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Mangrove zonation, community structure and healthiness in Kei Islands, Maluku, Indonesia

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Abstract. *Dharmawan IWE, Renyaan J, Nurdiansah D. 2022. Mangrove zonation, community structure and healthiness in Kei Islands, Maluku, Indonesia. Biodiversitas 23: 4918-4927.* Forest structure and quality were studied in an archipelagic site in Indonesia which consists of estuarine and oceanic mangrove habitats. This study aimed to determine mangrove structure and estimate the spatial distribution of forest healthiness along the zones dominated by different genera. Forest zones were investigated using the Random Forest method utilizing a cloud-free Harmonized Sentinel-2A-Surface Reflectance image. Community structure measurement followed a stratified purposive sampling design along forest zonation. A spatial-based mangrove health index (MHI) model was applied to analyze forest healthiness distribution in each zone. Mangrove area was clearly classified into six genera-dominated zones such as *Sonneratia*, *Rhizophora*, *Bruguiera*, *Ceriops*, *Xylocarpus* and *Lumnitzera* from seaward to landward. The *Rhizophora* zone had the most extensive area proportion at approximately 68% of the total mangrove area. This study revealed that *S. alba* species dominated in the outmost zone at about 200% of IVI, while *X. granatum* and *C. tagal* were calculated in a larger IVI value in the more landward area. On the other hand, *R. stylosa* had a majority species composition in *Rhizophora* forest. According to spatial analysis of MHI, most zones had a majority area of excellent condition, emphasizing that the entire mangrove forest was pristine.

Keywords: Community structure, google earth engine, mangrove health index, pristine mangrove, random forest, spatial analysis

INTRODUCTION

Mangrove is one of the most critical ecosystems in the coastal area. The ecosystem delivers various benefits and services to adjacent communities from ecological, coastal protection, and socio-economics perspectives (Haines-Young and Potschin 2018; Getzner and Islam 2020). As a primary producer in the coastal food web, the mangrove forest serves as a habitat, feeding, and nursery ground for marine and terrestrial fauna (Nagelkerken et al. 2008; Karimah 2017; Sukuryadi et al. 2021). The availability of economic biotas in mangroves allows local people to gain food sources, income, and wealth (Das et al. 2022). Mangrove ecosystem also protects the shoreline area from coastal climatic and geologic disasters (Marois dan Mitsch 2015; Hilmi et al. 2017; Sánchez-Núñez et al. 2019). In small islands, mangrove existence maintains saltwater intrusion and secures freshwater supplies to the local community (Damayanti et al. 2020). In terms of climate change issue, mangrove has been considered the most effective blue carbon ecosystem in sequestering greenhouse gas, storing carbon, and controlling the global warming effect (Inoue 2019; Alongi 2020).

The magnitude of mangrove ecosystem services is considerably influenced by the size of habitat area, community structure, and forest quality. An extensive forest provides more significant benefits to the communities. Mangrove area decline affects ecological services depletion and socio-economic behavior changes (Malik et al. 2017). Mangrove formation reduces inward waves and coastal disaster effects in more extensive areas (Koh et al. 2018). From the global perspective, the Indonesian mangrove has been significantly considered in regulating global blue carbon and mitigating climate changes since the most extensive mangrove area of the world exists in this country (Murdiyarso et al. 2015). Therefore, forest area analysis should equip future studies related to mangrove services.

Mangrove community structure reflects species composition and stands distribution in certain mangrove areas. It varies perpendicularly to the shoreline, depending on the gradient of the environmental characteristic (Raganas and Magcale-Macandog 2020). Variability of habitat delivers unique forest zonation based on mangrove species domination, mainly triggered by pore-water salinity and soil organic concentration dynamics from landward to seaward areas (Costa et al. 2015; Barik et al. 2018). Salinity gradient contributes to forest classification since each mangrove species has a different ability to regulate salt concentration from the environment (Chowdhury et al. 2019). Most seaward areas are composed of the most adaptive species coping with a higher salinity habitat, while landward zones tend to be occupied by lower salinity-tolerant species (Yuvaraj et al. 2017). A muddy substrate in estuarine mangroves provides a larger stand size compared to oceanic-sandy mangrove habitats in the less degraded forest (Dharmawan and Widyastuti 2017). Distal forest zones are more affluent in organic carbon content than the seaward zone (Irwanto et al. 2021). However, the explorative study on mangrove zones in Indonesian pristine archipelagic mangroves is limited due to a lack of resources and safety concerns.

Forest healthiness is one of the main components in determining forest degradation combined with area calculation (Besset et al. 2019). Large areas and complex structures of mangroves need to be supported by healthy forest conditions to optimize their benefits and services. Mangrove degradation decreases habitat quality, associated biota diversity, and abundance, which disrupts food web balance in the ecosystem (Sahu et al. 2015). The quality of ecosystem services is also depleted in continuously degraded mangrove areas (Kalor et al. 2019). Determination of forest healthiness was varied in several previous studies, which involved different approaches such as stand structure and biodiversity assessment (Prasetya et al. 2017), comprehensive parameters including forest structure, soil, and social-economic analysis (Faridah-Hanum et al. 2019), and remote sensing analysis (Maurya et al. 2021). A scientific, efficient, and low-cost approach would be challenging in determining forest state for a broader background of stakeholders and the largest mangrove area globally in Indonesia.

