

SIPI = (NIR - blue) / (NIR - red)

ARVI = (NIR - 2.red + blue) / (NIR + 2.red + blue)

The model successfully assessed MHI spatial distribution through cloud-free satellite images. Min-max standardization was applied to standardized MHI range values. Mangrove healthiness was classified into three basic categories based on the MHI range, i.e., poor (0-33%), moderate (33%-66%) and excellent (66%-100%) (Dharmawan and Ulumuddin 2021). A descriptive analysis was conducted along pixels on each zone to determine several values: mean, range (minimum and maximum), standard deviation, median, and first and third quartile.

RESULTS AND DISCUSSION

Mangrove classification

Mangrove forest in Benoa Bay was clearly distinguished into three genera-dominated zones, which were *Sonneratia*, *Rhizophora* and *Bruguiera* (Figure 2). These genera had different distribution preferences along the bay. *Sonneratia*-dominated zones tended to grow in the seaward area, while the *Bruguiera* forest was mainly found near the land and occupied a smaller area. This result was supported by a previous study that found *R. apiculata, S. alba*, and *B. gymnorrhiza* were the three major dominant plants in Benoa Bay mangroves (Sundra 2016). Martiningsih et al. (2015) found only two main dominant species, *R. apiculata* and *S. alba*, in Benoa Bay Bali. They did not find *Bruguiera* domination in their perpendicular transect lines. The *Bruguiera*-dominated zone was distributed along a limited and narrow area in the landward zone, which was difficult to cover using a limited line transect. Another study also revealed that *R. apiculata* and *S. alba* were the cosmopolitan species in this area, while *Bruguiera* mixed with those species (Prinasti et al. 2020). The *Sonneratia*-dominated zone was mostly composed of monospecific stands of *S. alba*, which was considered a native plant due to a larger tree diameter size of more than 15 cm (Dewi et al. 2021).

Forest classification results had a high overall accuracy and *kappa* coefficient at 97% and 0.94, respectively (Table 1). Those values indicated that classification based on training data through Random Forest was highly accurate in determining the genera-dominated zones' distribution in Benoa Bay. McHugh (2012) explained that a *kappa* statistic value in the highest range (0.9 - 1.0) indicated a high correlation between training and validation data variation. A similar technique has been applied by several studies to classify mangrove forests. Jhonnerie et al. (2015) implemented a random forest technique with 81% and 0.76 respective overall accuracy and *kappa* statistics to define mangrove forests using Landsat 5 TM and Alos Palsar Imageries. Another study declared a better accuracy at 95.89% with a *kappa* coefficient of 0.95 based on Worldview imagery (Jiang et al. 2021). Sentinel-2 imagery had a better spatial resolution; hence classification resulted in better accuracy. Based on Sentinel-2 imagery, mangrove ecosystem mapping in Qeshm Island, Iran, also had high overall accuracy and *kappa* coefficient at 93.23% and 0.92, respectively (Ghorbanian et al. 2021). Sentinel-2 was fitted to classify mangroves among species levels using random forest classification (Behera et al. 2021). However, the number and distribution of training data significantly affected classification accuracy and error (Millard and Richardson 2015).

According to area calculation analysis for each zone, *Rhizophora* forest had the most extensive mangrove area with approximately 603.56 ha or about 51% of the forest area in Benoa Bay (Figure 3). Similarly, the *Sonneratia* forest occupied an extensive area mainly along the seaward zone, with about 45% of the total mangrove forest. Only 41.65 ha or about 4% of mangrove forest was defined as a *Bruguiera*-dominated forest.

In this study, *Rhizophora* had a majority distribution in the middle to the landward area of mangrove forest both as a growing rehabilitated mangrove and as native stands. *Rhizophora* species were mostly selected and planted 30 years ago from 1992 to 1999 through The Development of Sustainable Mangrove Management Project established by a collaboration between Japan International Cooperatian Agency (JICA) and Indonesia's Ministry of Forestry to restore mangroves in TAHURA forest in Benoa Bay from abandoned ponds (JICA, 1999). Approximately 200 ha of abandoned ponds was rehabilitated using *Rhizophora* seedlings (JICA, 1999). A temporal analysis found that the mangrove area declined to 96.21 ha during a five-year observation from 2015 to 2020 in Benoa Bay (Nurhaliza et al. 2021).

