THE ECOLOGICAL ROLE OF MANGROVE CRABS IN MANGROVE FORESTS OF PENANG ISLAND

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THE ECOLOGICAL ROLE OF MANGROVE CRABS IN MANGROVE FORESTS OF PENANG ISLAND

by

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LIST OF ABBREVIATIONS

C	Carbon
$CaCO_3$	Calcium carbonate
CHN	Carbon Hydrogen Nitrogen
cm^2	Centimeter square
CO_2	Carbon dioxide
DBH	Diameter Breast Height
DW	Dry Weight
FAO	Food and Agriculture Organization
g	gram
JTPP	Jawatankuasa Teknikal Perancangan Dan Pelaksanaan Program Penanaman Pokok Bakau Dan Spesies-Spesies Yang Sesuai Di Pesisiran Pantai Negara
KeTSA	Kementerian Tenaga dan Sumber Air
kg	kilogram
m	metre
Mg	Megagram
NRE	Natural Resources and Environment Malaysia
ppt	part per thousand
SEM	Standard error of mean
SOC	Sediment organic carbon
SIC	Sediment inorganic carbon
Tg	Teragram
t	tonnes
U	Mann-Whitney U Test
^0C	degree Celcius
%	percentage

PERANAN EKOLOGI KETAM BAKAU DI HUTAN PAYA LAUT PULAU PINANG

ABSTRAK

Ketam bakau merupakan jurutera ekosistem penting dalam hutan paya laut yang mempengaruhi sifat sedimen, dinamik nutrien, dan perkembangan tumbuh-tumbuhan di zon pasang surut. Kajian ini bertujuan untuk (1) menilai komposisi himpunan spesies ketam bakau merentasi taburan lokasi dan tempoh waktu serta mengenal pasti korelasi antara kepelbagaian dan kelimpahan ketam dengan pemboleh ubah kawasan persekitaran, dan (2) mengkaji potensi peranan ekologi ketam bakau terhadap sifat sedimen dan pertumbuhan anak pokok bakau melalui eksperimen manipulatif lapangan di Balik Pulau, Pulau Pinang, Malaysia. Sebanyak 1,093 individu ketam telah direkodkan, terdiri daripada 13 spesies, kebanyakannya daripada famili Sesarmidae. Perbezaan ketara dalam komposisi himpunan ketam dikesan merentasi lokasi dan tempoh persampelan (PERMANOVA: p = 0.001), dengan *Perisesarma eumolpe* dan *P. foresti* menyumbang lebih 60% daripada variasi yang diperhatikan (analisis SIMPER). Corak komuniti ini menunjukkan korelasi signifikan dengan pembolehubah persekitaran seperti pH sedimen, saliniti, litupan kanopi, dan ketumpatan akar (BEST: $\rho = 0.129$, $p = 0.002$). Dalam kajian eksperimen, keputusan PERMANOVA menunjukkan terdapat perbezaan ketara dalam keadaan sedimen antara sangkar eksperimen ($p < 0.05$). Tindak balas anak pokok *Rhizophora apiculata* juga berbeza antara rawatan: pertumbuhan ketinggian anak pokok tertinggi dicatatkan dalam sangkar pengasingan ketam (7.94 ± 1.73 cm), manakala penghasilan daun paling tinggi direkodkan dalam sangkar kawalan (7.16 ± 0.70 helai daun), mencerminkan keseimbangan antara gangguan fizikal oleh ketam dan manfaat kitaran nutrien yang dipertingkatkan. Analisis perkaitan menunjukkan bahawa pertumbuhan ketinggian anak pokok berhubung kait secara positif dengan bahan organik ($\rho = 0.256$), kemasinan ($\rho = 0.400$), dan suhu ($\rho = 0.288$). Penghasilan daun pula menunjukkan hubungan positif dengan pH sedimen ($\rho = 0.311$), namun berkait secara negatif dengan kandungan hidrogen ($\rho = -0.296$) dan nitrogen ($\rho = -0.229$). Analisis BEST turut menunjukkan hubungan yang kuat antara aktiviti ketam (ketumpatan dan kehadiran lubang ketam) dengan kandungan hidrogen dan nitrogen dalam sedimen ($\rho = 0.759$), menekankan impak keberadaan ketam terhadap transformasi nutrien dan proses reduksi dalam sedimen. Oleh itu, ketam bakau memainkan peranan dalam pembentukan biogeokimia sedimen dan mempengaruhi perkembangan awal tumbuhan. Penemuan ini menegaskan kepentingan fungsi ketam dalam menyokong strategi pemulihan dan pengurusan hutan paya laut yang lebih berkesan.