Mangrove health index (MHI) is a single metric in determining forest quality developed by three dimensions of mangrove structure, i.e., size, distribution, and coverage (Dharmawan et al. 2020). It originated from field data collection measurements of stand structure parameters representing forest state in a small-scale quadratic plot. MHI values ranged from 0 to 100, distinguishing mangrove states into three healthiness categories such as poor, moderate, and excellent. A further study successfully transformed the plot-scaled MHI into a spatial index with a high determination to estimate the distribution of mangrove healthiness in a more extensive area scale analysis (Nurdiansah and Dharmawan 2021a). This study aimed to analyze mangrove community structure and health along forest zonation in archipelagic mangrove areas. Area calculation for each MHI category along forest zones would be involved in this study. Combining those parameters would lead to a comprehensive result as a basis for future mangrove management actions in these areas.

MATERIALS AND METHODS

Site description

Our study focused on Kei Archipelago mangrove forests around Kei Kecil and Kei Besar Island of Maluku (Moluccas) Province, Indonesia. Total mangrove area of this study covered about 99,260 ha, found in estuarine and oceanic habitat types at about 79.654 ha and 19.606 ha for each region, respectively (Figure 1). As many as ten sites were scattered along with the mangrove areas as indicative sites for conducting forest community structure assessment and collecting training validation data for classification analysis. Estuarine mangroves were primarily located in Kei Kecil Island, while oceanic mangroves mostly faced the Banda Sea on the north-eastern area of Kei Archipelago in Kei Kecil, Kei Besar, and surrounding islands. The estuarine habitats have typical mud domination on the substrate. Mangrove vegetation in this habitat has grown along bays; hence they are relatively protected from the direct influence of the sea environment. On the other hand, oceanic mangrove areas have a sandy to rock-rubble substrate domination and face the ocean directly. Oceanic mangroves probably have a more saline habitat since there is less freshwater input than estuarine ecosystems.

Mangrove classification analysis

Identification of forest zones was conducted using the Random Forest technique based on collected training area pixels (Kolli et al. 2022; Mahamunkar et al. 2022; Fikri et al. 2022). Harmonized Sentinel 2A Surface Reflectance images were gathered during September - October 2021 to produce a single cloud-free image. The Sentinel image was categorized into medium resolution since each pixel size covers about 10 m × 10 m area. Cloud masking for each image was conducted using the QA60 band. Masked image aggregation was applied based on the median value of each pixel and band as a reducer. The cloud computing platform, Google Earth Engine, was utilized to process forest classification based on genera domination. As many as 9581 pixels of training data were used to classify zones dominated by each genus. The number of forest zones was determined during the field survey, which found five genera domination on the bay, i.e., *Sonneratia*, *Rhizophora*, *Bruguiera*, *Ceriops*, and *Xylocarpus*, in a respective area from sea to land. Training area pixels were determined using manual observation on forest community assessment and completed with a manual interpretation on Google Earth based on canopy texture and color. The performance of classification based on the training data was assessed by 1063 pixels of validation data to examinecoloral accuracy approaches. Producer and consumer accuracy (%) tests were performed to investigate each classified zone's accuracy based on training data and total pixels, respectively. On the other hand, the classification performance on the entire bay area was summed up by overall accuracy value and a *kappa* coefficient calculation.

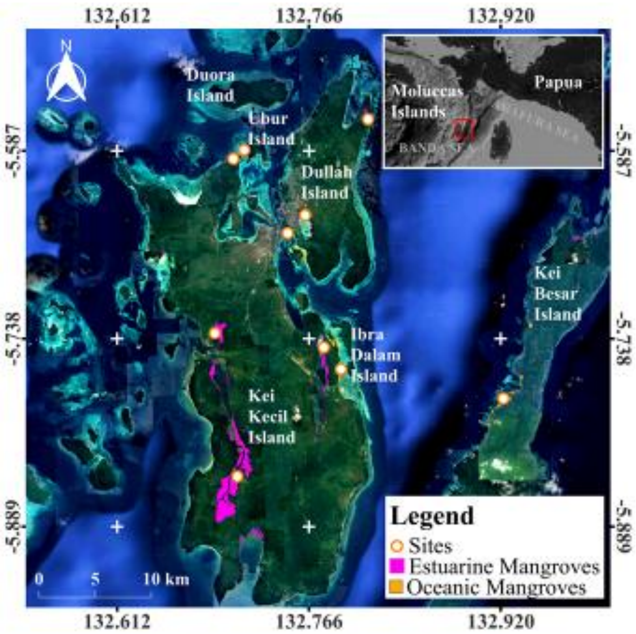

Figure 1. The study area of mangrove structure and healthiness in Kei Archipelago, Maluku (Moluccas) Province, Indonesia