Sonneratia forest area has experienced a gradual decline due to high sedimentation rates in Benoa Bay mainly triggered by highway and harbor construction through reclamation activities. A spatial study using Sentinel-2 imagery showed that the dieback affected approximately 2.43 ha of mangrove area. The damages expanded to about 7.41 ha in 2018 and reached 8.95 ha in January 2019 (MongaBay 2019). Andika et al. (2015) revealed that sedimentation area increased significantly by 1966.14 ha during the initial stage of highway construction in 2015. Consequently, pneumatophores of *Sonneratia* were buried by sediment deposition; hence oxygen uptake was inhibited. This case drove a dieback phenomenon in the mangrove forest (Nardin et al. 2021).

Mangrove community structure

The *Sonneratia*-dominated zones in this study had the lowest species diversity compared to other zones, with only four and two species on tree and sapling levels, respectively (Table 2). Species of *S. alba* had a majority distribution in *this zone* (IVI: 266.35%), followed by three other *Rhizophora* species, i.e., *R. apiculata*, *R. mucronata* and *R. stylosa*, at tree level and only *R. apiculata* at sapling level (Figure 4). The seaward forest dominated by *S. alba* was frequently found in a low mangrove species diversity. Similar studies on mangrove structure in Southeast Sulawesi, Central Sulawesi and West Java provinces only found three species in the *Sonneratia*-dominated zone (Rahman et al. 2014; Ramdani et al. 2015; Schaduw, 2020; Siregar et al. 2022). Mangrove in a Papuan small island was only composed of two species which were dominated by *S. alba*, and another species was *R. stylosa* (Nurdiansah and Dharmawan 2021a). Even in an oceanic mangrove on Owi Island-Papua, *S. alba* had total domination of the entire forest with a maximum IVI value. (Dharmawan and Pramudji 2019).

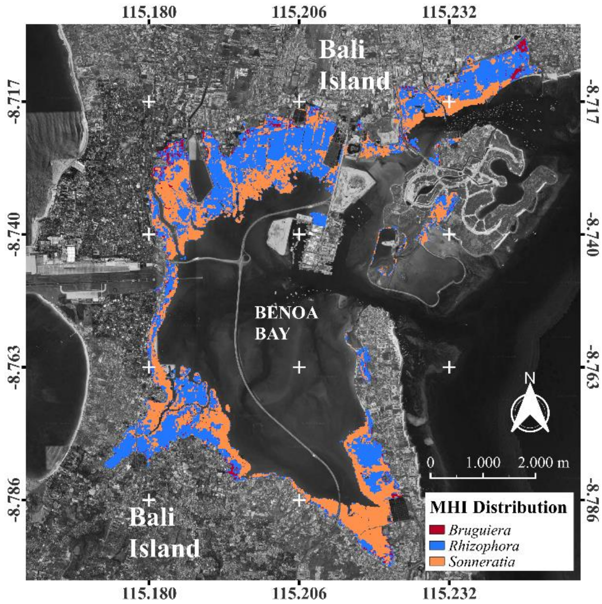

Figure 2. Spatial distribution of mangrove genera-dominated zones in Benoa Bay, Bali, Indonesia

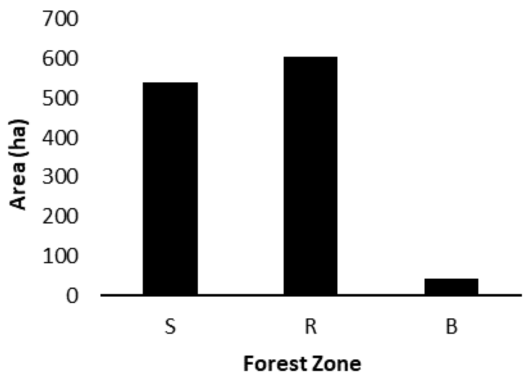

Figure 3. Area of each genera-dominated zone (S: *Sonneratia*; R: *Rhizophora* and B: *Bruguiera*) in Benoa Bay's mangroves