THE ECOLOGICAL ROLE OF MANGROVE CRABS IN MANGROVE FORESTS OF PENANG ISLAND

ABSTRACT

Mangrove crabs are important ecosystem engineers that influence sediment properties, nutrient dynamics, and vegetation development in intertidal mangrove forests. This study aimed to (1) assess the assemblage composition of mangrove crabs across spatiotemporal distributions, and determine correlations between crab abundance and diversity with environmental variables, and (2) examine the potential ecological roles of mangrove crabs on sediment properties and mangrove sapling growth through manipulative field experiments.in Balik Pulau, Penang, Malaysia. A total of 1,093 crab individuals, representing 13 species, mostly from the family Sesarmidae were recorded. Significant variation in crab assemblage composition was observed across sites and sampling periods (PERMANOVA: p = 0.001), with *Perisesarma eumolpe* and *P. foresti* contributing over 60% of observed variation (SIMPER analysis). These assemblage patterns were significantly correlated with environmental variables including sediment pH, salinity, canopy cover, and root density (BEST: ρ = 0.129, p = 0.002). In the experimental study, PERMANOVA results indicated significant differences in sediment conditions across cage treatments ($p < 0.05$). Across the exclusion, control and open cage treatments, sapling responses were different: height growth was greatest in exclusion cages (7.94 ± 1.73 cm), while leaf production was highest in control treatment (7.16 ± 0.70 leaves), suggesting a trade-off between the physical disturbance from crabs and the benefits of enhanced nutrient cycling. Correlation analyses revealed that sapling height was positively associated with organic matter (ρ = 0.256), salinity (ρ = 0.400), and temperature (ρ =

0.288), whereas leaf production was positively associated with sediment pH (ρ = 0.311) but negatively correlated with hydrogen (ρ = –0.296) and nitrogen content (ρ = –0.229). BEST analysis further demonstrated a strong correlation between crab activity (burrow density and abundance) and sediment hydrogen and nitrogen content (ρ = 0.759), highlighting crabs' influence on nutrient transformation and redox-sensitive sediment processes. Mangrove crabs therefore play a dual role in mangrove ecosystems by shaping sediment biogeochemistry and influencing early plant development. These insights underscore their functional importance in guiding effective mangrove restoration and management practices.

CHAPTER 1 INTRODUCTION

1.1 Research background

Mangrove ecosystems comprise salt-tolerant plants capable of surviving extreme environmental conditions between land and sea in tropical and subtropical regions worldwide (Saenger, 2002). Distributed predominantly between 30° N and 37° S latitudes, mangroves flourish at tidal heights of 1–4 meters (Feller et al., 2010). These ecosystems are structurally complex, providing sediment traps, barriers against intertidal waves, and habitat structures that support diverse marine species during their larval and juvenile stages (Van Lavieren et al., 2012; Lee et al., 2014). Beyond their ecological services, mangroves also offer timber, charcoal, and seafood resources that benefit local coastal communities (Faridah-Hanum et al., 2014).The distribution and zonation of mangrove species are primarily influenced by physicochemical factors such as salinity, sediment grain size, redox potential, and temperature, as well as biological interactions including propagule competition and macrofaunal activity (Kathiresan & Bingham, 2001; Hogarth, 2008; Cannicci et al., 2018). Despite relatively low plant diversity compared to other ecosystems, mangroves exhibit high productivity and play an essential role in coastal nutrient cycling and habitat stability (Donato et al., 2011; Alongi, 2014).

Within the mangrove environment, benthic organisms, particularly mangrove crabs are recognized for their contributions to sediment dynamics, nutrient cycling, and the maintenance of ecosystem health (Smith et al., 1991; Kristensen, 2008; Nobbs & Blamires, 2015). Acting as keystone species and ecosystem engineers, these crabs influence sediment biogeochemistry through their burrowing and feeding activities

(Escapa et al., 2007; Wang et al., 2010), thereby altering the mangrove floor's geomorphology, affecting nutrient availability, and supporting microbial community structure (Booth et al., 2019).

Mangrove crabs also play pivotal roles in leaf litter processing, contributing to nutrient cycling and primary productivity within the ecosystem (Robertson et al., 1992; Dahdouh-Guebas et al., 1998; Schories et al., 2003). The burrows of fiddler and sesarmid crabs enhance sediment aeration, facilitate drainage, and promote microbial activity, all of which contribute to improved soil conditions for mangrove sapling growth (Michaud et al., 2024). The complexity and distribution of crab burrows vary with geomorphic features, affecting sediment biogeochemistry and hydrology, which in turn influence mangrove regeneration patterns (Michaud et al., 2024). The excavation of sediment by crabs redistributes organic matter and nutrients, enhancing soil fertility and supporting the establishment of young mangrove plants (Gillikin & Kamanu, 2005). Thus, crab activities facilitate the decomposition of organic material, promote oxygen exchange in sediment, and create microhabitats that benefit other fauna and flora (Penha-Lopes et al., 2012; Qiu et al., 2019).

Despite these essential functions, detailed studies focusing on the ecology, distribution patterns, and ecological roles of mangrove crabs in Penang Island is limited.

1.2 Problem statement

Mangrove forests are experiencing significant degradation due to anthropogenic pressures, including deforestation, urban development, and aquaculture expansion (Alongi, 2002; Kanniah et al., 2015; Sanderman et al., 2018). The debate on the anthropogenic impact on the mangrove ecosystem centers on the direct and indirect disturbance in mangrove ecosystems (Alongi, 2002; Ashton, 2008; Faridah-Hanum et al., 2014; Friess et al., 2019). The impact of deforestation in mangroves has caused the shrinking of mangrove areas (Friess et al., 2019), with devastatingly high rates found at 25% of global mangrove area loss in Myanmar, also at the same rate loss recorded in Malaysia (Sanderman et al., 2018). Deforestation was detected to be the main factor contributing to mangrove loss in Malaysia (Faridah-Hanum et al., 2014; Kanniah et al., 2015). In Malaysia, about 40000 ha of forest area was lost between 2000 to 2012 (Sanderman et al., 2018).