Mangrove community structure assessment

Forest assessment was conducted to determine species composition and stand structure in each zone in the archipelagic area (Dharmawan et al. 2020). As many as 48 quadratic 10m × 10m plots were scattered purposively along the forest area following a stratified sampling design based on genera domination. Unfortunately, The *Lumnitzera* zone structure measurement was missed due to safety issues hence a manual observation was applied to describe the zone on the study result. Those measurement areas were included as training data during classification analysis. A field survey was conducted to measure mangrove stand diameter (DBH) on each plot which was applied to distinguish mangrove stands into two growth levels, i.e., tree (DBH≥5 cm) and sapling (DBH<5 cm). The number of measured stands on each plot was considered a forest density value on each growth level. Forest canopy coverage was estimated by using hemispherical photography through nine hemispheric photographs taken on each plot following Dharmawan (2020). Forest height was calculated by measuring the angle of the top forest canopy at 10 meters distance. The MonMang, an Android-based app, was used to record and process data directly on the field sites before being exported for further statistical analysis (Dharmawan and Khoir 2021). Important value index (IVI) was extracted from the app to determine species composition, while canopy coverage, density diameter, and height data represented forest structure parameters. A descriptive analysis including the mean and standard error value for each parameter was calculated, while one-way ANOVA followed by the Tukey HSD test was conducted to detect differences of each parameter among zones performed using a *tidyverse* package on the R-studio statistical software version 3.72 (2021).

Spatial distribution of MHI along forest zones

The distribution of forest healthiness in each forest zone was analyzed based on a spatial model of the Mangrove Health Index (MHI) (Nurdiansah and Dharmawan 2021a). The model consists of a combination of four vegetation indices, i.e., NBR (Normalized Burn Ratio), GCI (Green Chlorophyll Index), SIPI (Structure Insensitive Pigment Index), and ARVI (Atmospherically Resistant Vegetation Index). Analyzing each index in calculating the MHI value required five bands such as red, green, blue, Near Infrared (NIR), and Shortwave Infrared - (SWIR) on the cloud-free image. MHI values were divided into three ranges of forest conditions such as poor (0-33%), moderate (33%-66%), and excellent (66%-100%).

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

Where:

$$NBR = (NIR - SWIR) / (NIR + SWIR)$$
$$GCI = (NIR/green) - 1$$
$$SIPI = (NIR - blue) / (NIR - red)$$
$$ARVI = (NIR - 2.red + blue) / (NIR + 2.red + blue)$$

Calculated MHI values from the model were standardized following MHI categories using the min-max standardization method. A range of negative MHI values from -33 to 33% was standardized as a poor forest category, and a positive range from 66 to 133% was compressed into the excellent range. MHI determination and area calculation for each zone were performed in Google Earth Engine. Spatial MHI distribution along mangrove zones was visualized on thematic maps, which were designed using Quantum GIS version 3.22.

RESULTS AND DISCUSSION

Distribution of mangrove genera-dominated zones

Kei Archipelago clearly consisted of six genera-dominated zones along the forest area. Estuarine mangroves had a more complex mangrove formation than the oceanic forest (Figure 2). Five genera-dominated zones were identified from the estuarine habitat, while only three obvious patterns of mangrove-occupied oceanic habitat were recorded. The number of genera-dominated layers in this study was higher than the estuarine mangrove in Benoa Bay, which was composed of three mangrove zones (Sugiana et al. 2022). Another study in an archipelagic area of Papua found three zones along the mangrove area perpendicularly from landward to seaward (Nurdiansah and Dharmawan 2021a). A small coralline island in Java was only composed of a single forest layer dominated by *Rhizophora stylosa* Griff. (Dharmawan 2019; Nurrohman et al. 2020). Monospecific mangrove domination was common in flat oceanic islands with a narrow forest width, a uniform environmental characteristic, and sandy rock-rubble substrate domination (Dharmawan and Pramudji 2019).

The number of mangrove zones in the Kei Archipelago differed among habitat typologies. In the estuarine habitat, the mangrove forest was occupied by five zones, i.e., *Rhizophora*, *Bruguiera*, *Ceriops*, *Xylocarpus*, and *Lumnitzera*. Estuarine mangroves had a higher number of genera-dominated zones than the oceanic habitat, which was only distinguished into three forest layers: *Sonneratia*, *Rhizophora*, and *Bruguiera*. Each species of *Rhizophora* had a specific optimum range of salinity. *Rhizophora stylosa* was dominant in a more saline habitat with a sand-dominated substrate than *R. apiculata*, which preferred more estuarine and riverine habitats (Nugroho et al. 2019; Nurrohman et al. 2020; Edo et al. 2021). The distribution of *Sonneratia* was unclear and irregular along with estuarine forests in Kei Archipelago. *Xylocarpus* and *Lumintzera* domination was randomly scattered in a narrow area on the oceanic habitats. Both *Bruguiera* and *Ceriops* were the second layers of forest zonation in both estuarine and oceanic mangroves in Kei Archipelago. They were found with massive distribution and growth in a moderate salinity range, relatively less submerged, and mud-dominated areas (Irawan et al. 2021). Previous studies also identified those forests as the middle mangrove zone (Irwanto et al. 2020; Koroy et al. 2020). The presence of *Xylocarpus* and *Lumnitzera* zones in estuarine mangroves implied the existence of low saline and less submerged habitats in the most landward area. Both species were mostly found in higher land elevations with a drier substrate near land mangrove niches (Mughofar et al. 2018; Irwanto et al. 2020; Ma et al. 2020).