Table 1. Accuracy assessment for forest classification analysis based on field data validation for each mangrove zone

Accuracy Tests	Zone		
	Sonneratia	***Rhizophora***	***Bruguiera***
Producer accuracy (%)	98.99	93.58	92.60
Consumer accuracy	98.02	94.88	86.21
Overall accuracy			97.13
Kappa coefficient			0.94

Table 2. Mangrove species composition in three genera-dominated zones in Benoa Bay, Bali, Indonesia

Mangrove species	Zone					
	Sonneratia		***Rhizophora***		***Bruguiera***	
	Tree	**Sapling**	**Tree**	**Sapling**	**Tree**	**Sapling**
S. alba	+	+	+	+	+	-
R. apiculata	+	+	+	+	+	+
R. mucronata	+	-	+	+	+	+
R. stylosa	+	-	+	+	-	-
L. racemosa	-	-	+	+	-	-
B. gymnorrhiza	-	-	+	+	+	+
X. granatum	-	-	+	+	-	-
A. marina	-	-	-	-	+	+
Number of species	4	2	7	7	5	4

Note: (+): present; (-): absent

The *Rhizophora*-dominated zone was the most diverse with seven species found both at tree and sapling levels (Table 2). Mangrove species *R. mucronata* was the main component of this zone based on its IVI value 145.57%, followed by *S. alba*, *R. apiculata*, *R. stylosa*, *L. racemosa*, *X. granatum* and *B. gymnorrhiza* (Table 1). Another research was conducted on Indonesian mangroves in Gorontalo (Kasim et al. 2019), North Maluku (Serosero et al. 2020), East Kalimantan (Edwin et al. 2021), and West Lombok (Sukuryadi et al. 2021) recorded 9, 10, 15 and 12 species, respectively. However, species composition in Benoa Bay's *Rhizophora* zone had a higher species number than Mare Island (Akbar et al. 2016), Jakarta Bay (Sari et al. 2019), Situbondo, East Java (Hariyanto et al. 2019), Mantehage-Paniki Islands, North Sulawesi (Opa et al. 2019) and Cirebon (Purwanto et al. 2022) were only found five true mangrove species. Several mangrove species were co-dominantly identified with *Rhizophora*, such as *A. alba*, *B. hainesii*, *B. parviflora*, *E. agallocha*, *H. littoralis*, *L. littorea*, *S. hydrophyllacea*, *S. ovata* and *X. moluccensis*, as found in Riau (Prianto et al. 2006), and *A. officinalis*, *B. cylindrica*, *B. sexangula*, *S. caseolaris* in North Sumatra, Indonesia (Harefa et al. 2022). The importance value index of the *Rhizophora* genus in this zone was 217.23%, while the cumulative IVI of other species was only 82.77% (Figure 4). Additional research was conducted on Indonesian mangroves in North Gorontalo (Usman et al. 2013); North Sumatera (Hotden et al. 2014); West Bangka (Rosalina and Rombe 2021) and Benoa Bay (Dewi et al. 2021) found that the *Rhizophora* genus has a higher value compared to other species.

The *Bruguiera*-dominated zone consisted of five mangrove species in the tree stand category and four species on sapling levels (Table 2). *B. gymnorrhiza* was dominated in this zone at IVI 160.13%, followed by *S. alba*, which was only found at the tree level, while *R. apiculata*, *R. mucronata* and *A. marina* were observed in both stand levels (Table 2, Figure 4). The number of mangrove species found in this zone was more diverse than Sorong, Papua (Yanti et al. 2021), Okinawa Island, Japan (Kamruzzaman et al. 2017), and Kosrae Island, Federated States of Micronesia (Krauss and Allen 2003) which only found three mangrove species. *B. gymnorrhiza* was found to be monospecific on a small Papuan island (Dharmawan and Pramudji 2019).