In Penang, Malaysia, the urbanization on mangrove forests had critically impacted crab assemblage and species richness (Nordhaus et al., 2019). The important ecological functions of crabs therefore (Smith et al., 1991; Kristensen, 2008) may disappear, and remain unnoticed. This may be exacerbated by the gap in knowledge on other ecologically important crab species which may have been overlooked when compared with crabs of economic importance. Even when mangrove crabs are considered, families such as Sesarmidae and Ocypodidae have been studied extensively (Sasekumar, 1974; Tan & Ng, 1994; Ravichandran et al., 2011; Sharifian et al., 2020), however, other families have not been highlighted thus the mangrove crab relationship were understudied (Lee, 2008).

These other crab families may have been undetected due to problems arising from a lack of taxonomic identification to species level (Ng & Davie, 2008) and unknown functions of less studied species in some regions of the world (Lee, 2008). Current climate change and alteration of mangrove complexity might influence the ecological function of crabs which affects their distribution (Ravichandran et al., 2011; Sharifian et al., 2020) and physiology (Wolcott & O'Connor, 1992; Poon et al., 2010; Salgado-Kent & McGuinness, 2010). These changes can reduce the extent and effectiveness of bioturbation, leading to poorer sediment aeration and nutrient cycling that is critical for mangrove seedling establishment. At a global scale, the are numerous studies conducted to investigate the mangrove crabs assemblage in relation with the environmental heterogeneity and their key role in certain regions (Lee, 1998; Ravichandran et al., 2011; Sharifian et al., 2020; Katharoyan et al., 2025). However, the research on the local regional scale in Malaysia, ecspecially in Penang is limited. Hence, this study was undertaken to investigate the ecological role of mangrove crabs in Penang's tropical mangrove forests. Specifically, it aims to assess crab assemblage composition, spatiotemporal distribution and their relationships with environmental variables, as well as to explore their functional roles in influencing the environmental heterogeneity in the regional area and impact on mangrove sapling growth through field experiments.

1.3 Objectives

This study aimed to investigate the ecological role of mangrove crabs in tropical mangrove forest in selected area of Penang across spatial and temporal scale.

1) To assess the assemblage composition of mangrove crabs across spatiotemporal distributions, and determine correlations between crab abundance and diversity with environmental variables.
2) To examine the potential ecological roles of mangrove crabs on sediment properties and mangrove sapling growth through manipulative field experiments.

CHAPTER 2 LITERATURE REVIEW

2.1 Mangrove distribution and status

Giri et al. (2011) stated approximately 75% of mangroves are concentrated in 15 countries which are Indonesia, Australia, Brazil, Mexico, Nigeria, Malaysia, Myanmar, Papua New Guinea, Bangladesh, Cuba, India, Guinea Bissau, Mozambique, Madagascar, and the Philippines. Asia has the largest mangrove area covering about 42% of coastal ecosystems, followed by Africa (20%), North and Central America (15%), 12% of mangrove area in Oceania, and about 11% in South America (Giri et al., 2011). Among the 15 countries that have large mangrove areas; Indonesia, Malaysia, Myanmar, Papua New Guinea, and the Philippines contributed to the large mangrove ecosystem to make Southeast Asia as the most concentrated mangrove region (Giri et al., 2011). Approximately, about 6.9% of 15.6 million ha of mangrove area is protected under the existing protected area (Giri et al., 2011). From the whole mangrove forest area, Southeast Asia, Papua New Guinea, Amazon, Mekong Delta, Madagascar, and Sundarbans are the best-developed mangroves with diverse species (Giri et al., 2011).

However, mangrove areas had declined from 16.1 million ha in 1990 to 15.6 million ha in 2010 (FAO, 2010). The mangrove ecosystem is under serious threat, even with all the recognizable natural services they offer such as carbon reservoir function, marine nursery ground, wave breaker, and economic sources, the degradation of mangroves is still occurring at a very rapid rate (Giri et al., 2011; Sanderman et al., 2018). In Malaysia, the drastic diminishing of mangroves is on average 0.13 % yearly from 642,063 ha in the year 2000 to 629,038 ha in 2017 (Omar & Misman, 2020). The decline of mangrove forests happened due to urban development, shrimp farm, oil palm plantation, and other agricultural activities (Faridah-Hanum et al., 2014; Kanniah et al., 2015). The loss of mangroves in Malaysia led to a large amount of carbon being released, negating the mangrove function as a carbon sink. This loss contributes to carbon emissions of more than 14 million Mg CO_2 with an average carbon loss to the atmosphere estimated at 526, ,905 Mg CO_2 yearly (Omar & Misman, 2020).

2.2 Malaysia mangrove carbon assessment

In addition, the carbon stock assessment in Malaysia is still understudied, with only certain mangrove forests assessed and documented. The information on carbon stock in Malaysia was gathered and recorded in the states of Pahang (Omar et al., 2016) Selangor (Hemati et al., 2015; Hong et al., 2017; Sofawi et al., 2017), Perak (Eusop et al., 2018), Sarawak (Arianto et al., 2015; Pazi et al., 2016; Kamal et al., 2017) Sabah (Eswani et al., 2017), Johor (Sofawi et al., 2017), Terengganu (Yunus et al., 2008) and Kelantan (Sofawi et al., 2017).