Forest zone variability among habitat types reflected the adaptative ability of each mangrove species to environmental conditions. Estuarine habitat tends to have a broader range of salinity since it experiences a more frequent freshwater input from upstream areas (Suello et al. 2022). Organic content on the estuarine mangrove originated from allochthonous and autochthonous sources (Sasmito et al. 2020). Lack of particulate material export by tidal fluctuation and dense root system of mangroves allows deposition of higher organic materials in the substrate: hence estuarine mangroves were rich in organic content (Wang et al. 2021). Consequently, most of the mangrove zones were optimally developed along salinity gradients and higher soil organic contents in estuarine areas. In contrast, the oceanic mangrove substrate in this study area was dominated by sandy to rock-rubble composition. A previous study figured out the low organic content in oceanic mangroves compared to estuarine habitats (Saavedra-Hortua et al. 2020). Species of *Sonneratia alba* and *Rhizophora stylosa* were proven to be more adaptive among other species to less organic substrates in the seaward zone of oceanic mangrove habitat in Indonesia's small islands (Dharmawan and Pramudji 2019; Nurdiansah and Dharmawan 2021a).

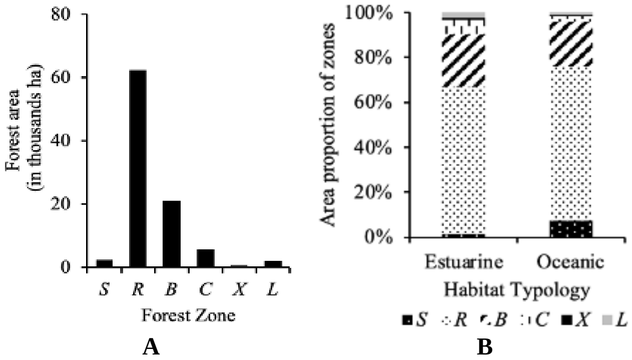

Figure 3. Area of each mangrove genera-dominated (S: *Sonneratia*; R: *Rhizophora*; B: *Bruguiera* C: *Ceriops*; X: *Xylocarpus*; L: *Lumnitzera*) in Kei Archipelago (A) and comparison of the proportion of zone area between estuarine and oceanic habitats (B)

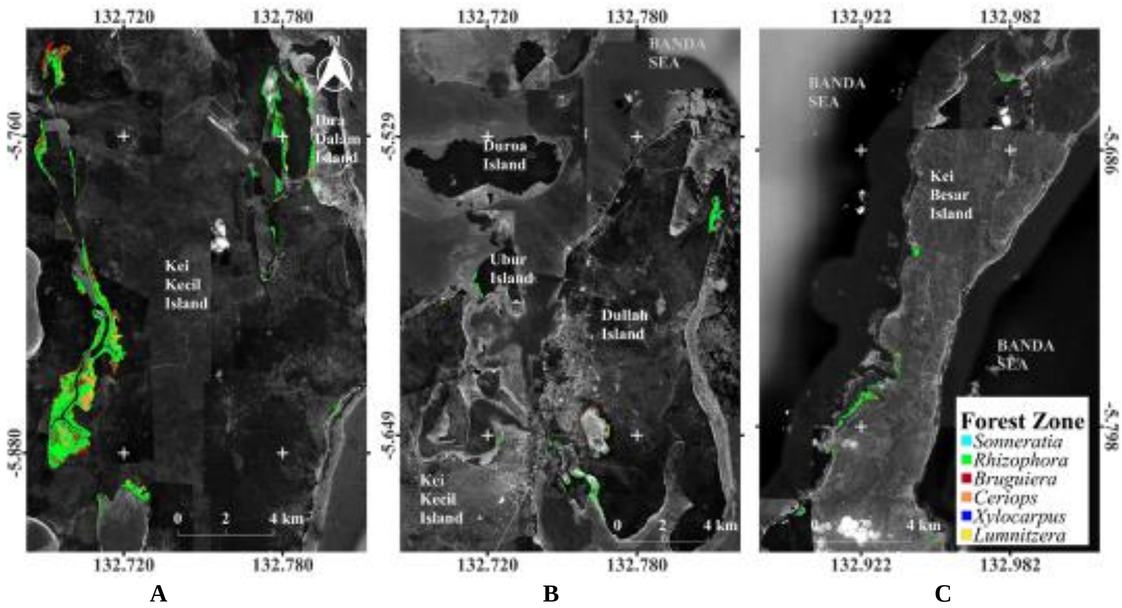

Figure 2. Distribution of genera-dominated zones displayed in three regions, i.e., southern Kei Kecil Island (A); northern areas of Kei Kecil Island (B) and Kei Besar island (C)

Table 1. Forest classification performance is based on common accuracy approaches to each genera-dominated zone (S: *Sonneratia*; R: *Rhizophora*; B: *Bruguiera* C: *Ceriops*; X: *Xylocarpus*; L: *Lumnitzera*) and the entire forest area

Accuracy tests	Forest zone					
	S	R	B	C	X	L
Producer accuracy (%)	80.00	97.02	90.95	95.92	73.81	91.52
Consumer accuracy (%)	72.73	85.76	95.77	97.92	100.00	99.17
Overall accuracy (%)	93.03					
Kappa coefficient	0.91					

