

ORIGINAL ARTICLE

Impact of wood-boring isopod *Sphaeroma terebrans* on the trunks of different mangrove species at a recovering forest in Batan Estuary, Aklan, Philippines

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ABSTRACT Mangroves are important tropical coastal ecosystems providing various ecosystem services such as carbon sequestration, coastal protection, mitigation of storm winds and surges, as well as serving as habitat for various organisms, etc. However, huge areas of mangroves were already lost because of anthropogenic activities such as conversion of mangrove to aquaculture ponds in the last half century. Therefore, numerous countries like the Philippines have made an immense effort to restore the lost mangroves by replanting. One of the threats to mangrove reforestation is the damage caused by burrowing of marine isopods *Sphaeroma terebrans*, i.e. the holes created by isopods in the mangrove trunk can cause mangrove trees to fall. In the present study, for three mangrove species, *Avicennia marina*, *A. alba*, and *Sonneratia alba*, isopod hole density at the trunk surface and decay extent of trunks were measured at a recovering forest in Batan Estuary, Aklan, Philippines. The trunk decay was evaluated using acoustic tomography by measuring the travel times and attenuation of the sound wave within the focal trunk. Also, we attempted to clarify the relationships among isopod hole density, trunk decay extent and relative height from mean lower low water (MLLW) level. The hole density decreased significantly with increasing time of exposure to the atmosphere (height relative to MLLW). The trunk decay area increased with decreasing relative height above the MLLW level in *A. marina*, but did not decrease significantly in the other tree species. The relationship between trunk decay volume and hole density was insignificant, but *A. marina* had a higher trunk decay volume than the other two species. The present results partially supported our hypothesis that trunk decay extent is a function of isopod hole density on the trunk surface, as well as the species of the host tree, i.e. interspecific differences in trunk decay area and volume were detected but the effect of hole density on the trunk decay volume was insignificant. The holes caused by isopods could be a trigger to start the formation of hollow space in the trunks but further research on the other influential parameters, such as tolerances to water quality, xylophagous fungus and physical disturbance, would be necessary to understand the decay process of mangrove trunks considering their interspecific differences.

Key words: acoustic tomography, *Avicennia marina*, hole density, hollow trunk, isopod, tidal elevation

INTRODUCTION

Mangroves are tropical intertidal plants adapted to thrive in the harsh marine environment. Based on the global spatial distribution of mangroves, the largest amount of forests was found in Asia (39.2 %), followed by Africa (19.3 %), South America (15.4 %), North America (14.3 %),

and Oceania (11.9 %) (Jia et al. 2023). Mangrove forests are one of the biologically diverse and productive marine ecosystems which support the coastal economy with valuable fishery resources and eco-tourism (Nagelkerken et al. 2000, Kathiresan 2012, Menéndez et al. 2018). Aside from these direct benefits, they provide coastal protection from strong winds and waves (Alongi 2008, Marois and



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Mitsch 2015, Menéndez et al. 2020, Zhang et al. 2022), help prevent erosion by stabilizing sediments (Adame et al. 2010, Willemsen et al. 2016, Das 2020, Pennings et al. 2021), and are efficient in carbon sequestration and storage (Alongi 2012 and 2014, Soper et al. 2019, Kida and Fujitake 2020, Rahman et al. 2021) that help to mitigate the effects of climate change. Due to their crucial role in providing protection to coastal ecosystems, numerous countries like the Philippines made an immense effort to restore the lost mangroves by replanting in abandoned fishponds and other areas for protection from wave damage (Samson and Rollon 2008).

Aside from mangrove conversion for aquaculture, agriculture, and urban development activities, one emerging ecological concern in the mangrove ecosystem is the proliferation of parasitic wood-boring isopods. Wood-boring isopods like *Sphaeroma* spp. are marine crustaceans that can tolerate wide salinity fluctuations (Singh and Sasekumar 1994) and found to frequently bore into the mangrove trees where they live and filter feed (Davidson et al. 2016). Colonization of isopod was rapid in the root tip region which is considered as the youngest part of the root (Brooks 2002). Aside from roots, these organisms can also be found burrowed into the stems, branches, and trunks in various mangroves species. Once the Sphaeromatid isopods colonize these mangroves parts, they create hollows by digesting the wood (Benson et al. 1999). This digestive activity leads to atrophy which undermines the structural support and stability of the trees or overall alteration of tree morphology (Brooks and Bell 2002, Davidson et al. 2014), resulting in the toppling of trees (Rehm and Humm 1973).

The threats and impacts of these parasitic crustaceans on mangrove forests have been highlighted by some researchers (Davidson et al. 2014, 2016, Talley and Crooks 2007, Liu et al. 2020, Thiri and Yang 2022, Wang et al. 2022, Ferreira et al. 2024). According to Fan et al. (2014), they reported that the death of some mangroves in Hainan and Guangxi, China was due to the outbreak of wood-boring isopods. The same authors revealed that mangrove death grows annually to 66.4 % from 2010 to 2013 in these regions, which is quite alarming. Sphaeromatid attacks were evident in mangrove forests growing along tidal channels (Svavarsson et al. 2002, Xin et al. 2020), thus limiting the growth and recruitment of mangroves in intertidal areas. Moreover, isopod infection rates were high in selected mangal communities like *Rhizophora* spp., *Avicennia* spp., *Kandelia* spp., *Bruguiera* spp., *Aegiceras* spp. (Fan et al. 2014, Xin et al. 2020, Thiri and Yang 2022, Harmonis et al. 2024) which can affect their distribution and would likely result in a loss of overall diversity.

Among many species of *Sphaeroma*, *S. terebrans* is widely distributed in tropical and subtropical regions such as in USA (Rehm and Humm 1973, Simberloff et al. 1978), Caribbean (Davidson et al. 2016), Belize (Ellison and Farnsworth 1992), South Africa and along the coast of West Africa (Smithsonian Institution, n.d.), China (Xin et al. 2020, Thiri and Yang 2022), Brunei (Hossain and Bamber 2013), and Indonesia (Harmonis et al. 2024). It has been found in different parts (i.e. roots, branches, trunks) of both live and dead mangrove trees (Singh 1994, Rehm and Humm 1973, Brooks and Bell 2001); and its outbreak caused the death of many mangrove forests in Dongzhai, China (Xin et al. 2020, Thiri and Yang 2022, Wen et al. 2025).