When considering the mangrove ecosystem valued in monetary gains for carbon, in Malaysia, the government had initiated the carbon credit income tax to promote sustainable development. The focus however was more on the palm oil crop as it is one of the largest economic incomes with a net trade profit of USD 63 M per year, through the generation of biomass energy from palm oil residue (Hong et al., 2017). The government should evaluate mangrove as one of the needed ecosystems to conserve as the revenue income for carbon trade in this ecosystem also give high revenue to the country about USD 5 to 17 M per hectare for undisturbed mangrove and USD 3 to 10 M per hectare for degraded mangrove forest (Hong et al., 2017). Not only for the profit, but also mangroves can give more impact on the ecological service function and are important for local coastal community socioeconomic (Estrada et al., 2015).

Mangrove carbon record in Malaysia mostly focused on the above and below ground estimation with different techniques used for the carbon estimation process such as the utilization of the Geographic Information System (GIS) technique (Omar et al., 2016), sediment core sample (Hemati et al., 2015; Hong et al., 2017; Sofawi et al., 2017) and through the vegetation biomass (Pazi et al., 2016; Eswani et al., 2017; Kamal et al., 2017). The inconsistency in the method used without any standardization to determine carbon stored in Malaysia mangrove results in variable carbon estimation. The GIS method covers both carbon storage parts with the calculation of area of deforestation and conversion to carbon by using vegetation biomass and the ratio of carbon dioxide molecular weight (Omar et al., 2018; Omar & Misman, 2020). The GIS method can generate results in less time and minimize human error were controlled on monitoring the status of mangroves, however can be costly for gadget tools and maintenance (Omar et al., 2018; Elmahdy et al., 2020). Other techniques used to determine carbon for belowground parts varied during estimation, ranging from the use of the Loss of Ignition (LOI) technique, Carbon-Hydrogen-Nitrogen (CHN) elemental analyzer, and conversion of organic matter concentration to organic carbon by using a constant number (Wang et al., 2011; Howard et al., 2014; Rozainah & Sahadev, 2020). The LOI technique is widely used because it is cost-efficient way to determine both organic matter and carbon (Rozainah & Sahadev, 2020).

Overall, as a tropical country that is inhabited by thriving mangrove ecosystems, there is a necessity to standardize the method and technique in carbon determination in the blue carbon strategy of Malaysia. Previous studies focused significantly on vegetation structure and sediment in carbon sequestration, however other components that may affect mangrove primary productivity such as major groups of macrofauna need to be considered in this ecosystem. The potential of gathering information from this perspective may help address the inaccuracy relating to overestimation in carbon stock data. This will contribute a more effective approach to assist policymakers when designing a policy to conserve and preserve mangroves in Malaysia.

Deterioration of mangrove ecosystem roles and functions has been linked to negative impacts on macrofauna that inhabit the mangroves (Bernardino et al., 2018). This is attributed to the close association between macrobenthos with the mangrove sediment. The further investigation about the relation between macrobenthos with any biogeochemical changes towards carbon sink and environmental changes need to be done in the Malaysia region, since the rapid shrinking of mangrove forest recorded, although the rehabilitation effort had been done (Omar & Misman, 2020). The specific study on the relation of macrobenthos towards carbon sequestration is still understudied in Malaysia with only some studies previously from Mokhtari et al. (2015 and 2016) can be found to describe the role of macrobenthos in carbon deposition in mangrove sediment in general.

2.3 Mangrove macrobenthos

Mangrove macrobenthos are organisms that live in mangrove mud or depend on the mangrove ecosystem for the entire life cycle such as Porifera, Mollusca, Arthropoda, Annelida, Nematoda, Sipunculoidea, Platyhelminthes and Ascidians

(Ellison, 2008). The study on mangrove macrobenthos included the diversity, assemblage, and density, and now include the contribution of macrobenthos to mangrove ecosystem services and function (Ellison, 2008; Lee, 2008; Hunting et al., 2010) .

Porifera, or sponges attach on mangrove roots, found on the root of *Rhizophora* spp., which produces tannins preferred by the sponges (Hunting et al., 2010). *Tedania ignis* recruitment responds to the concentration of tannins on the mangrove roots (Hunting et al., 2010). Poriferans can act as indicators for the biogeographic change in mangrove because recruitment processes are sensitive to type of substrate (Rützler et al., 2007; Setiawan et al., 2018). Mangrove sponges did not select fine size sediment grains, as smaller grains may clog the structures of these filter feeders (Rützler et al., 2007). They are found to prefer mud-sand substrate with coral granules, which could explain why patterns of sponge distribution under different mangrove species structures (Rützler et al., 2007; Setiawan et al., 2018).

Molluscs and Arthropoda phyla also gain more attention as their diversity, abundance, and biomass appeared to reflect the deforestation and subsequent rehabilitation of mangroves (Sasekumar & Chong, 1998; Ashton et al., 2003a; Skilleter & Warren, 2000). Population abundance of brachyuran crabs and gastropods were found to correlate positively with increasing mangrove age, thus indicating the maturity of the mangroves (Sasekumar & Chong, 1998 & Ashton et al., 2003a). Also, when there is disturbance happened, it affects the density of these macrobenthos too. Such as study on disturbance done by Skillter and Warren (2000) showed the construction of boardwalk shift the density of gastropod and crab. Gastropod density becomes lower while crabs become high in density as the piling structure give benefit to the crab to increase their burrow stability. However, the taxonomic identification of macrobenthos are in the process of revisions, as most families have yet to be properly identified and documented (Ellison, 2008, Lee, 2008).

