# THE ECOLOGICAL FUNCTION OF INTERTIDAL SEAGRASS FOR SEDIMENT ENTRAPMENT ON MIDDLE BANK SHOAL, PENANG

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# THE ECOLOGICAL FUNCTION OF INTERTIDAL SEAGRASS FOR SEDIMENT ENTRAPMENT ON MIDDLE BANK SHOAL, PENANG

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## THE ECOLOGICAL FUNCTION OF INTERTIDAL SEAGRASS FOR SEDIMENT ENTRAPMENT ON MIDDLE BANK SHOAL, PENANG


## ABSTRACT

Application of seagrass in eco-engineering for sustainable coastal protection requires a deeper understanding of seagrass functions for sediment entrapment. Knowledge gaps on the influence of intertidal seagrass in trapping sediments raised two main questions in this study; (1) what is the relationship between intertidal seagrass meadow structure and trapped sediment? and (2) which part of the intertidal seagrass meadow structure best explains the variability of trapped sediment? To answer these questions, seagrass shoot density, Leaf Area Index (LAI), and total aboveground biomass were used as predictors for sediments deposition rate on Middle Bank Shoal. Three seagrass species were found; *Enhalus acoroides, Thalassia hemprichii,* and *Halophila ovalis*, with shoot density, LAI, and total aboveground biomass ranged from 140-6181 shoot.$m^{-2}$, 1.60-10.03 $m^2.m^{-2}$, 26.28-295.79 gDW.$m^{-2}$, respectively, while total sediment deposition ranged from 3956 to 13237 gDW.$m^{-2}$.$day^{-1}$. Sediment deposition had a strong negative relationship with total aboveground biomass ($R^2$ = 0.49, $p<0.05$). Low sediment deposition in high aboveground biomass suggested seagrass reduced the deposition of both primary and resuspended sediment. Being an intertidal and multispecific meadow, seagrass functions for sediment entrapment probably focused more on retaining sediments from resuspension than deposition of suspended sediments.



**Keywords**: Intertidal Seagrass, Sediment Deposition, Seagrass Meadow Structures, Sustainable Coastal Protection.

**FUNGSI EKOLOGI RUMPUT LAUT DI ZON ANTARA PERBANI UNTUK MERANGKAP SEDIMEN DI BETING TENGAH, PENANG**


## ABSTRAK

Penggunaan rumput laut sebagai 'eco-engineering' untuk perlindungan pantai yang mampan memerlukan pemahaman fungsi rumput laut untuk merangkap sediment yang lebih mendalam. Jurang pengetahuan dalam memahami pengaruh rumput laut di zon antara perbani pada sedimen yang diperangkap menimbulkan dua persoalan kajian; (1) apakah hubungan struktur rumput laut di zon antara perbani dengan pemendapan sediment, (2) struktur rumput laut di zon antara perbani yang manakah dapat menerangkan variasi sedimen yang diperangkap. Untuk menjawab persoalan ini, ketumpatan pucuk, 'Leaf Area Index' (LAI) dan jumlah biomas atas tanah digunakan sebagai peramal untuk kadar pemendapan sedimen di Beting Tengah. Tiga spesis rumput laut dijumpai, iaitu; *Enhalus acoroides, Thalassia hemprichii* dan *Halophila ovalis*. Ketumpatan pucuk berkisar dari 140-6181 pucuk.$m^{-2}$, LAI: 1.60-10.03 $m^2.m^{-2}$ dan jumlah biomas atas tanah: 26.28-295.79 gDW.$m^{-2}$, manakala jumlah pemendapan sedimen pula berkisar dari 3956-13237 gDW.$m^{-2}.h^{-1}$. Antara struktur rumput laut di Beting Tengah, pemandapan sedimen mempunyai hubungan negatif dengan jumlah biomas atas tanah ($R^2 = 0.49$, $p<0.05$). Oleh sebab padang rumput laut ini mempunya pelbagai jenis spesis dan berada di zon antara perbani, fungsinya untuk merangkap sedimen mungkin lebih berfokus pada penahanan sedimen dari resuspensi berbanding pemendapan sedimen yang terampai.

**Kata Kunci**: Rumput Laut di Zon Antara Perbani, Pemendapan Sedimen, Struktur Padang Rumput Laut, Perlindungan Pantai Yang Mampan.

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| | | |
|---|---|---|
| LAI | : | Leaf Area Index |
| LSA | : | Leaf Surface Area |
| SDG | : | Sustainable Development Goal |

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# CHAPTER 1: INTRODUCTION

## 1.1. Seagrass for Sustainable Coastal Protection

The effect of global warming on sea-level rise in 2100 with stronger waves and storm surges (UN, 2017) poses a significant threat to the livelihood of coastal communities (Gracia et al., 2018; Sarkar et al., 2014). With 40% of the world population residing in coastal areas (UN, 2017), the demand for sustainable coastal protection that is adaptable to climate change has become an urgent priority.

However, designing seascapes that serve as both coastal defence and functional ecosystem is a major challenge. Hardening of shorelines with breakwaters, seawalls, and revetments has led to degradation of many marine ecosystems and habitat loss (Bouma et al., 2014; Gracia et al., 2018), which is ironic as the habitats itself plays an important role in coastal protection and stabilization (Duarte et al., 2013). As we uncovered more ecological functions of marine ecosystems, exploring the possibility of using them as a ‘soft’ engineering approach, not just for coastal protection but as part of the restoration effort too, has gained broad recognition as a new paradigm over the last decade (Cochard et al., 2008; Duarte et al., 2013; Gracia et al., 2018; Mitsch & Jørgensen, 2003; Paul, 2018). This combination of ecological and engineering principles that have value to both human and nature is known as ecological engineering (Mitsch & Jørgensen, 2003).