Since this crustacean creates destructive impacts, it poses a major ecological threat to mangrove restoration, reforestation and conservation projects worldwide. In the study of Baratti et al. (2005), an isopod sample obtained from the Philippines (location undisclosed) was morphologically identified as *S. terebrans* but not molecularly confirmed due to unavailability of specimens. Marine isopod sightings were observed in selected coastal mangrove areas around Batan, Aklan, Philippines. At present, information on the biology and impact of this parasitic isopod to the mangrove ecosystem remains largely limited.

One of the challenges to properly assess *S. terebrans* infestation was the lack of quantitative valuation methods to determine the degree of trunk damage in mangrove trees. Wood decay is difficult to detect by observation, hence, acoustic tomography (AT) was utilized aside from visual assessment. AT is a non-destructive tool which uses sonic waves to assess the internal health condition of trees by generating a two-dimensional map of each cross section (Koeser et al. 2017, Suchocka 2020, Maurer et al. 2006). In the present study, we hypothesized that trunk decay extent is a function of isopod hole density on the trunk surface, as well as the species of the host tree. Specifically, we attempted to (a) quantify the vertical profile of isopod hole density on the trunk surface for three mangrove species – *A. marina*, *A. alba*, and *S. alba*; (b) quantify the trunk decay of these species; and (c) analyze the relationships among isopod hole density, trunk decay, and tidal elevation in a recovering mangrove forest in Batan Bay, Aklan, Philippines.

MATERIALS AND METHODS

Study site

Batan Estuary is located north of Panay Island, west central Philippines (central coordinates 11°35'N, 122°29'E)

(Fig. 1). It is a semi-enclosed body of water made up of lagoons and rivers with a total water area of 2,640 ha (Altamirano and Kurokura 2010). Batan Bay, Tinagong Dagat and several tributaries are the three main components of the Batan Estuary. Batan Bay is the main component and exchanges seawater from Sibuyan Sea through a channel opening of about 940 m wide (based on Google Earth distance estimation, March 2024). There is a small outlet north of the estuary in Tambak, New Washington; but the water exchange is minimal and intermittent with the constant deposition of sediments even with periodic dredging conducted by the local government. Freshwater drains to Batan Estuary through the many tributaries that span five municipalities (Kalibo, New Washington, Balete, Altavas and Batan) to an estimated total estuary area of about 8,000 ha. An estimated 88 % of the primary mangrove area of 4,923 ha based on the 1953 topographic map, had been converted to registered fishponds of about 4,336 ha in the year 2000; and of which about 3,747 ha fishponds

remain active with an estimated 589 ha abandoned (Altamirano et al. 2010). Altamirano et al. (2010) estimated the remaining mangrove area in Batan Estuary to be about 406 hectares in 2008, close to the initial estimate of about 300 ha in 2006 (Altamirano 2007). Ikejima et al. (2006) reported the remaining mangroves to be found as narrow fringes along creeks and river banks. Also we confirmed approximately 320 hectares of mangrove areas in 2020 using a global database namely Global Mangrove Watch (Bunting et al. 2024). Some mangrove restoration stations have been established by universities, the government (Department of Environment and Natural Resources), and local communities (Ogawa et al. 2022).

Description of isopods

A portion of live *Rhizophora sp.* prop root from a fallen tree was opportunistically collected by the project

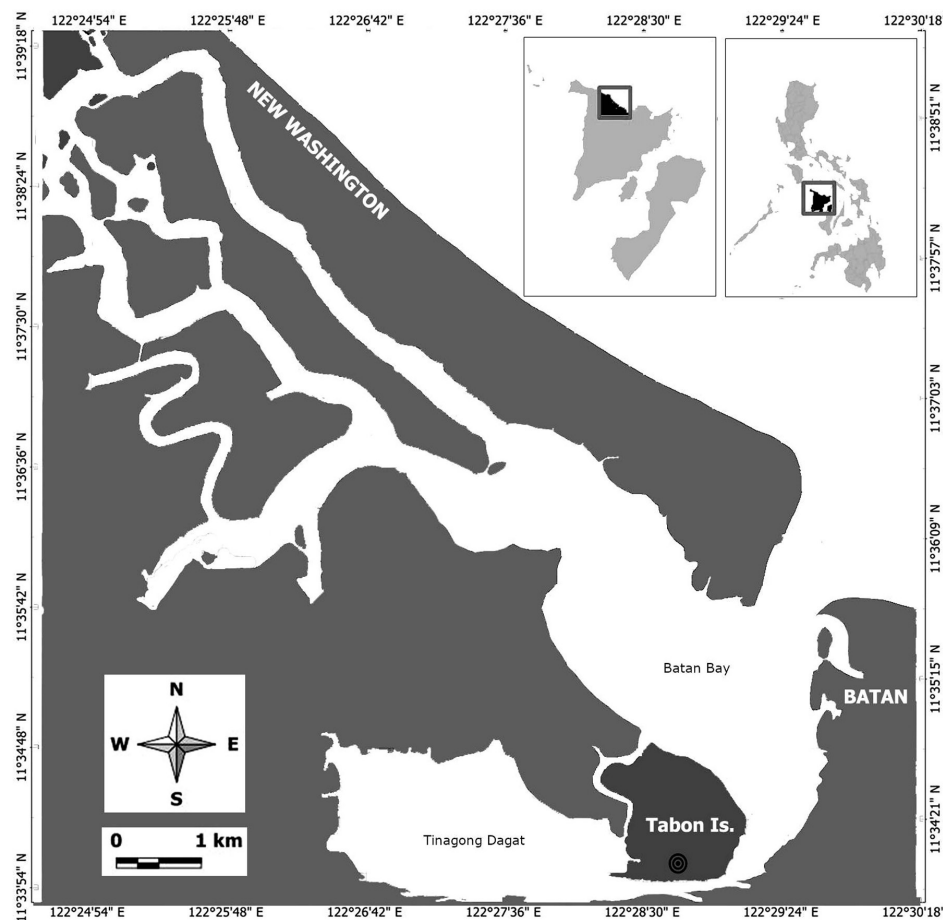


Fig. 1. Map showing the location of focal transect line (marked with a black double circle) near Tabon Island in Batan, Aklan, with detailed views of Batan Estuary system. Inset pictures display the Panay island (right) and the location of the study area (left), marked with rectangles.

team during a fieldwork expedition in January 2023. The prop root had not dropped to the substrate yet, but was already consistently submerged by tidal inundation resulting in it being infested by wood-boring isopods. The prop root was cut from the main tree using a dive knife, and placed in a resealable storage bag for transport back to the Aklan State University laboratory. There, the prop root was dosed with formalin as a fixative before being stored in a freezer-safe resealable storage bag. It was stored in the freezer until it was transported via air cargo when the project team travelled back to Manila.