Regarding genera-dominated forest area, Kei archipelagic mangroves were highly dominated by *Rhizophora* forest at about 65.27% and 68.71% of total mangrove forest in both estuarine and estuarine mangroves, respectively (Figure 3). In the entire forest area, the *Rhizophora*-dominated zone occupied approximately 63,937 ha, much larger than other zones. This genus has been recognized as a cosmopolitan mangrove group distributed in the Indo-West Pacific region, including the Indonesian archipelago (Yan et al. 2016). *Xylocarpus* forest distribution was limited in the study area, which mainly lived in the estuarine mangrove at about 723.4 ha or approximately 1% of the forest area. The *Lumnitzera*-dominated zone had a slightly higher proportion of area than the *Xylocarpus* forest at about 3%. *Xylocarpus* and *Lumnitzera* domination did not form a regular patterned zone in oceanic mangroves. On the other hand, the *Sonneratia* zone was distributed mainly along the outmost area of oceanic habitats. The zone represented a more significant proportion of oceanic mangroves at about 7.4%, compared to its size in the estuarine habitats at approximately 1.61%.

The performance of forest classification in this study indicated a highly accurate result since the value of a calculated overall accuracy was in the highest category between 90-100% (McHugh 2012) (Table 1). It was also represented by a *kappa* coefficient larger than 0.9 indicating the result was close to the current condition of forest structure (Jog and Dixit 2016). Another study performed a similar overall accuracy and *kappa* value for distinguishing mangroves in the coastal area using Random Forest technique through Sentinel images (Ghorbanian et al. 2021). The number and consistency of training data played significant roles in performing a better producer accuracy value (Millard and Richardson 2015). In this study, a narrow and scattered area of *Xylocarpus* zones resulted in the lowest value of this accuracy test at 73.81%. However, the largest zone of *Rhizophora* forest in Kei archipelagic mangrove was highly accurate based on the producer accuracy test since as many as 97.02% of training pixels were classified as *Rhizophora*-dominated zone. In contrast, validation data pixels for the *Xylocarpus* zone had the best performance in the classification result since they produced an excellent value in the consumer accuracy test.

Mangrove community structure

Ten mangrove species were found on six genera-dominated zones in Kei Archipelagic mangrove, and each zone had a typical mangrove species composition. The *Sonneratia*-dominated zone was majorly located on the seaward area of the oceanic mangrove and composed of four mangrove species which was dominated by *S. alba* species at more than 200% of IVI (Figure 4). Rhizophoraceae members were also present in this zone, such as *Rhizophora stylosa*, *R. mucronata* and *B. gymnorrhiza*, with IVI at about 50.60%, 35.95%, and 11.51%, respectively. The *Sonneratia* zone had the lowest number of mangrove species compared to other zones. A lower species number in *Sonneratia* forest was also found in previous studies, such as a monospecific *S. alba* in Biak Papua (Dharmawan and Pramudji 2019); two species in Miossu-Middleburg Island (Nurdiansah and Dharmawan 2021a) and four species in Asam Beach, Belitung Island (Irawan et al. 2021). Higher salinity and lower organic matter in the *Sonneratia* zone were responsible for a lower species composition related to mangrove adaptation. Species of *S. alba* have a better preference for growing in sandy and rock-rubble substrates with low organic content and high salinity than other mangrove species (Wang'ondu et al. 2013).

Rhizophora-dominated areas consist of more mangrove species than the *Sonneratia* forest. As many as seven species were found in this zone which was dominated by *R. stylosa* with the highest IVI at 194.30%. This species domination indicated that the *Rhizophora* forest had a higher saline environment and sandier substrate in this study area. Species of *R. apiculata* and *R. mucronata* were found in a low value of IVI at about 38% and 19%, respectively. Those species had a lower saline environment than *R. stylosa*, and they were adaptive in a wide range of lower water salinity ranges (Irawanto et al. 2021). Other members of Rhizophoraceae also lived along with *Rhizophora* forests, such as *C. tagal* and *B. gymnorrhiza*, with much lower IVI proportions in a respective numbers at about 16.37% and 22.68%. Those species tended to be well-adapted to a muddy substrate with a higher organic content (Robert et al. 2015). This result indicated that *Rhizophora* habitats seemingly lack organic matter since the domination of *R. stylosa* was recorded in the present study. However, future comprehensive studies including environmental analysis should be applied to emphasize this indication.