Vegetated coastal habitats play important roles in natural coastal protection. Their capability to change environments make them good candidates as ‘soft’ engineering structures, (Duarte et al., 2013), and among them, seagrass was rated as one of the most valuable ecosystems on earth (Costanza et al., 1997). Seagrass is a group of submerged flowering plants or angiosperms that are adapted to inhabit the temperate and tropical regions of marine environments (Unsworth & Cullen, 2010).

While seagrass provides a variety of ecosystem services that include habitat provision, feeding grounds, biodiversity support, water filtration, and carbon sequestration (Ho et al., 2018; Phang, 2000; Unsworth & Cullen-Unsworth, 2017), its function in trapping sediment is an important key to shoreline protection against erosion and sea-level rise via sediment accretion and seabed elevation (Bos et al., 2007; Gacia & Duarte, 2001; Terrados & Duarté, 2000). Understanding the role of seagrass in sediment entrapment is one of the crucial steps to assess the potential of seagrass in ecological engineering. Hence, parallel to our global Sustainable Development Goals in 2030 Agenda for Sustainable Development (UN, 2016), this study may be beneficial towards achieving Goal 13 – adapting to climate change, and Goal 14 – conserving life below water.

## 1.2. Problem Statement

Studies on seagrass started since the 1970s but in Southeast Asia, they only took off in the mid-1990s in which they discussed mainly on aspects such as seagrass morphology, distribution, and fauna-interaction (Ooi et al., 2011). There were not many publications that focused on the ecological function of seagrass then, and today, this information is still lacking.

Seagrass has the ability to trap sediments and reduce resuspension (Fonseca & Fisher, 1986), promote coastal stabilization, and mitigate erosion. Although there is scientific evidence supporting the function of seagrass for sediment entrapment, they are usually disparate, site-specific, and mostly focused on temperate and subtidal meadow (Gacia & Duarte, 2001; Paladini de Mendoza et al., 2018). Unlike the temperate meadows, tropical ones are usually multispecific meadows, which means a meadow that has more than one seagrass species (Gacia et al., 2003; Ooi et al., 2011). Meanwhile sediment resuspension in the intertidal is generally higher than the subtidal (Koch, 1999), therefore raising questions on seagrass-sediment interaction in tropical intertidal environments.

In Peninsular Malaysia, one of the largest intertidal meadows is located in Penang Island. There is no documentation available about this meadow other than its existence being pointed out in the $19^{th}$ century historical map of Penang Island (Chee et al., 2017). At the time of writing, mega-reclamation projects near the meadow were in progress, and more reclamation projects are expected to happen in the near future as part of the Penang Transport Master Plan (Chee et al., 2017). Thus, the ecosystem may be at risk and the magnitude of impact will be unclear due to the lack of baseline data. Because of the above, the intertidal seagrass meadow in Penang Island was used as a case study not just to fill in the existing knowledge gap, but for the intention of providing information that can support sustainable development in the future.

## 1.3. Scope of Work

### 1.3.1. Research Questions and Hypotheses

Due to the knowledge gap on seagrass-sediment interaction in the intertidal environment as stated in Chapter 1.2, two research questions arise: (1) what is the relationship between intertidal seagrass meadow structure and trapped sediment? and (2) which part of the intertidal seagrass meadow structure best explains the variability of trapped sediment? To answer these questions, this study tested two hypotheses: (1) trapped sediment has a positive relationship with intertidal seagrass meadow structure due to the ability of seagrass to increase sediment entrapment, and (2) variability of trapped sediment on intertidal seagrass meadow is best explained by the Leaf Area Index (LAI) because greater contact surface area aids seagrass in trapping more sediment.

### 1.3.2. Aim and Objectives

This study aims to explore the ecological function of intertidal seagrass in trapping sediments on the Middle Bank Shoal in Penang Island. The act of trapping sediment is a physical interaction between seagrass morphology and sediment flux. Therefore, to achieve this aim, the objectives of this study are (1) to characterize seagrass meadow structure that refers to the size, shape, and quantity of seagrass, which includes measurement of total aboveground biomass, Leaf Area Index (LAI), and shoot density; (2) to quantify sediment trapped by seagrass via measurement of total sediment deposition rate within seagrass patches; and (3) to establish the relationship between intertidal seagrass meadow structures and trapped sediments via regression model analysis. Figure 1.1 shows the summary of the scope of work in this study.