To extract the burrowed isopods from the collected prop root, it was halved longitudinally using a dive knife, exposing the burrows created that penetrated until the cortex. The isopods and other associated macroinvertebrates were collected using featherweight forceps, and fixed in 90 % ethanol for long-term preservation and storage. Photodocumentation of the isopods and associates were done using an Olympus SZ51 Stereo Microscope (Fig. 2). Taxonomic identification of the wood-boring isopods was done using Richardson (1905), with confirmation provided through electronic communication by Dr. Guiseppe Messina of the Research Institute on Terrestrial Ecosystems, Italian National Research Council.

Determination of trunk decay

In total, 34 trees were randomly selected along a transect (Fig.1) including 16 *A. marina* trees, 10 *A. alba* trees, 8 *S. alba* trees, and the trunk diameters at three specific heights: above, at the upper limit, and at the widest deformation of the isopod-affected area (Table 1). Furthermore, in each tree, the diameter was measured at three heights (20, 40, 60 cm from the ground level) for obtaining of tomogram using the ArborSonic 3D Acoustic Tomograph (Fakopp Enterprise Sopron) (Table 2). The decayed area in the tomogram was defined as the areas where the sound velocity is under the average of minimum

and maximum values in each tree (Fakopp Enterprise 2017). The decay volume was determined by assuming that the decayed space has the shape of circular truncated cone in each segment, and the decay area at the ground level was the same with that at 20 cm height since measurement at ground level was practically impossible because of insufficient space to install the equipment and the influence of soil at the trunk base.

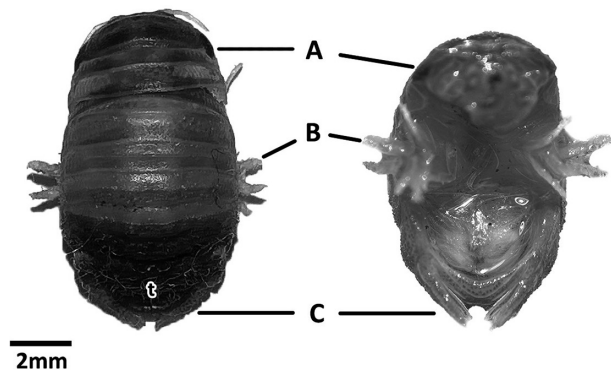


Fig. 2. Dorsal and ventral view of the wood-boring isopod, *Sphaeroma terebrans*. Notable morphological characteristics of the species include its (A) large laterally posterior eyes, (B) four distinct pairs of peraeopods, and (C) serrated uropods flanking the pointed plates of the telson (t).

Table 2. Mean values of decay area (%) at three measurement heights (20, 40 and 60 cm from ground level) and mean decay volume (%) from 0 to 60 cm for each species: *Avicennia marina*, *A. alba* and *S. alba*. Numbers in parenthesis indicate SE.

Species (no. of trees)	Decay area (%)			Decay volume (%)
	20 cm	40 cm	60 cm	
<i>A. marina</i> (16)	76.9 (7.6)	45.1 (9.1)	2.0 (0.7)	56.8
<i>A. alba</i> (10)	12.3 (3.5)	7.8 (3.3)	3.1 (2.9)	9.1
<i>S. alba</i> (8)	12.1 (9.0)	10.6 (3.0)	7.4 (5.4)	9.6

Table 1. General attributes (trunk size and height) of mangrove trees by species: *Avicennia marina*, *A. alba* and *Sonneratia alba*. Trunk size was measured at heights without isopod holes, at the upper limit of isopod holes, and the widest part of the trunk deformed by presence of isopod holes. Numbers in parenthesis indicate the range of sample values.

species (no. of trees)	trunk diameter (cm)			height (m)
	non-deformed (isopod-free)	isopod upper limit	widest deformation	
<i>Avicennia marina</i> (16)	9.6 (4.8 – 13.3)	11.1 (5.7 – 22.0)	19.7 (10.3 – 31.8)	6.4 (2 – 9)
<i>Avicennia alba</i> (10)	16.9 (4.3 – 30.9)	19.0 (6.2 – 33.1)	30.7 (8.4 – 48.1)	8.9 (4.5 – 12)
<i>Sonneratia alba</i> (8)	12.6 (4.7 – 22.1)	13.4 (6.0 – 25.5)	21.8 (8.7 – 37.9)	8.3 (5 – 11.5)

Quantifying the vertical variation in the density of isopod holes

For each of the mangrove individuals we studied, a tide-calibrated benchmark level was established. This was done by initially fixing a point at an elevation that was higher than the maximum height of isopod holes in the area. The tidal calibration was done by referencing the height difference of such a fixed point to the high tide mark, corresponding to the predicted high tide of that day. Such a reference level was calculated to be +1.85 m (x in Fig. 3) relative to the mean lower low water (MLLW) level. The same initial benchmark was then established in each of the subject mangrove individuals, using a level hose. For each of these trees, general attributes were also gathered including tree height and trunk size. For the trunk size, portions where deformation due to isopod infestation, upper isopod hole limit and isopod-free (no deformity) regions were separately measured (Table 1).

Along the main trunks of these tidally referenced mangrove individuals, the vertical variation in the density of isopod holes was evaluated by counting all the isopod holes within each grid of the rectangular sampling quadrat (Fig. 3, Q). The vertical elevation of each row of quadrat grids was then calculated, considering the height of the top of the quadrat (Fig. 3, y), and as related with the tidal

elevation benchmark (Fig. 3, x, z). Hole density values were then expressed as the total number of holes within 5 columns and 10 rows (50 grids; grid size = 1.25 cm × 1.25 cm; total area = 78.125 cm²), scanning vertically from top to bottom, applying a 10-row running cumulative. To relate with corresponding trunk decay values of the trees (see also relevant section below), hole density values were also expressed per 10-row trunk volume (n isopod holes per liter), using the respective circumference values of the trunks at which tomogram measurements were made. To generate summary values for each of the mangrove species, the average hole densities ($\pm$ se) within elevation ranges were computed. A total of 34 mangrove individuals were studied, including *A. marina* (16 trees), *A. alba* (10) and *S. alba* (8), with sample numbers being proportional to the relative abundance of the species.