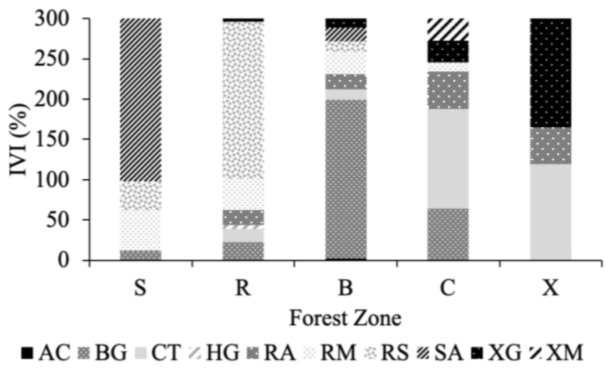

Figure 4. Species composition for each genera-dominated zone (S: *Sonneratia*; R: *Rhizophora*; B: *Bruguiera*; C: *Ceriops*; X: *Xylocarpus*) based on IVI (%). Species Abbreviations: AC: *Aegiceras corniculatum* (L.) Blanco; BG: *Bruguiera gymnorrhiza* (L.) Lam.; CT: *Ceriops tagal* C.B. Rob.; HG: *Heritiera globosa* Kosterm.; RA: *Rhizophora apiculata* Blume; RM: *R. mucronata* Poir.; RS: *R. stylosa* Griff.; SA: *Sonneratia alba* Sm.; XG: *Xylocarpus granatum* J.Koenig; XM: *X. molluccensis* M.Roem

The muddy habitat of *Bruguiera* forests supported the most diverse mangrove species in this archipelagic mangrove. As many as nine mangrove species were found in this zone. Species of *B. gymnorrhiza* were highly dominated at 197.74% of MHI value. This species preferred to live in a less saline environment with a high content of organic matter (Zhu et al. 2012). Previous studies also identified the domination of *B. gymnorrhiza* in the middle zone of mangrove forests (Urashi et al. 2013; Kamruzzaman et al. 2016). The middle zone had a lower salinity than the seaward area due to the balance of freshwater input from the upper land area and saltwater from tidal flow (Bathmann et al. 2021). Environmental condition in this area was the most preferred habitat for mangroves and led to a higher diversity of mangrove species (Ragavan et al. 2015). Previous studies revealed that the middle zone had higher species diversity than other zones (Win et al. 2019). Salt tolerant species of *S. alba* and *R. stylosa* and less tolerant species of *C. tagal* and *X. granatum* were found in this zone, indicating that this area served a wide range of environmental physio-chemistry parameters.

Along the estuarine habitat, mangrove areas in the front of the landward zone were occupied by *C. tagal* as the main component of forest structure. This species was dominant at approximately 134% of the total IVI proportion. Overall, six mangrove species were identified from the measurement area in the *Ceriops*-dominated zone. Species of *B. gymnorrhiza* are also distributed in this zone with more than 50% of IVI, followed by *R. apiculata* at about 45%. Among other zones, *X. molluccensis* was only found in this area with a narrow IVI value. High content of organic and less saline conditions allowed high domination of poor salinity tolerant species such as *C. tagal* and *X. granatum*. This domination was also detected clearly in most landward areas along the *Xylocarpus*-dominated zone. Those species were dominant and had a similar IVI value at about 119% and 134%, respectively. Another species found in this zone was *R. apiculata* which was relatively cosmopolite in the estuary. Domination of *X. granatum* frequently occurred in the landward zone with the lowest water salinity and less submerged by tidal water (Dasgupta et al. 2012; Siddique et al. 2017).

Canopy coverage of mangroves in the study sites ranged from 69.76±2.15% in the *Sonneratia*-dominated zone to 81.49±2.52% in the *Xylocarpus* forest (Figure 5). It was found that the mean value of *Sonneratia* canopy coverage was significantly different among zones based on TukeyHSD analysis. Previous studies also calculated the lowest canopy coverage in *Sonneratia* forest compared to other zones. For instance, a fringing mangrove in Padaido Archipelago had the most canopy coverage in the *Sonneratia* zone at about 61.32% among different zones (Dharmawan and Pramudji 2019). In another study in Tidore Archipelago in North Moluccas Provinces, the *Sonneratia* forest was composed of large mangrove stems, while it had a lower percentage of canopy coverage (Nurdiansah and Dharmawan 2018). It indicated a single variable of stand structure was not appropriate for determining forest degradation state since mangrove canopy shape was varied among species (Dharmawan 2020). Mangrove canopy coverage analysis in Benoa Bay-Bali showed a higher percentage at *Rhizophora* forest than *Sonneratia*-dominated zones in respective values at about 77.91% and 52.35%. On the other hand, a pristine mangrove occupied by *Rhizophoraceae* domination was found consistently in dense coverage such as Wondama Gulf and Liki Island estuaries at about 90.0% and 80.4%, respectively (Dharmawan and Widyastuti 2017; Nurdiansah and Dharmawan 2021b). High canopy coverage in the *Ceriops*-dominated zones was detected in similar value to this study along less disturbed archipelagic mangroves in Middleburg-Miossu Island and Raja Ampat (Nurdiansah and Dharmawan 2021a; Pribadi et al. 2020).