Overall, there were eight species of mangrove found in Benoa Bay along all zones. Previous studies in the bay have reported other species such as *Aegiceras floridum*, *Avicennia officinalis*, *A. rumphiana*, *B. cylindrica*, *B. sexangula*, *Ceriops tagal* and *S. caseolaris* (Wiyanto and Faiqoh, 2015; Prinasti et al. 2020). The distribution of mangrove species along forest zones is mainly determined by variations in environmental characteristics. Mangrove substrates in Benoa Bay are mainly dominated by mud in the land zone to the middle area and sandy soils in the sea zone. Prinasti et al. (2020) and Imamsyah et al. (2021) reported that the soil types in Benoa Bay ranged from fine sand to gravel with dominant coarse sand. Sugiana et al. (2021) found that the mangrove landward and middle zone in Benoa Bay had a predominant muddy substrate and significantly lower salinity levels than seaward sites. Those studies have confirmed the mangrove species distribution pattern in the Bay. *S. alba* tends to grow in sandy, rocky or coral rubble substrates usually located in higher salinity areas (Noor et al. 2006; Dharmawan and Pramudji 2020; Nurdiansah and Dharmawan, 2021a). This species also tolerates high salinity levels (Pillai and Harilal 2016), and even sandy to gravel mud soil (Bessie et al. 2013; Lewerissa et al. 2018). *S. alba* has been considered a pioneer species that forms the main layer of the seaward side of the forest where there is a sandy substrate (Goltenboth et al. 2006; Jenoh et al. 2016; Mughofar et al. 2018). Forests dominated by this species contained less diversity (Rahman et al. 2014; Supriadi et al. 2015; Wiyanto and Faiqoh 2015; Andiani et al. 2021; Dewi et al. 2021; Sugiana et al. 2021). *Rhizophora* and *Bruguiera* were frequently found in muddy substrates and lower salinity areas, even though *Bruguiera* had a preference for less submerged substrates (Primantara et al. 2019; Khairunnisa et al. 2020).

In terms of stand distribution, the most significant tree stand density was found in the *Rhizophora*-dominated zone at an average of 4750 ± 2867 stands.ha^{-1}, while *Sonneratia* forest had the lowest tree density at 2332 ±786 stands.ha^{-1} (Table 3). The number of tree stands in the *Sonneratia* zone had a significant difference (ANOVA: $p < 0.05$) compared to *Rhizophora* and *Bruguiera*-dominated zones. Similar conditions were found in East Kalimantan (Ardiansyah et al. 2012) and Middle Maluku (Nanulaitta et al. 2019), where *S. alba*-dominated zone had lower tree and sapling density than *R. apiculata*, also *R. mucronata* in Benoa Bay (Andiani et al. 2021; Dewi et al. 2021; Sugiana et al. 2021) and *B. gymnorrhiza* in Biak Regency, Papua (Rambu et al. 2019). Tree density was highly correlated to the stand diameter average. The high density of mangroves causes competition in getting nutrients and solar radiation, which disrupts the lateral growth of mangroves (Syukri et al. 2018). This study found that the *Sonneratia*-dominated zone had the largest average trunk diameter at 14.12±3.15 cm, while the *Rhizophora* and *Bruguiera* zones were found at 9.94±2.39 cm and 7.86±1.91 cm, respectively. Dharmawan et al. (2020b) explained that less-disturbed forests dominated by *S. alba* tended to have a larger trunk size due to the sparser distribution in certain areas. Compared to other studies, *Sonneratia* stands diameters in Benoa Bay seem to be lower than Belitung Island with 15.46±1.92 cm of diameter average (Suyarso et al. 2018) and Ternate with 16.63±1.73 cm of mangrove diameter average (Arbi et al. 2018). Compared to similar research in West Halmahera, North Maluku, which found similar species to Benoa Bay, tree density in *Sonneratia*, *Rhizophora* and *Bruguiera* mangroves were lower than Benoa Bay at 1200 stands/ha, 3600 stands/ha and 2000 stands/ha respectively (Gabi et al. 2021). A dense mangrove forest tends to have a small stands diameter. The result was supported by Dharmawan et al. (2020a), who conducted research in Biak-Numfor Regency and Siringoringo et al. (2017) in North Nias Regency; while *S. alba* dominated the mangroves forest, it was mostly had low density with a large diameter.