Calculating air exposure of isopod holes along elevation gradient

As the density of the isopod holes along the mangrove trunks appeared to decrease with elevation, the possible influence of the lack of tidal inundation (air exposure index) was evaluated. The daily predicted tides for Batan Bay (year 2023) were generated from WXTIDE32 software. To determine which days over quarters and the entire year

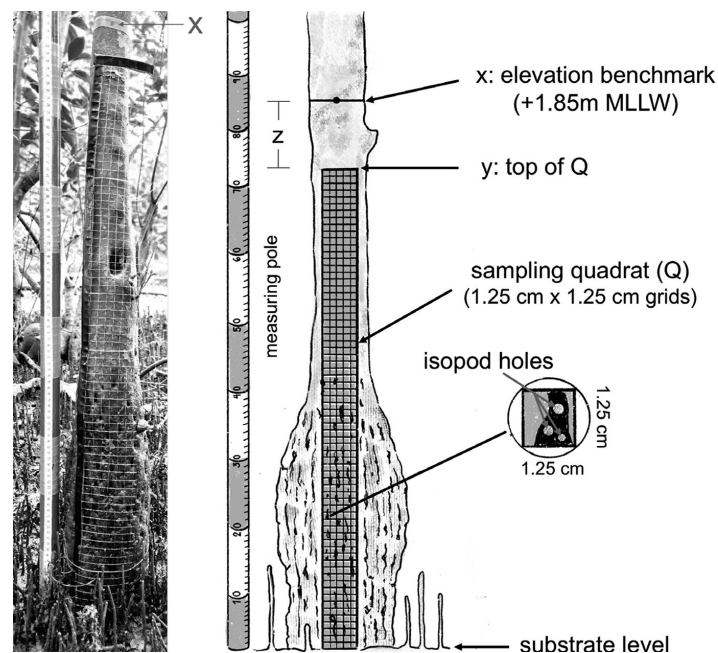


Fig. 3. Schematic diagram of counting isopod holes along the main mangrove trunk in relation to elevation with respect to the mean lower low water (MLLW) level: (x) elevation benchmark; (y) top of the sampling quadrat (Q); and (z) distance between (x) and (y). Actual field photo also shown with (x) indicated.

when certain elevations (i.e., +1.0, +1.2, +1.4, +1.6, and +1.8) were not flooded, the maximum tide for each day was extracted. Air exposure index was then calculated as the number of days over three weeks when these certain reference elevations were higher than the highest tide of the day. Air exposure index values were then expressed as percentages over 21 days.

Statistical modelling

To evaluate the effects of species and measurement height on the decayed areas of the trunk, the general linear mixed model was constructed. As the measurement was repeated for each individual tree, Tree ID was assigned as a random effect to exclude the bias of measurements depending on individual trees. Also, the interaction between measurement height and species was considered as a fixed effect. For measurement height, the heights from ground height and MLLW were tested. For comparison of associated models, AIC was calculated for each model where the AIC balances the goodness of fit of the model with its complexity, penalizing models that have too many parameters to avoid overfitting, and lower AIC value means a better model. Furthermore, using the result of the best model, multiple comparisons among species were conducted.

To evaluate the effects of species and hole density on the decayed volume, a linear regression model was constructed. The mean hole density and average hole density within the focal area (10 cm width $\times$ 60 cm height) were tested with effect of species. The interaction between hole density and species was also added as an explanatory variable. For comparison of associated models, AIC was calculated. Furthermore, using the best model, multiple comparisons among species were conducted.

To construct the linear mixed and linear models, we used “nlme” package and basic package, respectively, in open source statistical software R ver. 4.4.1 (R Core Team, 2024).

RESULTS

The wood-boring isopod found to be infesting the recovering mangroves of Tabon were identified to be *S. terebrans* Bate, 1866 (Bate 1866). Belonging to the family Sphaeromatidae, it is identified by having a dorso-ventrally compressed elliptical body, large laterally oriented eyes, and the ability to roll itself into a ball as a defense mechanism called conglobulation (Richardson 1897). The

collected specimens ranged from 3–13 mm in length, indicating the presence of juveniles, sub-adults, and adults. They were tan to brown, with their body colour darkening with age. The features of *S. terebrans* which distinguish it apart from other known wood-boring *Sphaeroma* species are (Fig. 2): (A) large laterally oriented eyes, (B) four pairs of robust posterior pereopods which lack the plumose setae lining the anterior three pairs that function for filter feeding, and (C) the hairy, serrated uropods that flank the triangular telson of the animal (Richardson 1905, Thiel 1999, Hossain and Bamber 2013). In addition, the plaetelson was covered with tubercles, with larger ones occurring in fours anterior to the segment, further differentiating it from *S. quadridentata* which has a smooth dorsal telson, and the more irregularly distributed tubercles of *S. walkeri* (Richardson 1905, Hossain and Bamber 2013). Supplementing reports of presence by Messana (1994) and Primavera et al. (2011), this is the first formal description of *S. terebrans* found in the Philippines.

The mean density ($\pm$ SE) of isopod holes on mangrove trunks at the study site could be as high as 39.3 ± 3.1 holes within 50 grids (grid size: 78.125 cm^2), or equivalent to ca. 51 holes per 100 cm^2 (Fig. 4a, *A. alba*). The three subject mangrove species (*A. marina*, *A. alba*, and *S. alba*; see tree attributes in Table 1) differed in their peak isopod hole densities, with *S. alba* having significantly lower value (ca. 23 ± 3.5 per 50 grids; ca. 29 holes per 100 cm^2) than the two *Avicennia* species, which had comparable peak values (Fig. 4a). Nonetheless, all the isopod hole density curves of the three mangrove species showed peak values at about the same elevation range (i.e., +1.0 to +1.2 m MLLW), and all decreased proportionately towards higher elevation (Fig. 4a). Evaluating the lack of tidal inundation (% dryness; air exposure index) at various elevations along the mangrove trunks, the resulting curves (i.e., quarterly, and annually; Fig. 4b) resembled closely the isopod hole density curves from peak towards higher levels (Fig. 4a). In fact, when regressed directly, the hole density values were strongly related to the corresponding air exposure values for all three species (all p-values < 0.01 ; R^2 range: 0.898 to 0.997; Fig. 5). Incidentally, no isopod holes were recorded higher than 1.8 m MLLW. At this height, the annual mean air exposure index (% dryness) was 62 % (Fig. 4b), with some dry episodes lasting longer than 21 consecutive days, more particularly during the first quarter of 2023 (i.e., not inundated for 25 days; Fig. 4b). In contrast, the air exposure index values at the elevation zone of peak isopod densities were < 5 % (Fig. 4b; Table 3). More specifically, a total of only 6 dry days occurred at this elevation zone for the entire year of 2023 (i.e., 3 days in Q1, 3 days in Q2; never a dry