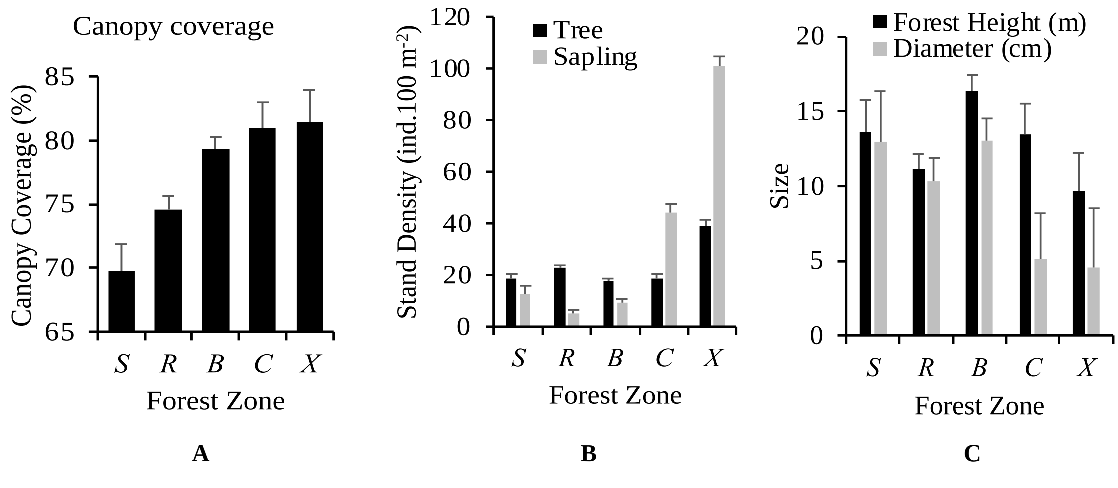

Figure 5. Species composition for each genera-dominated zone (S: *Sonneratia*; R: *Rhizophora*; B: *Bruguiera*; C: *Ceriops*; X: *Xylocarpus*) based on the Importance Value Index (%)

The highest canopy coverage in the *Xylocarpus*-dominated zone was supported by the densest stand distribution in both tree and sapling levels which had a significant difference from other zones (ANOVA: $p<0.05$). Tree and sapling densities of this forest zone were 39±5 stand.100m^{-2} and 101±11 stand.100m^{-2}, respectively (Figure 5). Other zones had a similar tree density ranging from 18±5 stand.100m^{-2} found in *Bruguiera* forest to 23±2 stand.100m^{-2} in *Rhizophora*-dominated zone. On the other hand, *Ceriops*-zone was also found to be significantly different from *Sonneratia*, *Rhizophora*, and *Bruguiera* forests. A study in a pristine *Ceriops* forest on Papua small island revealed that sapling density was higher than tree density which was similarly found in the present study (Nurdiansah and Dharmawan 2021a). Benoa Bay-Bali mangroves were more dominated by tree stand level than sapling stands, especially in *Sonneratia* and *Rhizophora* forests (Andiani et al. 2021). Less disturbing mangroves were commonly occupied by tree stands than sapling stands, such as mangroves in Wondama, Raja Ampat, and Liki Islands (Dharmawan and Widyastuti 2017; Pribadi et al. 2020; Nurdiansah and Dharmawan 2021b). Moreover, *B. gymnorrhiza* trees were found fully dominated in Auki islands with no sapling stands on the mangrove forest due to a dense forest canopy that inhibits sapling growth (Dharmawan and Pramudji 2019).

According to the stand size, denser forests in *Ceriops* and *Xylocarpus* forests had a lower mean trunk diameter than other zones (Figure 5). Consequently, the stands were focused on vertical growth to gain height. It was implied by a significant difference in trunk diameter in those sizes compared to other zones (ANOVA, $p<0.05$), while their height was relatively similar. Only the *Bruguiera* forest differed significantly among zones in the forest height reaching approximately 16.36±0.88m. The largest stand diameter was identified in the *Sonneratia*-dominated zone at about 13.0±3.4cm, while the *Xylocarpus* zone had a lower stand size diameter at approximately 4.5±4.0cm due to the domination of sapling levels. Pristine mangrove forests mainly have a larger stand size, both height, and diameter, due to a lack of anthropogenic activities. In a cultural-protected forest of Middleburg-Miossu, mangrove stem reached approximately 24 cm in stem diameter and 17.6 m in height, similar to this study area (Nurdiansah and Dharmawan 2021a). Another study showed a massive size of mangroves at about 19.77 cm in stem diameter in a pristine mangrove area (Dharmawan and Widyastuti 2017). In contrast, frequently logging mangrove areas had a much-lowered diameter size of about 6.50 - 10.66 cm on Bintan island, which is dominated by *Rhizophora* (Dharmawan 2018). *Rhizophora* woods are favored for selective logging, which has a better quality of charcoal and firewood than other mangrove woods (Malik et al. 2017). Secondary mangrove forests in Sekotong, Lombok, have grown, ranging from 6.10 to 10.57 cm at average diameters (Japa et al. 2019).

Mangrove health index distribution

Most genera-dominated zones in Kei Archipelagic mangrove had the excellent category of mangrove health index. This category has a massive proportion of more than 60% of the total mangrove area in this study site (Figure 6). As the top-two-largest mangrove area, *Rhizophora* and *Bruguiera* forests were dominated by healthy forests at about 60% of the zones area proportion which significantly contributed to the total mangrove area condition. The excellent mangrove forests were also found in *Sonneratia* and *Ceriops* forests at approximately 50% and 50% of their total area, respectively. The moderate healthiness category was calculated in a dominant proportion at two narrow zone areas, *Xylocarpus* and *Lumnitzera*, which had no significant influence on the overall condition of mangrove healthiness in the present study. Another study showed stable mangrove coverage in the most extensive urban area, Tual City in Kei islands, from 1999 to 2019 through satellite imagery analysis (Suyadi et al. 2021). Excellent mangrove conditions were also identified in a nearby archipelago in Moluccas Province, in particular Sula Islands, by previous studies based on forest canopy coverage assessments (Akbar et al. 2016; Baksir et al. 2018). Overall, archipelagic mangroves, especially in eastern Indonesia, were commonly in more health conditions due to a lack of anthropogenic threats compared to the western region (Ilman et al. 2016).