In contrast with tree density, sapling stands in the *Sonneratia* mangrove zone were found at a lower density than in other zones at 356 ± 324 stands.ha^{-1}. However, the average had no significant difference to *Rhizophora* zones (ANOVA: $p > 0.05$). The highest sapling density was found in the *Bruguiera* zone with 1514 ± 883 stands.ha^{-1}, significantly different from other zones (ANOVA: $p < 0.05$). In pristine forest, sapling density in *Rhizophora* was relatively limited since tree stands dominated space (Dharmawan and Widyastuti 2017) and nutrient competition (Koch 1997). In contrast, degraded mangrove forests have been found to have many saplings; for instance, from 2010 to 2017, the mangrove forest in East Java experienced a massive decrease caused by illegal logging of 39,756.2 ha (Rudianto and Bengen 2020). A previous study on Belitung Island found a variable comparison of sapling density in each genera-dominated zone (Akhrianti et al. 2019). The forest had no saplings in *Sonneratia* forest, while *Bruguiera* had a limited number at only 320 stands/ha, and a frequently harvested *Rhizophora* forest was found to have saplings density of up to 3600 stands/ha compared to Benoa Bay. The low density of mangrove sapling in the *Sonneratia* zone was caused by the allelopathic secretion ability of *S. alba*, which inhibits lower stands growth (Xin et al. 2013; Lin et al. 2015; Zhang et al. 2018).

Mangrove canopy coverage in Benoa Bay ranged from 52.99%±12.72% to 78.08%±6.51%. *Sonneratia*-dominated forests had the lowest canopy coverage, which was significantly different ($p < 0.05$) from both *Rhizophora* and *Bruguiera* zones (Table 3). The species *S. alba*, which dominated in the *Sonneratia* zone, tended to have a lower coverage due to sparse leaf density and lower stand distribution. At the same time, *Rhizophora* and *Bruguiera* were characterized by a canonical shape of canopy with individual dense leaves (Dharmawan 2020). A previous study also found that the *Sonneratia* forest had a lower canopy coverage both in Benoa Bay (Andiani et al. 2021; Dewi et al. 2021; Sugiana et al. 2021) and also other locations, i.e., at Tidore Island (Nurdiansah and Dharmawan 2018) and Middleburg-Miossu Island, West Papua (Nurdiansah and Dharmawan 2021a).

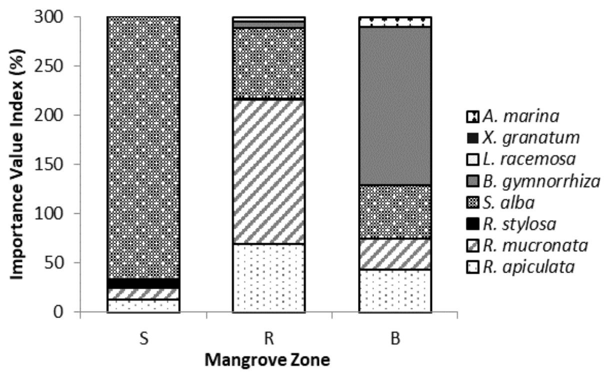

Figure 4. Importance value index (IVI) of each mangrove species along zones (S: *Sonneratia*; R: *Rhizophora* and B: *Bruguiera*) in Benoa Bay, Bali, Indonesia

Table 3. Mean value of tree and sapling density (stands.ha^{-1}), diameter (cm), height (m) and canopy coverage (%) on each mangrove zones in Benoa Bay, Bali, Indonesia