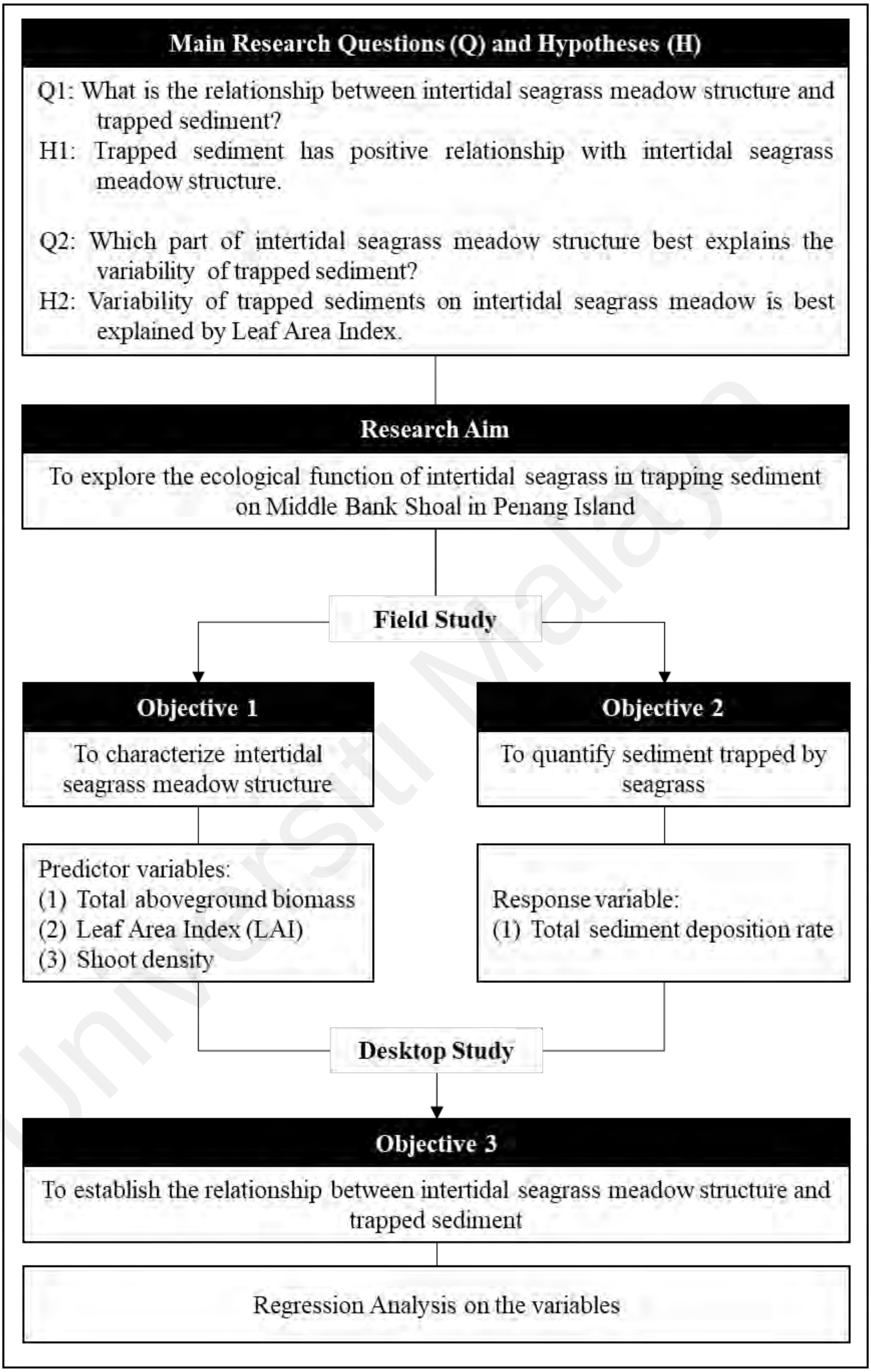


**Figure 1.1: Diagram for the summary of scope of work. Objective 1 and 2 are field studies for data collection, and objective 3 is a desktop study that involves statistical analysis to test hypothesis 1 (H1) and hypothesis 2 (H2).**

### 1.4. Significance of this Study

Overall, this study will fill in the knowledge gap in our understanding of the ecosystem services of seagrass meadow for future coastal protection. Generally, studies of marine ecosystems have been biased towards coral reefs and mangroves. Lack of explorations on seagrass meadows has caused the importance of seagrass ecosystems to be underrated (Ruiz-Frau et al., 2017). Because the possibility of using marine vegetation as an adaptation to coastal protection seems promising, understanding the ecological function of seagrass is important for ecological engineering to succeed (Mitsch & Jørgensen, 2003) and thus, this study shall add value to seagrass as an ecosystem engineer. Studies on the function of seagrass in trapping sediment have mostly focused on subtidal meadows (Gacia & Duarte, 2001; Gacia et al., 1999) and intertidal meadows are often overlooked. Hence, this study will provide a different insight into how intertidal seagrass aids in sediment entrapment. Besides that, quantifying seagrass meadow structure and sediment deposition will also contribute to baseline data for seagrass in Penang. This will help to measure the real extent of the impacts of mega-reclamation projects planned for the meadow and its surrounding coast and the effectiveness of mitigation programmes.

# CHAPTER 2: LITERATURE REVIEW

## 2.1. Overview: Seagrass Ecosystems

### 2.1.1. What is Seagrass?

Seagrass is a group of flowering plants that is adapted to complete immersion in the marine environment (Unsworth & Cullen-Unsworth, 2017). It has the ability to grow and pollinate underwater, with anchoring systems that enable it to withstand water movement (Spalding et al., 2003). These adaptations have led to various morphological features amongst seagrasses, such as flattened leaves, elongated or strap-like leaves, and extensive networks of roots and rhizomes (Spalding et al., 2003).

A seagrass meadow can be monospecific – a one-seagrass species meadow (Gacia & Duarte, 2001; Ganthy et al., 2013; Koch, 1999); or multispecific – a meadow comprising a community of many species (Gacia et al., 2003; Japar Sidik et al., 2006; Ooi et al., 2011), and the meadow size can range from a small $1m^2$ patch to thousands of hectares (Unsworth & Cullen-Unsworth, 2017).