According to the area proportion of MHI categories, the mangrove forest in Kei Archipelago was categorized as a pristine mangrove since most pixels were in excellent range value. It was also supported by a minimum proportion of poor conditions in less than 5% of forest area. However, the poor forest areas significantly existed along *Ceriops* forests at approximately 10% of the total *Ceriops* area, which was identified on the largest mangrove bay in Kei Kecil Island and represented by light blue color areas (Figure 7). Field observation found a lack of anthropogenic activities in those areas, so the poor areas were mainly caused by the natural standing state of the *Ceriops* vegetation. In those areas, the unhealthy *Ceriops* were composed of stunting stands dominated by sapling growth levels and less canopy coverage (Figure 8). Stunting mangroves were natural and predominantly observed in arid habitats with distinctive geomorphology, altered hydrology, and different characteristics of soil biogeochemistry (Adame et al. 2021).

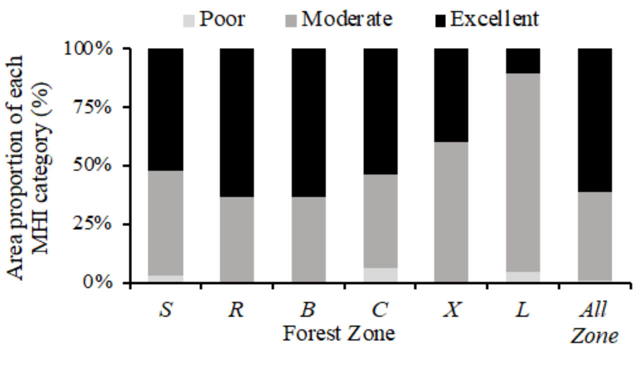

Figure 6. Area proportion of each Mangrove Health Index (MHI) category (%) among forest zones in Kei Archipelagic mangroves area (S: *Sonneratia*; R: *Rhizophora*; B: *Bruguiera* C: *Ceriops*; X: *Xylocarpus*; L: *Lumnitzera*)

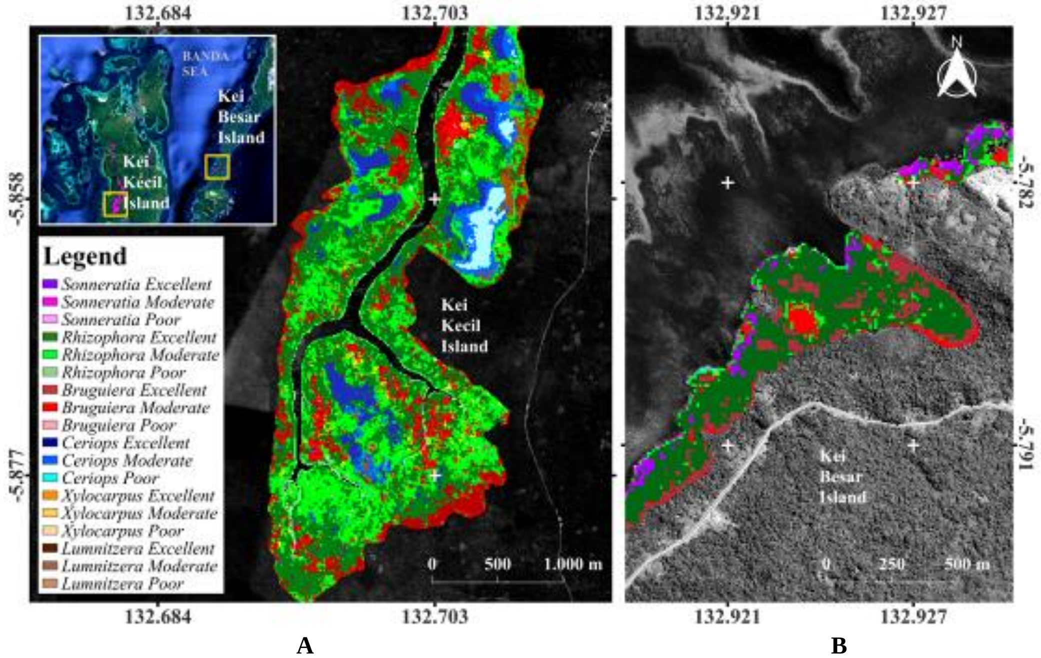

Figure 7. Spatial distribution of Mangrove Health Index (MHI) categories along forest zones on selected areas in Kei archipelago i.e., estuarine forest in Kei Kecil Island (A) and oceanic mangrove in Kei Besar Island (B)

Figure 8. Poor forest condition of *Ceriops tagal* species domination in Kei Kecil Islands mangrove, Maluku, Indonesia

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