Parameter	Zone		
	Sonneratia	***Rhizophora***	***Bruguiera***
Tree Density (stands.ha^{-1})	2332 ±786^a	4750 ± 2867^b	5157 ± 1615^c
Sapling Density (stands.ha^{-1})	356 ± 324^a	700 ± 1120^a	1514 ± 884^b
Diameter (cm)	14.12 ± 3.15^a	9.94 ± 2.39^b	7.86 ± 1.91^c
Height (m)	9.14 ± 2.29^a	10.57 ± 2.39^a	10.55 ± 3.00^a
% Canopy Cover	53.00 ± 12.72^a	75.33 ± 6.23^b	78.08 ± 6.51^b

Note: Letters a, b, and c represented the results of the one-way ANOVA followed by the Tukey HSD test which different letters gave had indicated the significant difference ($p < 0.05$) result of each parameter among mangrove zones

Forest height average was not significantly different among sites in Benoa Bay (ANOVA: $p > 0.05$). The height of the mangrove stands in the *Sonneratia*, *Rhizophora*, and *Bruguiera* zones were 9.14±2.29 m, 10.57±2.39 m, and 10.55±3.00 m, respectively. Stand size of mangrove was naturally influenced by environmental characteristics of mangrove habitat and competition ability in nutrient, light, water, and CO_2 uptake (Mustika et al. 2014). It was related to the natural adaptation of each mangrove species to habitat conditions. The current size of the mangrove stand was also affected by historical threats faced by the forest. In the 1990s, Benoa Bay mangroves experienced a massive conversion into aquaculture ponds; hence Indonesian government dan JICA took the initiative to restore them during 1992-1999 (JICA, 1999). In contrast, less disturbed mangrove forest in several mangrove sites in Indonesia were found in a larger forest height, such as Tidore: 29.43±3.38 m (Nurdiansah and Dharmawan 2018), Padaido islands: 16.64±1.74 m (Dharmawan and Pramudji 2019) and Middleburg-Miossu Island: 15.49±0.64 m (Nurdiansah and Dharmawan 2021a).

Spatial distribution of MHI

The spatial distribution of mangrove healthiness in Benoa Bay was varied, seemingly depending on threat sources and their intensity. Anthropogenic activities around the mangrove areas significantly impact their growth and distribution since it is located in a semi-closed bay. Reclamation activity in the bay potentially reduced mangrove areas and healthiness, in particular in the seaward zone. Several studies showed the potential impact of reclamation in reducing mangrove ecosystem function and services, including habitat, carbon, and biodiversity losses (Wang et al. 2010; Tay et al. 2018; Slamet et al. 2020). Mangrove degradation due to reclamation had not only a direct relationship to land use shifting in the reclaimed area but also an indirect impact on the massive sedimentation rate in the adjacent ecosystems on the bay (Andika et al. 2015).

The impact of anthropogenic threats in Benoa Bay since 2015 was figured out through spatial distribution of mangrove healthiness in this study. Based on the mean value of MHI from all pixels, the mangrove condition was categorized into a moderate state at 60.91±10.06% and ranging from 0.16% - 99.98% (Table 4). This study had similar results on MHI values to Middleburg-Miossu Islands, estimated at 60.70% (Nurdiansah and Dharmawan 2021a). Middleburg-Miossu mangrove had a similar pattern of canopy coverage to Benoa Bay mangroves which were denser in the *Rhizophora*-dominated forest. However, the site had a lower stand density range from 800 stand ha^{-1} to 3300 stand ha^{-1} and was composed of larger trunk diameter at about 7.23 cm-24.67 cm. Those three parameters were the main components in calculating plot-based MHI (Dharmawan et al. 2020). Another study on Liki Island computed a similar mean value of MHI at about 60.03% (Nurdiansah and Dharmawan 2021b). *Rhizophora*-dominated forest in Benoa Bay mangrove was found with the highest MHI average at 67.15±9.08% and ranging from 0.40% to 96.91%, while the *Sonneratia* zone had the lowest MHI, 60.34±8.93% in a slightly wider range than *Rhizophora* zone at about 0.16% - 99.98%.