### 2.1.2. Global Seagrass Distribution

Extensive seagrass meadows are present in shallow coastal water on all continents except Antarctica (Figure 2.1). They can be found in isolated patches, or co-exist with other marine habitats such as corals, mangroves, bivalve reefs, rocky benthos, as well as bare sediments (Spalding et al., 2003). While seagrasses typically grow on soft substrate (sand and mud), some species (e.g. *Phyllospadix*) can also grow on rocky substrates (Spalding et al., 2003). Their growth and distribution are largely controlled by light and nutrient availability, depth, salinity, temperature, and hydrodynamic condition (Adams et al., 2016; Spalding et al., 2003).

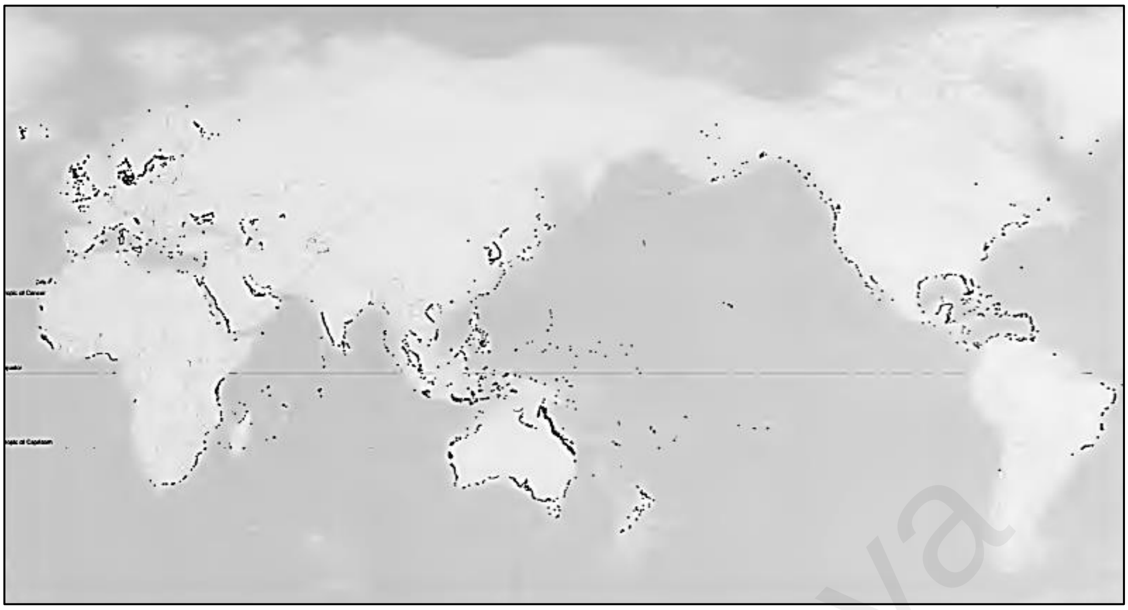

**Figure 2.1: Global seagrass distribution. Source: Green & Short (2003).**

To date, there are 13 seagrass genera recorded worldwide (Frederick T. Short et al., 2001), and their distributions are limited in the geographic region to either temperate and tropical regions, with a few genera overlapping in both regions (Table 2.1). The northern and southern temperate regions are dominated by *Zostera* and *Posidonia* species, respectively (Short et al., 2001). These species are widely distributed in the temperate region and tend to form broad monospecific stands (Short et al., 2001). Meanwhile, tropic Indo-Pacific region has the greatest species diversity, in which Southeast Asia is considered to be the centre of global seagrass biodiversity (Green & Short, 2003). Among the seagrasses in Southeast Asia, *Thalassia hemprichii* is the most widespread species as it can be found even in the remote South China Sea Oceanic Islands (Fortes et al., 2018).

**Table 2.1: Global distribution of seagrass genera by geographic region. Source: Short et al. (2001).**

| Seagrass Genera | Geographic Region | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII | IX | X |
| *Amphibolis* | | | | | | | | | | • |
| *Cymodocea* | | | | | | • | | | • | |
| *Enhalus* | | | | | | | | | • | |
| *Halodule* | • | | • | • | | • | • | • | • | |
| *Halophila* | • | | | • | | • | | • | • | • |
| *Heterozostera* | | • | | | | | | | | • |
| *Phyllospadix* | • | | | | | | | | | |
| *Posidonia* | | | | | | • | | | | • |
| *Ruppia* | • | | • | • | • | • | | • | • | • |
| *Syringodium* | | | | • | | | | • | • | • |
| *Thalassia* | | | | • | | | | | • | |
| *Thalassodendron* | | | | | | | | • | • | • |
| *Zostera* | • | | • | | | • | | • | • | • |
| Total | 5 | 1 | 3 | 5 | 1 | 6 | 1 | 6 | 9 | 8 |

Note: I-North Pacific, II–Chile, III–North Atlantic, IV–Caribbean, V–Southwest Atlantic, VI–Mediterranean, VII–Southeast Atlantic, VIII-South Africa, IX-Indo Pacific, X-South Australia.

### 2.2. Seagrass in Malaysia

#### 2.2.1. The Distribution

Seagrasses in Malaysia inhabit intertidal and shallow subtidal waters, semi-enclosed lagoons, mangroves, estuaries, and coral reefs including backreefs and forereefs (Rozaimi et al., 2017). Extensive but discontinuous seagrass meadows can be found along the coast of Peninsular and East Malaysia (Figure 2.2). Their distributions are primarily driven by light and nutrient availability, silt-clay content, sedimentary movement, herbivory, and competition (Adams et al., 2016; Gacia et al., 2003; Ooi et al., 2011; J. Terrados et al., 1998).