Carbon in the form of carbon dioxide gas (CO_2) released in the marine environment is cycled and used in the photosynthesis process by the phytoplankton (Filgueira et al., 2019). Mangroves and other associate mangrove vegetation process carbon by photosynthesis to grow, with the carbon mostly stored in their biomass production (Shiau & Chiu, 2020). Then, the cycle continues where carbon is transferred to filter feeders such as bivalves that feed on the phytoplankton (Filgueira et al., 2019). Carbon in the form of organic matter in mangroves is is also an important food source for other macrobenthos such as gastropod and crabs (Penha-Lopes et al., 2010; An et al., 2014).

Crabs and molluscs are mangrove macrofauna involved in the carbon cycle in mangrove ecosystems through processes of calcification, respiration, and food assimilation (Kristensen, 2007; An et al., 2014; Filgueira et al., 2019). Filgueira et al. (2019) described how calcifying organism influence both organic and inorganic carbon via biogenic calcification through the production of calcium carbonate ($CaCO_3$). The cycle of carbon sequestration in shells involves absorption and reabsorption. The calcification process occurs in crabs during carapace growth and moulting, while in Mollusca carbon is required to produce $CaCO_3$ for shell development (Luquet, 2012; Filgueira et al., 2019). Therefore, these macrofauna may have a significant effect on the carbon cycle, and possibly carbon capture in mangroves.

2.4 Mangrove crab

Mangrove crabs are actively involved organism in the mangrove carbon cycle through their feeding behaviour (Robertson et al., 1992; Kristensen, 2008; Lee, 2008; An et al., 2014) and bioturbation process (Otani et al., 2010; Wang et al., 2010; Andreetta et al., 2014; Qiu et al., 2019; Guimond et al., 2020). These crab activities helps in maintaining the balance of the intertidal ecosystem and indicated them as the ecosystem engineer in mangrove (Smith et al., 1991; Senger, 2002; Gutiérrez & Jones, 2006; Kristensen, 2008; Nobbs & Blamires, 2015).

Previous studies on crabs as ecosystem engineers and keystone species were done with several experiments and observational studies conducted at rocky shore (Silva et al., 2010; Hull & Bourdeau, 2017), mudflat (Botto & Iribarne, 1999; Tanaka et al., 2013, 2017), tidal marsh (Taylor & Allanson, 1993; Escapa et al., 2007; Thomas & Blum, 2010; Martinetto et al., 2016; Guimond et al., 2020) and in mangrove ecosystems (Micheli, 1993; Brousseau et al., 2002; Mokhtari et al., 2015, 2016; Qiu et al., 2019). These studies revealed crabs play important parts in structuring the population of infaunal and meiofaunal organisms (Tanaka et al., 2013, 2017). For example, the removal of crab at rocky shore influenced other benthos significantly, indicating crabs as a key intertidal predator (Silva et al., 2010; Hull & Bourdeau, 2017). The same pattern can be observed at tidal mudflats area where crabs significantly affected the infauna by controlling food availability (Botto & Iribarne, 1999; Tanaka et al., 2017).

2.5 Mangrove crab distribution thorugh environmental drivers impact their assemblages and functional roles

Mangrove crabs are more diverse in the Indo-West Pacific region compared with lower diversity in the South-East Pacific and East Atlantic regions (Sasekumar 1974; Tan & Ng 1994; Ashton et al., 2003a; Ashton et al., 2003b; Ravichandran et al. 2011; Sharifian et al., 2020). Sesarmidae is the most diverse crab family that can be found in mangroves worldwide represented by 172 species. Other crab families in mangroves represented by species number respectively comprise Ocypodidae with 121 species accounted, Macrophtalmidae with 71 species, Dotilidae with 49 species, Camptandriidae with 36 species and family Oziidae with 30 species (Ravichandran et al., 2011; Sharifian et al., 2020). In mangrove forest of Malaysia, most mangrove crabs belong to the Sesarmidae family which from 192 species recorded in Peninsular Malaysia, 44 species come from Sesarmidae (Sasekumar 1974; Tan & Ng 1994; Ashton et al., 2003a).

Despite mangrove crabs role are pivotal in ecosystem functioning, their role in sustaining the intertidal ecosystem was always subjected to complex habitat structures designed by the vegetation and geographical setting (Lee, 1998; Ravichandran et al., 2011). For crab assemblage composition, most investigations have been conducted in mudflats and saltmarsh areas, and little is known on the effect of crab in the mangrove itself. Crabs not only shape the surroundings but are also affected by environmental changes. For example, disturbances in the mangrove create a different environment for the crab to survive by competing for space and food (Bernardino et al., 2018; Cannicci et al., 2018). Environmental physicochemical changes can cluster them by species group composition, which segregates them into zones (Ravichandran et al., 2011; Mokhtari et al., 2015). Additionally, the environmental parameters that are consistently discussed in relation to affecting crab distribution are temperature and sediment morphology (Frusher et al., 1994; Gimínez et al., 2005; Martinetto et al., 2011; Mokhtari et al., 2015; Sharifian et al., 2020).