According to the MHI spatial distribution area, most of Benoa Bay mangroves were recognized as excellent health state at approximately 564.96 ha (47.74%) (Figure 5 and 6). Meanwhile, the moderate and poor categories covered about 40.76% and 11.51% of the total mangrove area in the bay, respectively. The excellent mangrove category was mainly found in the *Rhizophora*-dominated zone of 445 ha, whereas the moderate and poor categories were mainly found in the *Sonneratia*-dominated zone.

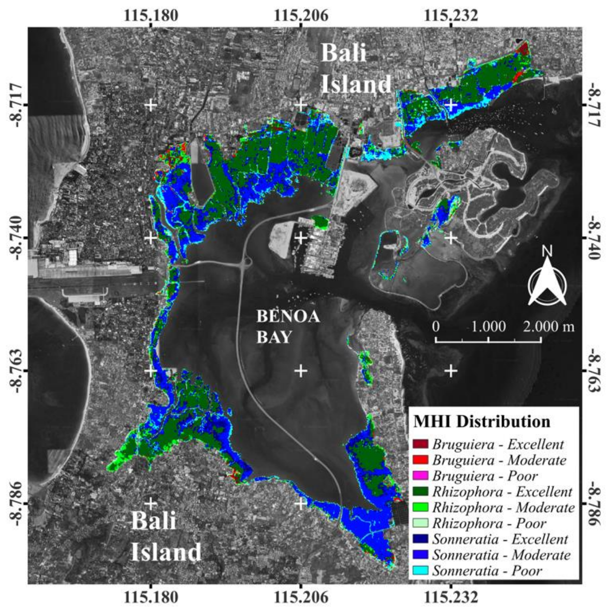

Figure 5. Distribution of MHI for each mangrove zone in Benoa Bay, Bali, Indonesia

Table 4. Descriptive statistical parameters of MHI value on each genera-dominated zone in Benoa Bay mangrove

Descriptive statistical parameters	Forest zone			
	Sonneratia	***Rhizophora***	***Bruguiera***	**All zones**
Mean ± Standard deviation (%)	60.34±8.93	67.15±9.08	65.13±4.87	60.91±10.06
Min	0.16	0.40	38.95	0.16
Max	99.98	96.91	76.58	99.98
Median (Q2)	62,75	70.25	65,61	63.24
Q1	57,76	66.25	62,12	58.76
Q3	65,75	72.25	68,86	66.24

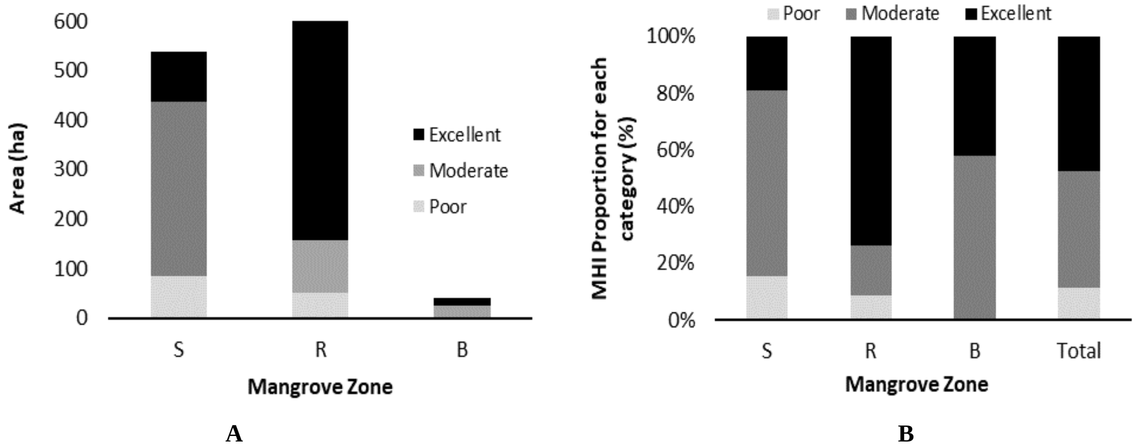

Figure 6. Area of each MHI category (A) and their proportion (B) on each genera-dominated zone in Benoa Bay, Bali, Indonesia