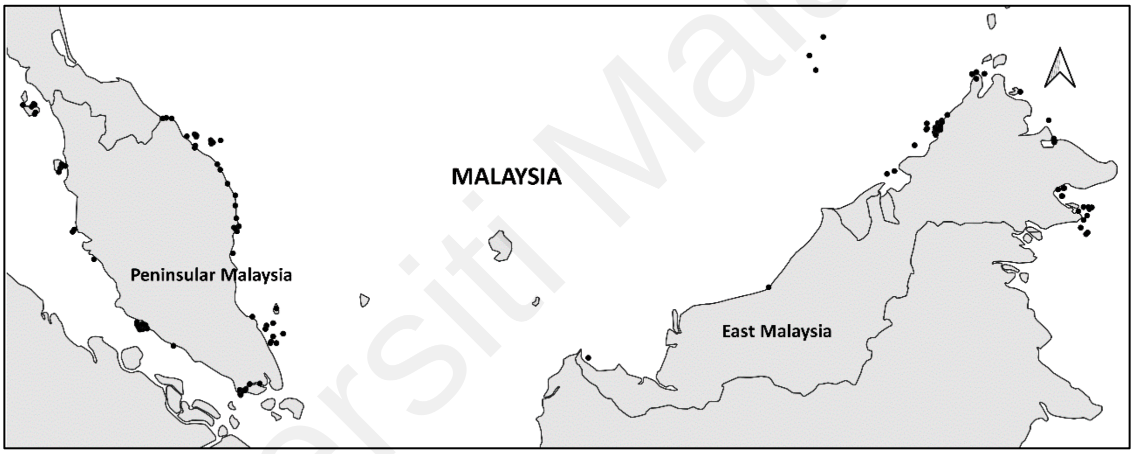


**Figure 2.2: Malaysian seagrass distribution. Source: Data downloaded from UNEP-WCMC, Short (2018) were compiled from varied source materials.**

There are 21 seagrass species in Southeast Asia and 16 species have been recorded in Malaysia (Fortes et al., 2018). Species diversity ranges from the small and fast-growing *Halophila* spp. (mean leaf height ~ 5cm) to the large and long-lived *Enhalus acoroides* (~60cm) (Ooi et al., 2011). Each species is morphologically different in plant size, leaf shape, and canopy height, hence contributing to a meadow's structural complexity (Ho et al., 2018). The most developed and diverse seagrass communities in Malaysia were recorded at the south and east coast of Peninsular Malaysia, Sabah, and Sarawak (Japar Sidik et al., 2006).

### 2.2.2. Status and Knowledge Gaps

Like other coastal ecosystems such as coral reefs and mangroves, seagrass around the world are threatened by anthropogenic activities, and Malaysia is no exception. Hossain et al. (2015) mapped significant losses of seagrass areal cover in Kelantan, Terengganu, and Sarawak due to coastline changes and anthropogenic activities, while Penang Island faced a serious decline of seagrass shoot density (Anisah Lee & Anscelly, 2016). Despite this situation, protection and conservation of marine habitats in Malaysia via Marine Protected Areas have only focused on coral reefs and mangroves habitats, while seagrass habitat protection has been indirect and incidental (Ho et al., 2018).

The lack of information on seagrass is probably one of the reasons for its lack of acknowledgment in Malaysia. Malaysian seagrass is known to cover only less than 0.02% of its territorial seas (Fortes et al., 2018), and this figure is most likely undervalued. The estimates of meadow sizes in Malaysia are rarely reported and they are geographically unbalanced, with most of them focused on the east coast of Peninsular Malaysia (Fortes et al., 2018). Furthermore, researches on seagrasses in Malaysia are mainly discussed on the distribution, ecology, and fauna-interaction; while their functions and ecosystem services are poorly studied (Fortes et al., 2018; Ho et al., 2018; Ooi et al., 2011).

## 2.3. The Ecological Functions of Seagrass Ecosystems

Seagrass meadows are one of the key components of coastal environments as they offer various ecosystem services (Costanza et al., 1997; Fortes, 2018; Nordlund et al., 2018). Ecosystem services refer to "essential goods and services to human health, wellbeing, livelihood, and survival" provided by an ecosystem (Ruiz-Frau et al., 2017), and for seagrass meadow, these include food security, water quality, and coastal protection.

Seagrass meadows play a vital role in our global fisheries production. A healthy and productive meadow provides nursery and foraging ground for many commercially important shellfish and finfish (Fortes, 2018). Ho et al. (2018) found that the majority of fish populations in a seagrass meadow were commercially important carnivores, and species diversity was significantly linked to the meadow's seagrass cover. Besides that, seagrass meadows also provide habitat support for vulnerable fauna such as seahorses, dugongs, and sea turtles (Hughes et al., 2009), which makes them ecologically important as well.

Due to the global decline of coastal ecosystems from anthropogenic activities, there is a growing interest in the role of seagrass in environmental assessments over the last decade (Ruiz-Frau et al., 2017). Previous studies showed the seagrass species *Enhalus acoroides* had high potential as a bioindicator for trace metal pollution (Birch et al., 2018; Nguyen et al., 2017; Nordiani et al., 2018); while both *Halophila ovalis* and *Halodule uninervis* were nutrient sponges, crucial for nutrient removal to mitigate eutrophication (Mellors et al., 2005). Seagrass meadows also have the potential to be used as a proxy for the overall health of primary ecosystems as they are sensitive to disturbance and environmental changes (Purvaja et al., 2018).