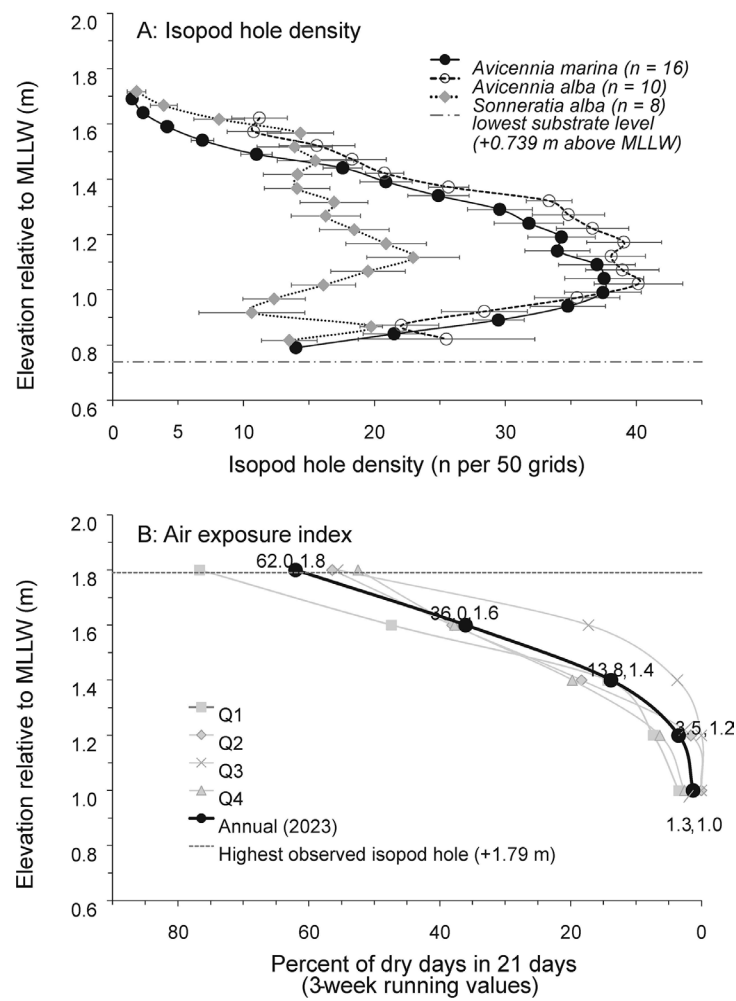


Fig. 4. Density of isopod holes, tidal elevation, and air exposure index: (a) vertical variation in the density of isopod holes ($\pm$ SE) on the trunk surface of three mangrove species with their corresponding sample size (n). The lowest substrate elevation (+ 0.739 m MLLW) in the area is also indicated. (b) Air exposure index curves at various elevations showing quarterly (Q1-Q4) and annual curves for 2023. The elevation of the highest observed isopod hole (+ 1.79 m MLLW) is also shown.

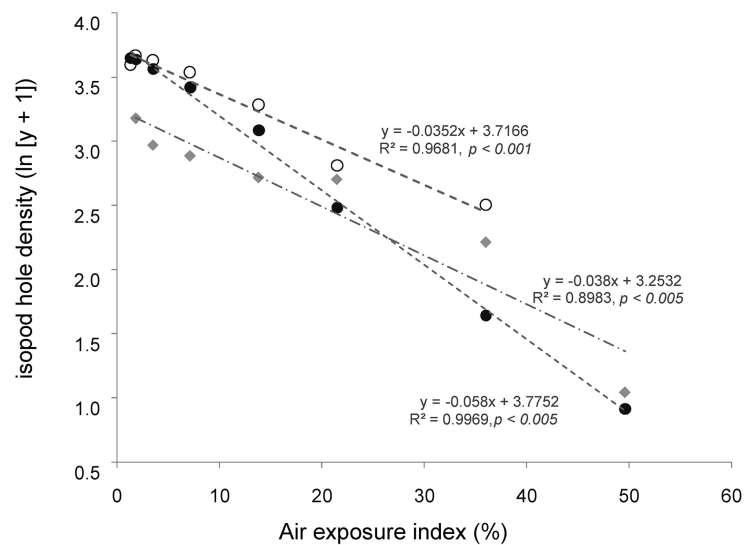


Fig. 5. Air exposure index and isopod hole density (log-transformed; $\ln [y + 1]$) showing species-specific regression lines together with their corresponding equations, R^2 and p-values.

Table 3. Elevation and corresponding air exposure index of the upper vertical limit and peak isopod hole density of three mangrove species: *A. marina*, *A. alba* and *S. alba*.

species (no. of trees)	vertical limit		peak density	
	elevation* (m)	annual air exposure index	elevation* (m)	annual air exposure index
<i>Avicennia marina</i> (16)	1.7	49.6 %	1.0	1.3 %
<i>Avicennia alba</i> (10)	1.6	36.0 %	1.0	1.3 %
<i>Sonneratia alba</i> (8)	1.7	49.6 %	1.1	1.8 %

* relative to mean lower low water (MLLW)

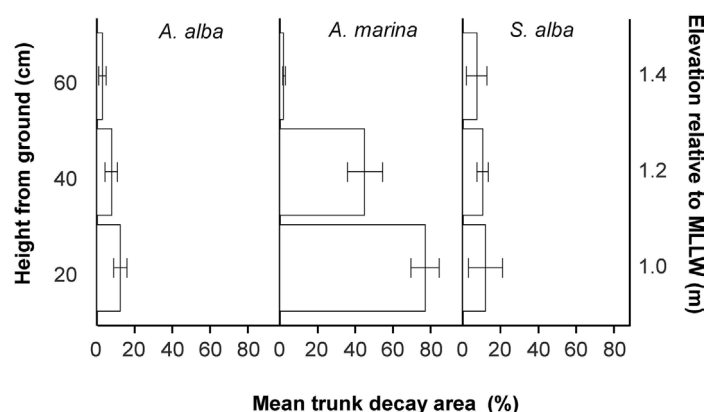


Fig. 6. Vertical profile of trunk decay area (%) in three mangrove species. Error bars mean SE.

day in Q3 and Q4), and such rare dry episodes never lasted for more than a day.