The salinity (Katharoyan et al., 2025) and temperature factors (Sharifian et la., 2020; Katharoyan et al., 2025), clearly illustrates the differences in crab distribution along a latitudinal gradient. This difference in species composition is highly correlated with temperature changes, reflecting the ability of crabs to adapt to a specific area. Regarding the sediment, where crabs currently inhabit, the impact of crabs on sediment physiochemical changes and other fauna in the intertidal zone is actively debated, with various results recorded. Pülmanns et al. (2016) determined that there is no significant effect on crab abundance in wetland habitats concerning sediment parameters. They also claim that changes in sediment parameters mostly occur at the temporal level, with climate playing a crucial role. This finding contradicts other studies where crabs play a central role in altering sediment properties through their sediment reworking activities (Gimínez et al., 2005; Mchenga & Tsuchiya, 2013; Mokhtari et al., 2016).

2.5.1 Crab feeding activity

The feeding behaviour of mangrove crabs plays a crucial role in the carbon cycle within the mangrove ecosystem, interacting with other benthic organisms. In mangroves, the primary source identified for this process is leaf litter, contributing an estimated 64 t DW ha-1 per year (Schories et al., 2003). Feeding sources remain similar for male and female crabs, changing only in response to interruptions in biological and physical factors (Poon et al., 2010). Despite the absence of a specific feeding pattern, mangrove crabs are acknowledged as significant contributors to ‘cleaning’ the mangrove forest floor. This is attributed to leaf processing activities by crabs, which consumes , shreds, and buries leaf litter when no other food sources are available (Dahdouh-Guebas et al., 1997;Skov & Hartnoll, 2002). Leaf litter has been found to be part of mangrove crab diet, although not the most preferred food source (Kristensen et al., 2008). In addition to leaf litter, crabs appeared to select more animal-based food materials (Brousseau & Baglivo, 2005). Their diet comprises various sources such as insects, molluscs, decapods and leaf fractions (Fratini et al., 2000; Brousseau & Baglivo, 2005). Feeding sources remain similar for male and female crabs, changing only in response to interruptions in biological and physical factors (Poon et al., 2010). Previous research estimates indicate that crabs consume 50% of leaf litterfall, with 90% of crab stomach content comprising of plant-based material (Dahdouh-Guebas et al., 1997; Lee, 1998; Alongi, 2009).

Crabs assimilate more organic carbon sources as evidenced by the high enzymatic reaction during the digestion of the polysaccharide structure of plant cellulose compared to other macrobenthos (An et al., 2014). Crabs are selective to the type of leaf and may not consume all types of leaves (Erickson et al., 2004, Thongtham & Kristensen, 2005 and Nordhaus et al., 2006). Therefore, leaf litter may not be representative of the overall crab diet and may include other plant material (An et al. 2014). The crab gut may contain food particles such as algae or microphytobenthos, derived from random sediment food selection (Nordhaus & Wolff, 2007 and Bui & Lee, 2014). Enzyme reaction tests indicate that crabs likely initiate cellulose and hemicellulose breakdown through feeding and excretion, contributing to the organic carbon cycle (Robertson et al., 1992; An et al., 2014).

Observations reveal that crab's continuous organic matter consumption exceeds or matches daily leaf litter production (Schories et al., 2003; Nordhaus et al., 2006). Active leaf removal and processing behaviour were found to promote carbon mineralization in the mangrove forest (Nordhaus and Wolff, 2007). Skov and Hartnoll (2002) found crabs process leaf litter through consumption by leaf break down, pulling and storing the leaf fragment into their burrow to avoid competition. From This fragments the leaf and speeds up the composition and decaying process (Robertson et al., 1992). This justifies mangrove crabs as essential connectors for consumable organic matter, fostering microbial communities responsible for carbon pathways through ingestion, feces, and burying of mangrove litter (Kristensen, 2007, 2008). This process enhances nutrient cycling and contributes to the high rate of sedimentary bacterial productivity (Saenger, 2002; Booth et al., 2019) subsequently contributing to the carbon cycle (Li et al., 2019; Shiau & Chiu, 2020).

In the experiment by Penha-Lopes et al. (2012), crabs were found to be crucial in maintaining carbon mineralization in a steady state through feeding. However, another effect arises as faunal abundance leads to increased carbon dioxide emission, primarily from respiration and burrow activity(Taylor & Allanson, 1993; Penha-Lopes et al., 2012). This effect is counteracted by microbial and bacterial populations in mangrove sediment responsible for the rate of organic matter mineralization (Das et al., 2016). An anoxic mangrove environment initiates anaerobic microbes, slowing anaerobic decomposition and increasing the capacity of mangrove sediment to retain more organic carbon (Das et al., 2016).

2.5.2 Crab burrow

The autochthonous and allochthonous carbon material inputs in mangrove contribute to dynamic carbon storage in the benthic community (Kristensen, 2007; Shiau & Chiu, 2020). Organic carbon concentration varies across geographical regions, influenced by factors such as nitrogen concentration, in which mangroves act as sinking areas for nitrogen from upstream sources and from tides (Shiau & Chiu, 2020). The nitrogen content affects the nitrification and denitrification process, which influences the carbon mineralization pathway (Alongi, 2009; Fanjul et al., 2011). In addition, biogenic structure such as roots (pneumatophores) and burrows (Penha-Lopes et al., 2010; Alongi, 2020) also contribute to this pathway.