Seagrass may also contribute to shoreline protection (Ondiviela et al., 2014) for climate change adaptation (Unsworth & Cullen-Unsworth, 2017). They modify hydrodynamics via flow reduction (Fonseca & Koehl, 2006) and wave attenuation (Fonseca & Cahalan, 1992), which help in trapping sediments (Gacia & Duarte, 2001; Gacia et al., 1999; Panyawai et al., 2019), and reducing turbidity (Daby, 2003), thereby improving conditions for their optimal growth and other organisms in the ecosystem, as well (Adams et al., 2016; De Boer, 2007). Seagrass also has the capacity to sequester large amounts of organic carbon from the atmosphere and water column, and store them within its biomass and sediments, which is an important function for climate change mitigation (Panyawai et al., 2019; Ricart et al., 2015; Rozaimi et al., 2017; Unsworth & Cullen-Unsworth, 2017). This capacity is what makes it recognized as a "blue carbon" ecosystem (Fortes, 2018).

## 2.4. Seagrass for Coastal Protection

### 2.4.1. Seagrass Role for Sediment Entrapment

Seagrass is widely known as an "ecosystem engineer" due to its ability to change its abiotic environment (Bos et al., 2007). Seagrass presence helps to stabilize sea bed and prevent erosion (Gacia & Duarte, 2001; Paladini de Mendoza et al., 2018; Widdows et al., 2008) via hydrodynamic modification (Fonseca & Cahalan, 1992; Fonseca & Fisher, 1986; Fonseca & Koehl, 2006; Madsen et al., 2001; Paladini de Mendoza et al., 2018; Widdows et al., 2008). The morphologies of seagrass species such as leaf length, leaf shape, canopy height, shoot density, and biomass, give complex three-dimensional structures of a seagrass meadow and may affect both hydrodynamic and sediment flux differently (Panyawai et al., 2019). To understand the seagrass-hydro-sediment interaction, this section will first review the influence of seagrass structures on hydrodynamics, followed by sediment flux.

#### 2.4.1.1. Seagrass and Hydrodynamics

Generally, weak currents and wave actions promote sediment deposition/accretion, whereas the opposite hydrodynamic conditions increase resuspension/erosion (Fonseca & Fisher, 1986; Gacia & Duarte, 2001; Gacia et al., 1999; Koch, 1999; Paladini de Mendoza et al., 2018). The efficiency of seagrass in reducing flow velocity and wave energy increases with a greater percentage of seagrass plant occupying the water column (Figure 2.3) (Fonseca & Cahalan, 1992; Fonseca & Fisher, 1986; Ward et al., 1984). This varies with water level (tides) and canopy height (Fonseca, 1989; Fonseca & Cahalan, 1992; Fonseca & Fisher, 1986; Paladini de Mendoza et al., 2018). The attenuation of strong hydrodynamic energy is the most efficient when seagrass occupies the entire water column (Fonseca & Cahalan, 1992; Fonseca & Fisher, 1986; Paladini de Mendoza et al., 2018; Ward et al., 1984).

Seagrass influences hydrodynamics mainly by introducing a frictional force that creates drag on flow velocity (Fonseca & Fisher, 1986). Higher friction will greatly decrease flow velocity. The magnitude of friction depends on leaf shape and cross-section area (Fonseca & Fisher, 1986). Species with smaller cross-section area and smooth cylindrical leaf blades like *Syringodium filiforme* give little friction compared to bigger and flat-bladed leaves like *Thalassia testudinum* (Fonseca & Fisher, 1986). Meanwhile, seagrasses with more flexible leaves are easily bent in strong currents, cause faster friction loss and little hydrodynamics reduction (Fonseca & Fisher, 1986).

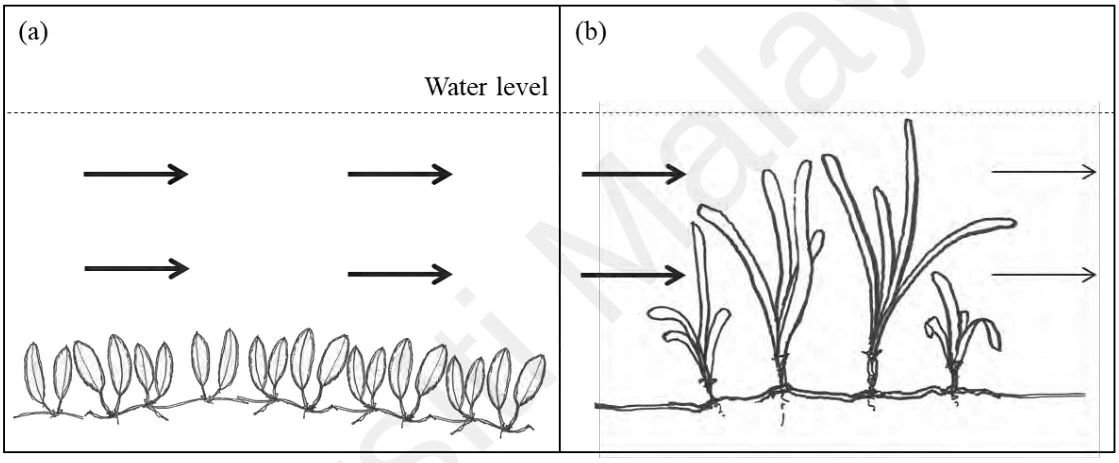


**Figure 2.3: Current flow comparison between two different seagrass canopy height in water column. Flow reduction in low canopy seagrass (a) that occupies a small fraction of water column is less efficient than high canopy seagrass (b) that occupies the whole water column. Arrows indicate current flow, where thicker arrow shows higher velocity.**