The trunk decay area was measured at three heights for each tree trunk where the heights of 20, 40 and 60 cm from the ground correspond to 1.0, 1.2 and 1.4 m respectively (Fig. 6). The trunk decay area showed a decreasing tendency upward in each species. The mean values of decay area in each species ranged from 3.1 ± 2.9 SE % at 60 cm height to 12.3 ± 3.5 % at 20 cm height in *A. alba*, from 2.0 ± 0.7 % at 60 cm height to 76.9 ± 7.6 % at 20 cm height in *A. marina* and from 7.4 ± 5.4 % at 60 cm height to 12.1 ± 9.0 % at 20 cm height in *S. alba*, respectively (Table 2).

The linear mixed model suggested that relative height to the MLLW level was better predictor than height from ground height since the model having MLLW showed AIC of 872.9 (Table 4) which was lower than 910.1 in the model having height from ground level (details are not shown). The AIC of the full model summarized in Table 4 was lower than 929.5 for a model having SP (mangrove species) and MLLW without their interaction, 967.3 for a model having SP only, and 974.9 for a model having MLLW only. ANOVA based on the linear mixed model suggested that the effects of MLLW, species, and their interaction were significant ($p < 0.001$). The linear mixed model was

configured with a reference level of *A. alba*, the result suggested that the height had a significantly negative effect in *A. marina* (Table 4). On the other hand, the effects of other two species were insignificant as well as associated height effects specific to species, i.e. interactions between height and *A. alba* or *S. alba* were insignificant ($p > 0.05$). Thus, the upward decreasing trend of trunk decay was significant for *A. marina* only. The pairwise multiple comparisons, utilizing the result of the linear mixed model, indicated that trunk decay was significantly higher in *A. marina* compared to that in other species ($p < 0.05$) (Fig. 7).

The mean values of trunk decayed volume (at height range from 0 to 60 cm) were 9.0 ± 2.6 SE % in *A. alba*, 56.8 ± 6.3 % in *A. marina* and 9.74 ± 13.7 % in *S. alba*. ANOVA based on the simple linear regression model suggested that the effect of species was significant ($p < 0.001$) but the effect of mean hole density was insignificant ($p > 0.05$) (Table 5). The AIC value was 306.8 for the full model and higher than 302.9 for the model having SP as a single fixed effect. The pairwise multiple comparisons based on the simple linear regression model having SP as a single fixed effect suggested that trunk decay volume was significantly higher in *A. marina* than the other two species ($p < 0.05$) (Fig. 8).

Table 4. Mean, SE and probability (P) values of the full linear mixed model parameters and their interactions: relative height to mean lower low water level (*MLLW* in cm) and species (*SP*; i.e., *Avicennia alba* *AA*, *Avicennia marina* *AM*, and *Sonneratia alba* *SA*). AIC* was calculated as 872.9.

Parameters	Mean	SE	P values
<i>MLLW</i>	-23.1	20.8	0.271
<i>SP_AA</i>	35.1	25.0	0.164
<i>SP_AM</i>	267.8	19.7	$2.2 \times 10^{-24**}$
<i>SP_SA</i>	27.5	29.1	0.347
<i>MLLW:SP_AM</i>	-164.6	26.3	$2.4 \times 10^{-8**}$
<i>MLLW:SP_SA</i>	1.25	4.05	0.758

* AIC: Akaike Information Criterion

** indicates $p < 0.01$

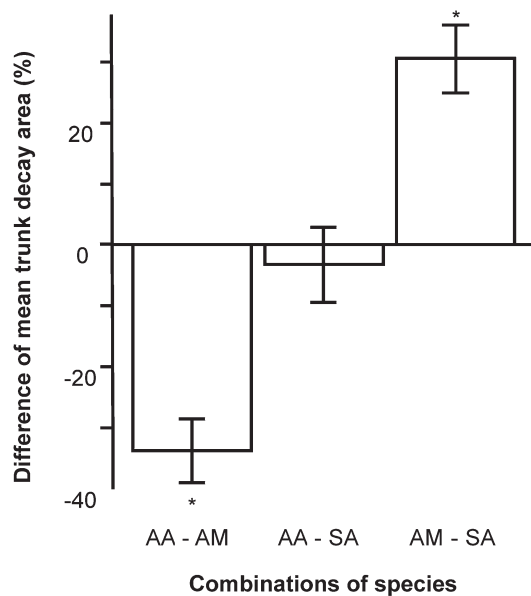


Fig. 7. Multiple comparison of trunk decay area among three species based on the results of linear mixed model. Error bars mean SE.

DISCUSSION

The isopods collected were morphologically identified as *S. terebrans* by Messana (2024, pers. comm.) and this would be the second report (first documented in Roxas City, Capiz, by Primavera et al., 2011) of its presence in the Philippines. Sightings of these marine isopods are anticipated, as these organisms are associated with mangrove forests and is only limited in the tropical and subtropical regions (Estevez 1978 as cited in Powell 2020). As filter feeders, they prefer an environment with high suspended organic particulates in order to survive (Svavarsson et al. 2002, Nagelkerken et al. 2008), however, living in the

Table 5. Mean, SE and probability (P) values of the full linear regression model parameters and their interactions: density of isopod holes (*Hole*, cm^{-2}) and species (*SP*; i.e., *Avicennia alba* *AA*, *Avicennia marina* *AM*, and *Sonneratia alba* *SA*). AIC* was calculated as 306.8.

Parameters	Mean	SE	P values
<i>Hole</i>	12.7	29.2	0.667
<i>SP_AA</i>	3.9	13.6	0.778
<i>SP_AM</i>	56.4	8.3	$2.35 \times 10^{-7**}$
<i>SP_SA</i>	-0.7	10.8	0.951
<i>Hole:SP_AM</i>	-11.4	34.3	0.742
<i>Hole:SP_SA</i>	41.0	51.9	0.436