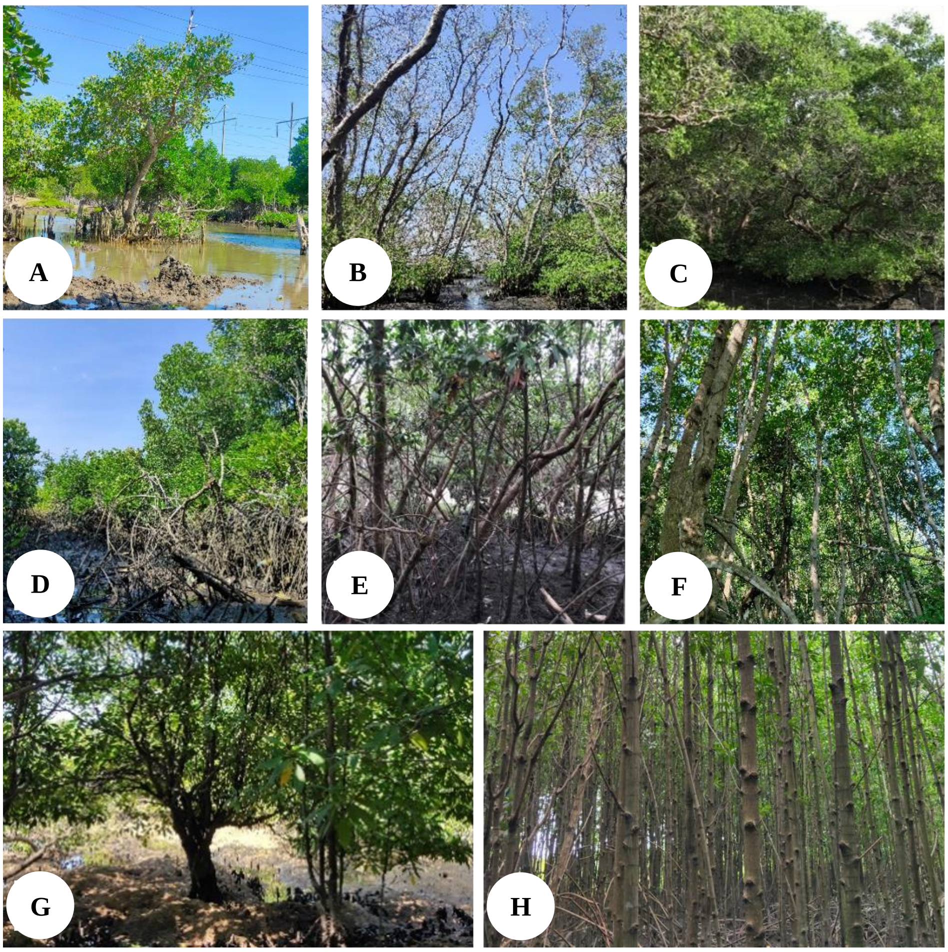

Figure 7. Field observation for each category of MHI along mangrove zones in Benoa Bay, Bali, Indonesia. A-C. a respective poor, moderate, and excellent condition of *Sonneratia*-dominated forest; D-F. represented poor, moderate, and excellent category of *Rhizophora* dominated zone, respectively; G-H. moderate and excellent *Bruguiera* forest

Figure 8. Mangrove dieback phenomenon in Benoa Bay, Bali, Indonesia, due to massive sedimentation on the seaward area

A high area proportion of MHI in the poor category was contributed by the *Sonneratia* zone, followed by *Rhizophora* and *Bruguiera* zones. It was mainly caused by a large area of dieback in the most seaward zone (Figure 8).Dieback is a deadly gradual process of mangrove stands initiated by reducing canopy density or a massive loss of mangrove leaves due to continuous depletion of oxygen uptake through root systems. The dieback mangrove is primarily triggered by sedimentation, which buried mangrove roots in Benoa Bay. Satellite imagery analysis showed that the dieback event expanded near the reclamation sites (Prasetio 2019). Mangrove dieback in the bay mostly affected the *S. alba* species since this species was dominant in the seaward where the massive sedimentation occurred (MongaBay 2019).

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