Seagrass presence also raises the critical threshold of bed shear stress as canopy friction increases (Fonseca & Fisher, 1986). Bed shear stress is a hydrodynamic force that applies to bed sediments, and when the force exceeds its critical threshold, it induces sediment movement and causes erosion (Fonseca & Fisher, 1986). Seagrass with higher canopy friction increases the bed threshold, hence stabilizes the seabed more as stronger hydrodynamic force is required to move bed sediment (Fonseca & Fisher, 1986).

### 2.4.1.2. Seagrass and Sediment Flux

Total sediment flux includes: (1) primary deposition of suspended particles from the water column, and (2) resuspended flux from those that had settled earlier but had resuspended (Gacia et al., 1999). Based on a model used by Gacia et al (1999), total sediment flux increases exponentially towards seabed (Figure 2.4), in which primary flux is parallel to the asymptotic value of the total flux curve, and the difference between total and primary flux will be the resuspended sediment (Gacia et al., 1999).

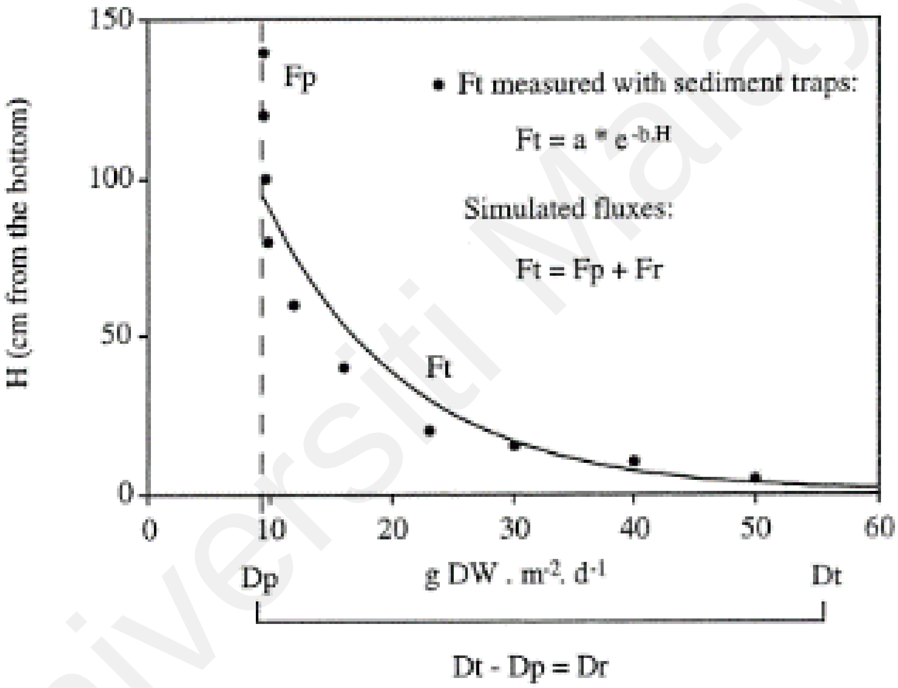


**Figure 2.4: Illustration of vertical sediment flux profile. Ft=total sediment flux, Fp=flux of primary sediments, Fr=flux of resuspended sediments, Dt=total deposition, Dp=primary deposition, Dr=resuspended deposition. Ft decreases exponentially with increasing height from the seafloor. Unit of sediment flux in gDW.m$^{-2}$.d$^{-1}$. Source: (Gacia et al., 1999).**

The variation of total sediment flux is influenced by hydrodynamic conditions and water depth (Dauby et al., 1995; Gacia et al., 2003, 1999; Paladini de Mendoza et al., 2018; Ward et al., 1984). Strong wave energy and wind-driven current significantly increase total deposition by increasing resuspended flux, especially in shallow water (Dauby et al., 1995; Gacia & Duarte, 2001; Paladini de Mendoza et al., 2018; Ward et al., 1984). In studies conducted at *Posidonia oceanica* meadow, depositions at 7m depth were significantly greater than the depositions at 10m and 36m depth (Table 2.2). When compare with other meadows, the minimum total deposition also increases as depth decreases (Table 2.2). This is because strong turbulences from surface waves and currents may reach the bed sediment in shallow water, hence induce resuspension and total deposition (Fonseca & Cahalan, 1992; Gacia & Duarte, 2001; Koch, 1999; Paladini de Mendoza et al., 2018; Ward et al., 1984). As for the contribution of primary flux in total deposition, the amount of flux depends on the source of sediment load. Gacia et al. (2003) found that total depositions in sites closer to anthropogenic activities (such as port and quarry) within the same depth were higher than those in pristine areas.