* AIC: Akaike Information Criterion

** indicates $p < 0.01$.

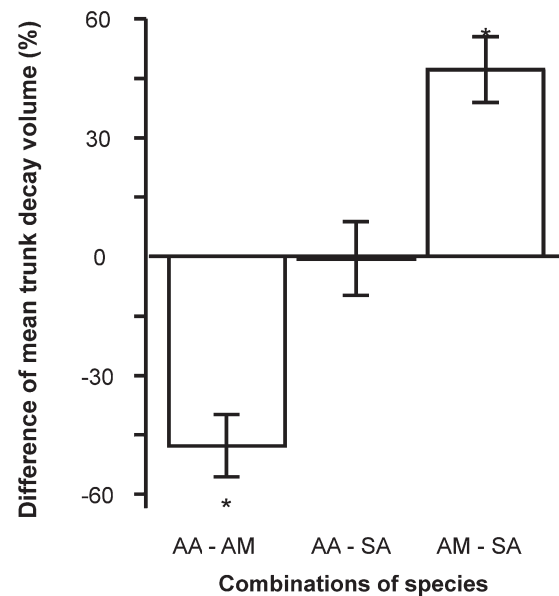


Fig. 8. Multiple comparison of trunk decay volume among three species based on the results of simple linear regression model. Error bars mean SE.

intertidal zone, they are subjected to several stressors such as desiccation and hypoxia due to tidal fluctuations (Powell 2020). In this study, isopod hole density (approximately 39 holes/50 grids or ca. 51 holes/100 cm^2) peaked at an elevation between 1.0 to 1.2 m having an annual air exposure of less than 5 %, with a limited number of dry days (only 6 days in a year). This may explain the high isopod burrow density in the submerged trunks (0 to 40 cm from the ground), regardless of species measured. This suggests that *Sphaeromids* prefer areas that are always inundated and with limited air exposure in order to feed and sustain other metabolic processes including waste removal, mating, and reproduction (Rehm and Humm 1973, Messana 1994, Baratti

et al. 2005, 2011). Isopods, just like any other intertidal organisms, are sensitive to prolonged desiccation, thereby, inhabiting areas with low air exposure to avoid stress is essential for their survival. Among the three mangrove species, hole density values were comparable in both *A. alba* and *A. marina* while *S. alba* had the lowest density. Even at the 1.0 m mark, where mangroves were almost always submerged, isopod attacks on *S. alba* were still low. We hypothesized that *A. marina* could retain more moisture than other species, which helps the isopods to survive for a longer period of time, and based on our observations, some water could still be found in its natural depressions during low tide. In contrast, hole density decreased towards higher elevation, and at 1.8 m MLLW no holes were observed. At this height, the annual air exposure was high (62 %) and typically dry for 21 consecutive days. This implies that the high annual air exposure can already be considered an extreme environment for isopods due to high risk of desiccation and could limit their distribution pattern.

Earlier reports have contradicted findings on the burrowing behavior of *S. terebrans* (Rehm and Humm 1973, Thiel 1999, Simberloff et al. 1978, Powell 2020, Brooks and Bell 2002, Wilkinson 2004, Davidson et al. 2016). According to Estevez (1978 as cited in Powell 2020), the burrowing activity is driven by refuge and caused no harm to mangroves; and the colonization of isopods in prop roots stimulates root branching which aids *R. mangle* to survive strong wave action (Simberloff et al. 1978). However, our study revealed that isopod attacks caused trunk decay on mangrove stands, compromising their internal structure and stability. Numerous sources had the same observation that these infestation causes heavy damage resulting in the deaths of mangroves worldwide (Perry and Brusca 1989; Brooks 2002, Svavarsson et al. 2002, Hossain and Bamber 2013, Liu et al. 2020, Wang et al. 2022). Once settled, *Sphaeromids* mostly attack the trunk and root parts of mangrove trees. In this study, only the trunks were evaluated due to the severity of infestation while roots showed little to no visible impacts. The high isopod proliferation in the trunk bases may be the result of their soft texture, making them an ideal habitat for marine isopods to thrive (Wilkinson 2004), thereby a probable explanation for the high hole density in the submerged trunks. As previously mentioned, *S. terebrans* are filter feeders, but they have also an ability to consume wood in order to gain nutrition, with the discovery of cellulose digesting enzymes in its hindgut (John 1968 as cited in Benson et al. 1999, Benson et al. 1999). This further confirmed their ability to digest wood and may explain the high trunk decay observed.

Among mangrove species, *A. marina* was severely affected and showed significantly highest mean decay area and volume, regardless of height measurements from the ground. Highest decayed area (76.7 to 45.1 %) was observed between 20 cm and 40 cm, corresponding to the 1.0 to 1.2 m MLLW range, which is almost always flooded. A similar observation was also noted, showing a decreasing pattern of trunk decay at higher elevation, but specific to *A. marina* only. Although both *A. alba* and *S. alba* were also attacked, they exhibited less damage and insignificant association with height-related effects. Moreover, trunk decay volume increased significantly with mean hole density, however, the relationship between decay volume and hole density is somewhat arbitrary. Burrowed isopods may initiate and hasten the degradation of mangroves. However, the holes observed may not be solely caused by isopods and are probably one of the many contributors in the process.

Presence of other organisms such as crabs, worms, mollusks, bacteria, and fungi (Wilson 1989, Kohlmeyer et al. 1995, Guo et al. 2005, Sridhar 2005, Nagelkerken et al. 2008, Kristensen 2008, Salmo et al. 2017, Devadatha et al. 2021, Murugesan and Balasubramanian 2021), may also create holes or damage, further contributing to trunk decay. This study supports previous research findings that air exposure and tidal elevation play a significant role in isopod colonization of mangroves and the negative correlation of these factors. Furthermore, tidal elevation with reference to MLLW can be an indicator on the type of mangrove species to survive, thereby, influencing mangrove distribution and species diversity. In this case of *S. terebrans* outbreak, *A. marina* was severely damaged compared to *A. alba* and *S. alba*. Both *A. marina* and *A. alba* belong to the same genus but the impacts of infestation differ significantly. Some papers documented the heavy infestation in several species such as *A. alba* (Harmonis et al. 2024), *S. alba* (Harmonis et al. 2024), *Bruguiera sexangula* (Xin et al., 2020), *B. gymnorhiza* (Xin et al. 2020), and *R. mangle* (Rehm and Humm 1973, Brooks and Bell 2001). Additionally, isopod attacks in Capiz (a nearby province) targeted mostly *Rhizophora* saplings accounting for almost 80–90 % of the mortality (Primavera et al. 2011). Meanwhile, in this study, both saplings and mature *Rhizophora* spp. were not attacked upon field inspection. This selectivity of infestation among mangrove species could be attributed to the presence of several factors such as phytochemical compounds and nutritional properties (Rahmania et al. 2018, Nabeelah et al. 2019). Mangroves have been found to primarily contain secondary metabolites (i.e. terpenoids, tannins, steroids, alkaloids, flavonoids, and saponins, Nabeelah et al. 2019), and secrete them when stressed or attacked. These

metabolites possess therapeutic benefits to treat a wide array of diseases in humans due to their pharmacological effects. Among the phytochemicals present, the three mangrove species usually differ in phenolic, tannin, and saponin properties. However, tannin plays a significant part in the defense mechanism of plants by increasing resistance against pathogens (Bandaranayake 2002). Tannin found in mangroves can be extracted as condensed tannin (Hernes et al. 2001) and is highly abundant in *Rhizophora* species (Basak et al. 1996, Rahim et al. 2008) but undetectable in *A. marina* (Zhou et al. 2010). With low tannin content, plants like *A. marina* are more vulnerable to pathogen attacks and susceptible to environmental stress, making them an ideal target of isopods. However, these assumptions on the effects of phytochemicals and nutrient content warrants further investigation to properly determine the cause of infestation.