Biotic and abiotic factors, including crab abundance and burrow count, are consistently studied in various regions with different crab community structures. Highlighting the selection of crab taxa at a specific level becomes essential due to limited knowledge on crab distribution in particular regions(Ravichandran et al., 2011; Sharifian et al., 2020). In the Indo-West Pacific region, Sesarmidae, Ocypodidae, and Dotilidae families are major contributors to crab assemblages that maintain mangrove ecosystem function (Cannicci et al., 2008; Ravichandran et al., 2011; Sharifian et al., 2020). The same composition is observed in the Penang study site, with diverse crab families from Sesarmidae and Ocypodidae (Nordhaus et al., 2019).

Understanding crab burrow morphology is crucial, with previous descriptions of burrow morphology comprising of crab family, size and zonation (Morrisey et al., 1999; Agusto et al., 2021). Observations of crab abundance and burrow count are fundamental in determining suitable crab accommodation sites (Morrisey et al., 1999; Skov et al., 2002; Cannicci et al., 2008; Agusto et al., 2021). Although crab burrow counts may serve as an estimate of crab abundance, this technique may result in overestimatation of crab population and density (Skov & Hartnoll, 2002). Crab burrows play a significant role in the decomposition of organic substances into nutrient sources for mangrove vegetation through oxidation processes (Taylor & Allanson, 1993; Hogarth, 2008; Thomas & Blum, 2010; Andreetta et al., 2014).

Understanding the burrow structure of crab families is vital for determining their potential as bioindicators for the mangrove ecosystem.. The latest description of crab burrow morphology by Agusto et al. (2021) provides specific information at the family level while considering species differences.. The Sesarmidae family construct complex burrows with multiple shafts in the sediment, Varunidae family construct U-shaped burrows, while Ocypodidae and Dotilidae families construct single opening J-shape burrows (Agusto et al., 2021).

The outcome of modification in sediment characteristics and parameters have been attributed to crab burrowing activity which reworks the sediment (Michaels & Zieman, 2013; Mokhtari et al., 2016; Gillis et al., 2019). Crab burrows in mangrove ecosystems for example are considered important biogenic structures that traps organic carbon sources (Penha-Lopes et al., 2010). Crab burrowing enhances gaseous exchange, introducing oxygen into anoxic mangrove sediments (Gutiérrez & Jones, 2006; Kristensen, 2008; Wang et al., 2010), affecting biogeochemical properties (Kristensen et al., 2008; Wang et al., 2010; Andreetta et al., 2014; Pülmanns, 2014; Natálio et al., 2017), enhance nutrient availability (Mchenga & Tsuchiya, 2013) and flourishing bacterial communities (Booth et al., 2019; Li et al., 2019).

High densities of crab burrows has positive effects on promoting mangrove litter decomposition, accelerating nutrient use efficiency by plants (Mchenga &

Tsuchiya, 2008; Smith et al., 2009; Wang et al., 2010). For example, burrow density was found to affect the growth rate of white mangrove, sediment salinity and redox potential (Smith et al., 2009). Crab burrows can provide an ideal condition to remove excess nitrogen loads by nitrate reduction process which occur on the burrow wall (Mchenga & Tsuchiya, 2008). Burrow construction affects the gaseous exchange in the sediment (Michaels & Zieman, 2013; Agusto et al., 2021). The gaseous exchange is useful to the anoxic mangrove environment to enhance the production of microbes and sustain the carbon mineralization pathway (Kristensen et al., 2008; Shiau & Chiu, 2020). Overall, in maintaining the vital role of mangrove as a carbon reservoir area, the crab burrow is a useful biogenic structure that helps in the carbon storage pathway (Kristensen, 2007; Kristensen et al., 2008; Araújo et al., 2012; Craig et al., 2021).

2.6 Experimental Crab study

Previously, researchers had addressed the future impact on mangrove carbon reservoir capacity fate through experimental (Amaral et al., 2009; Penha-Lopes et al., 2012) and natural field studies (Penha-Lopes et al., 2012; Tanaka et al., 2013; Abdullah & Lee, 2016; Natálio et al., 2017). The experimental study was setup in various design based on abiotic-abiotic (fauna/floral and environment profile) and biotic-abiotic interactions and responses (Peterson, 1979; Resetarits Jr et al., 1995; Cooke et al., 2017). In Malaysia, experimental study involving manipulating the natural habitat to study mangrove crab influences on carbon concentration in mangrove is still not explored in detail.

An observational study by Mokhtari et al. (2015 and 2016) defined crab distribution with preferences to specific environmental range in the mangrove ecosystem. The large spatial scales could be a problem due to differences in environmental heterogeneity in each area. Knowledge on relation between mangrove crab and carbon store is urgently needed, the initiative can be taken by establishing the small-scale study pertaining to localize scales used by crabs while involving manipulated experimental conditions.