According to Harmonis et al. (2024), abiotic factors, specifically, temperature, salinity, and dissolved solids can influence the outbreak of marine isopod *S. terebrans*. Based on the researchers' visual observation, water turbidity around the area is apparently high. The site is situated in the vicinity of Tinagong Dagat, where there are numerous aquaculture activities like shellfish (i.e. slipper shaped oyster, green mussel, whiteleg shrimps) and finfish farming (milkfish), since these are the primary source of income of the surrounding communities. Most oyster farmers employ the traditional bamboo stake method as their primary culture technique, and by using this technique, each bamboo stake is pushed onto the soil bottom for larval settlement and grow-out culture. Also, these farms are so close to each other that boat navigation is becoming difficult. Presence of these bamboo stakes in a dense manner might alter the natural water dynamics of the area and possibly increase sediment accumulation in the long run. As for finfish farming, sometimes co-cultured with crustaceans, brackishwater fishponds are primarily utilized and are usually located near each other. Both incoming and discharged water from fishponds flows to and from Tinagong Dagat (the only source of tidal water for animal rearing), which might be a contributing factor in the increasing water turbidity and probably organic load (authors' personal observation). Aside from this, the estuary, Tinagong Dagat, is also fed by several river outlets that bring more terrestrial inputs (i.e. agricultural run-off and household wastes) eventually increasing the nutrient availability around the area. The overabundance of nutrients promotes excessive growth of algae and other microorganisms which serves as natural food sources of marine isopods, resulting in isopod proliferation. Moreover, according to a recent report of Wen et al. (2025), *S.*

terebrans abundance is correlated with dissolved inorganic nitrogen, dissolved inorganic phosphorus, total suspended solids, chlorophyll *a*, and zooplankton abundance.

Usually, *S. terebrans* are found in small quantities in the mangrove community (Xin et al. 2020). However, its huge presence in the study area may indicate environmental degradation which might be due to the presence of high organic loads and poor water circulation. This finding sparks a great concern on the extent of isopod infestation around Batan Bay and its distribution in nearby mangrove areas. Since the first sighting (Capiz) of this marine isopod in Panay is near the study site, its distribution could be through the dispersal of infested floating mangrove woods, like previous reports had noted (Baratti et al. 2005, Xin et al. 2020). Moreover, we can conclude that the infestation of *S. terebrans* could be related to the water quality of the area, and can serve as an indicator of environmental health status. The high marine isopod occurrence in the area is not an isolated incident, became neighboring mangrove areas also displayed the same moderate to critical conditions as the study site (authors' personal observation).

This paper demonstrated the feasibility of using the ArborSonic 3D Acoustic Tomograph ArborSonic 3D Acoustic Tomograph, an emerging technology in tree diagnostics, in detecting and quantifying internal trunk decay caused by isopods in mangroves. It is interesting to note that this is the first paper reporting the use of the ArborSonic 3D Acoustic Tomograph as a diagnostic tool in mangrove forest.

CONCLUSION

For three mangrove species, *A. marina*, *A. alba*, and *S. alba*, isopod hole density at the trunk surface was explained by the relative height above MLLW level, and hole density decreased significantly with increasing time of exposure to the atmosphere. In addition, the trunk decay area increased with decreasing relative height above the mean sea level in *A. marina*, but did not decrease significantly in the other tree species. The relationship between trunk decay volume and hole density was insignificant, but *A. marina* had a higher trunk decay volume than the other two species. These results partially supported our hypothesis that trunk decay extent is a function of isopod hole density on the trunk surface, as well as the species of the host tree, i.e. interspecific differences in trunk decay area and volume were detected but the effect of hole density on the trunk decay volume was insignificant. The holes caused by isopods could be a trigger to start a formation of hollow

space in the trunks but further research on the other influential parameters, such as tolerances to xylophagous fungus, water quality, and physical disturbance, would be necessary to understand the decay process of trunks in mangroves. Moreover, due to the accuracy and reliability of AT, aside from its low cost, portability and low invasiveness, this tool could be effective in the monitoring of old and endangered trees to ensure their long-term survival. Findings of this study could provide critical information to decision-makers in drafting appropriate sustainable coastal resource management plans, focusing on mangrove rehabilitation and conservation of mangroves, to address the growing concern on marine isopod infestation. The loss of mangroves caused by isopod destruction around Batan Estuary could lead to significant ecological changes in the coastal ecosystem. These modifications can create new mangrove zonation patterns by establishing the lower intertidal limits of species affected, particularly, *A. marina*; a shift in the mangrove community structure and potential impacts on other marine life as well as decrease in biodiversity.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflict of interest.

AUTHORSHIP CONTRIBUTION STATEMENT

Jean Rose H. Maquirang: conceptualization, logistics

arrangement, data collection and analysis, manuscript preparation, review and editing. **Rene N. Rollon:** conceptualization, data collection and analysis, manuscript preparation, review and editing. **Rempei Suwa:** conceptualization, data collection and analysis, manuscript preparation, review and editing. **Yasmin Primavera-Tirol:** conceptualization, data collection and analysis, manuscript preparation, review and editing. **Giannina Marie G. Albano:** conceptualization, data collection and analysis, manuscript preparation, review and editing. **Green Ann A. Cruz:** conceptualization, data collection and analysis, manuscript preparation, review and editing. **Maia Patricia D. Garcia:** conceptualization, data collection and analysis, manuscript preparation, review and editing. **Ryan M. Basina:** logistics arrangement, data collection, map preparation. **Kazuo Nadaoka:** conceptualization, manuscript preparation, review and editing.

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