Experimental manipulative studies comprised of ecological and biogeochemical components in intertidal ecosystems (Kristensen & Alongi, 2006; Abdullah & Lee, 2016; Tanaka et al., 2013, 2017; Otero et al., 2020). For example, exclusion experiments utilize cage as an exclusion device is a method used to study relationships between crabs with environmental properties and infaunal organisms (Tanaka et al., 2016; Abdullah & Lee, 2016; Natalio et al., 2017). Aside from the crab exclusion experiment, crab removal technique is also another approach used (Pülmanns et al., 2016). The cage experiment is usually done to remove the large target macroinvertebrate organism, however this introduced some bias to the community inside the cage affected by fluctuating light intensity, sediment accumulation, and limited food sources (Peterson, 1979; Resetarits Jr et al., 1995; Cooke et al., 2017). Therefore installation of cages must be done with caution and account for this type of effect that might occur later in the experiment. The main common effects on both methods were decreased crab burrows, resulting in lowered competition for food (Dye & Lasiak, 1986; Tanaka et al., 2013; Abdullah & Lee, 2016), decreased microbial community densities (Dittmann, 1996; Kristensen & Alongi, 2006; Booth et al., 2019), and modified sediment properties which also affect the infaunal density (Tanaka et al., 2013; Abdullah & Lee, 2016). For the crab removal method, the crab was removed actively since there is no barrier installed around the study area, thus the probability for other crab intruders to enter the study plot without being noticed is high. The active removal might produce artificial disturbance to the natural environment which will effect the result of observation (Pülmanns et al., 2016).

To lower the impact of the cage experiment, current studies have included partial cage setups and control plots (Tanaka et al., 2013; Pülmanns et al., 2016; Lee & Abdullah, 2016; Tanaka et al., 2017). These treatments setup aim to reduce and separate the effects of cage experiment when some organisms are excluded. It is important to be cautious about control treatments in which the targeted organism might not be present, as they can move to other suitable environments (Peterson, 1979). Therefore, it is necessary to use both conventional observational assessment methods and experimental methods to complement the significance of the study according to specific objectives.

CHAPTER 3 THE ASSESSMENT OF MANGROVE CRAB ASSEMBLAGE COMPOSITION IN RELATION WITH ENVIRONMENTAL VARIABLES

3.1 Introduction

Mangrove crabs are among the most ecologically important macrofauna in tropical intertidal zones, holding key roles in ecosystem processes such as sediment turnover, organic matter decomposition, and nutrient cycling (Kristensen, 2008; Cannicci et al., 2018). Their interactions with the physical and biological components of mangroves, particularly through bioturbation and feeding activities, directly affect habitat structure and biogeochemical processes (Lee, 1998; Fratini et al., 2000; Penha-Lopes et al., 2012).

Understanding the composition and distribution of mangrove crab assemblages across different habitats is essential for evaluating their functional roles in ecosystem maintenance. Spatial and temporal variations in crab communities are often linked to environmental variables such as sediment type, salinity, organic matter content, and vegetation complexity (Stepiani et al., 2021). However, despite the broad distribution of crabs in Southeast Asian mangroves (Sharifian et al., 2020) species-specific ecological roles remain understudied, particularly in relation to habitat heterogeneity and seasonal changes.

This chapter focuses on assessing the assemblage composition of mangrove crabs in three mangrove forests along the west coast of Penang, Malaysia: Pulau Betong, Kuala Sungai Burung, and Kuala Sungai Pinang. The study explores how crab communities vary across space and time and how their abundance and diversity relate to the environmental heterogeneity and habitat variables such as canopy cover, sediment characteristics, and root density. These insights help clarify the ecological drivers shaping crab communities in tropical mangrove ecosystems of Penang Island.

3.2 Materials and methods

3.2.1 Site description

Sampling was conducted at the mangrove forests in the western region of Penang Island located at Balik Pulau in 2019 (Figure 3.1). Mangroves in Penang were cleared and transformed into aquaculture and settlement area with only 7.42 km^2 remaining on the island (Beh et al., 2010; Nordhaus et al., 2019). Current estimates in 2020 of the total mangrove area recorded in Penang was 1967 ha (Omar & Misman, 2020). In this study, three sites were chosen which comprised of Pulau Betong, Kuala Sungai Burung and Kuala Sungai Pinang. All these sites were under the jurisdiction of the Penang Forestry department and categorized as permanent forest reserve (NRE, 2016). The sampling period was conducted in June, August, October and December 2019. Based on Weather and Climate (2019), Balik Pulau, Penang experienced the beginning of southwest monsoon season in June 2019 with moderate rainfall. Then in August 2019, the region experienced warm and humid weather, typical of the monsoon season with frequent rainfall. In October, the high humidity still recorded with frequent rainfall, while in December 2019 the northeast monsoon season started brought the frequent rain and high humidity level to the region.

Figure 3.1 Map of sampling locations comprising A) Pulau Betong, B) Kuala Sungai Burung and C) Pulau Betong located at the west region of Pulau Pinang

3.2.1(a) Site description of Pulau Betong

The Pulau Betong site was located at Balik Pulau, Pulau Pinang (5°18'50.31"N 100°11'49.84"E). This mangrove area exposed to the 2004 Tsunami (Abdullah et al., 2005), and most part of it was cleared for aquaculture site (Nordhaus et al., 2019). The mangrove sediment comprised fine coarse sand and clay (Zolkhiflee et al., 2021). The seaward-facing site of Pulau Betong was dominated by *Avicennia marina* (DBH= 17.67 ± 5.79 cm with a height average of 10.65 ± 6.02 m). Towards the landward area,