Theoretically, seagrass traps sediment by promoting sediment deposition and retaining sediment from resuspension (Fonseca, 1989; Gacia & Duarte, 2001; Paladini de Mendoza et al., 2018). However, the latter seems to be more significant than the former. Previous studies have shown resuspended flux dominates total deposition, where it is governed by seagrass (Dauby et al., 1995; Gacia & Duarte, 2001; Paladini de Mendoza et al., 2018). Lower total depositions observed in seagrass meadows compared to barren bottom were due to lower resuspension (%Fr in Table 2.2), whilst primary sediment depositions in both meadow and barren bottom were moderate (Gacia & Duarte, 2001; Gacia et al., 1999; Paladini de Mendoza et al., 2018; Ward et al., 1984). Wilkie et al. (2012) also found no significant difference in primary deposition between vegetated and unvegetated bottom in flume experiment, and they suggested that the settlement of suspended sediment is influenced by low flow environment more than the presence of seagrass.

**Table 2.2: Minimum and maximum deposition rate measured in different areas from previous studies. %Fr and %Fp are the mean contribution of resuspended and primary flux from total deposition, respectively.**

| Site | Deposition Rate ($gDW.m^2.d^{-1}$) | | Depth (m) | Bottom | % Fr | % Fp | Reference |
|---|---|---|---|---|---|---|---|
| | Min | Max | | | | | |
| Chesapeake Bay, US | 390 | 1585 | <2 | RM | - | - | Ward et al. (1984) |
| | 380 | 5534 | | Unvegetated | - | - | |
| Bay of Calvi, FR | 0.3 | 10 | 36 | PO | 70 | 30 | Dauby et al. (1995) |
| Fanals Point, ES | 2.0 | 215 | 15 | PO | 85 | 15 | Gacia & Duarte (2001) |
| | 1.5 | 494 | | Unvegetated | 95 | 5 | |
| Latium Coast, IT | 3.58 | 2520 | 7 | PO | 72 | 28 | Paladini de Mendoza et al. (2018) |
| | 23.08 | 5000 | | Sand patch within meadow | 81 | 19 | |
| | 50.80 | 6820 | | Unvegetated | 94 | 6 | |
| Philippines | 18 | 175 | <3 | EA, TH, CR, CS, HU | - | - | Gacia et al. (2003) |
| Vietnam | 76 | 681 | <3 | EA, TH | - | - | Gacia et al. (2003) |

Note: RM – *Ruppia maritima*, PO – *P. oceanica*, EA – *E. acoroides*, TH – *T. hemprichii*, CR – *C. rotundata*, CS – *C. serulata*, HU – *H. uninervis.*

The influences of seagrass on sediment flux depend on its architecture. Panyawai et al. (2019) found more complex structures (in terms of canopy height, density, and leaf surface area) increased sediment deposition. Seagrass with longer leaf length and higher canopy height can increase sediment stabilization by trapping suspended particles and reducing bottom resuspension (Gacia & Duarte, 2001; Gacia et al., 1999; Ganthy et al., 2013; Paladini de Mendoza et al., 2018). Higher Leaf Area Index (LAI) in meadows has been associated with increased sediment deposition (Gacia et al., 1999) and reduced resuspension (Gacia & Duarte, 2001). LAI is the value of leaf surface area per ground area (Gacia et al., 1999). Although Gacia et al. (1999) showed a strong positive correlation between sediment deposition with LAI, a non-linear relationship was observed when LAI exceeded 4 $m^2.m^{-2}$ and it was probably due to the interference of sediment deposition when dense seagrass leaves bend (Gacia et al., 1999).

Besides that, seagrass meadows also affect sediment flux via the 'skimming flow' effect (Widdows et al., 2008; Wilkie et al., 2012). Skimming flow occurs when dense seagrass leaves bend from strong current and in doing so, modify the vertical current profiles; i.e low flow velocity at the bottom canopy, and high flow velocity above canopy top that skims over the lead blades (Widdows et al., 2008; Wilkie et al., 2012). The phenomenon affects sediment flux in two different ways: (1) bent leaves provide a 'seal' on the bottom canopy environment by deflecting flow above it and protect seabed against resuspension/erosion, and (2) higher flow above canopy top prevents the deposition of suspended sediment (Widdows et al., 2008; Wilkie et al., 2012).

Different seagrass species give different effects on sediment stabilization (Fonseca & Fisher, 1986). Bigger seagrass species stabilize seabed more than smaller species via greater hydrodynamic reduction (Fonseca & Cahalan, 1992; Fonseca & Fisher, 1986). However, Fonseca (1989) found that seagrass species from the smaller end of the size spectrum, such as *Halophila* spp., protected the seabed against erosion by increasing the bed threshold, equally as well as the larger seagrass group. Because of its size, the allocation of dense *Halophila* spp. biomass closer to the seabed forms a ‘leaf mat’ well above the sediment surface (Fonseca, 1989). This formation raises the bed threshold higher than bare sand as it deflects the near-bed flow above the canopy level (Fonseca, 1989). Similar to the skimming effect, the leaf mat seals bottom sediment from erosion too, hence stabilizes the seabed (Fonseca, 1989; Widdows et al., 2008; Wilkie et al., 2012).

While most studies agreed that seagrasses protect sediment against erosion, Koch (1999) found that seagrass meadow with leaf blades held in sheath had high near-bed flow and caused higher resuspension than barren bottom. A seagrass plant has an uneven vertical distribution of aboveground biomass due to its morphology. Seagrass with sheath (a sleeve-like structure that holds seagrass leaf together at base) has lower biomass allocation at the bottom than the top canopy (Figure 2.5) (Koch, 1999). Low near-bed biomass means less flow resistance, which leads to stronger flow near the sediment surface that induces resuspension (Koch, 1999).

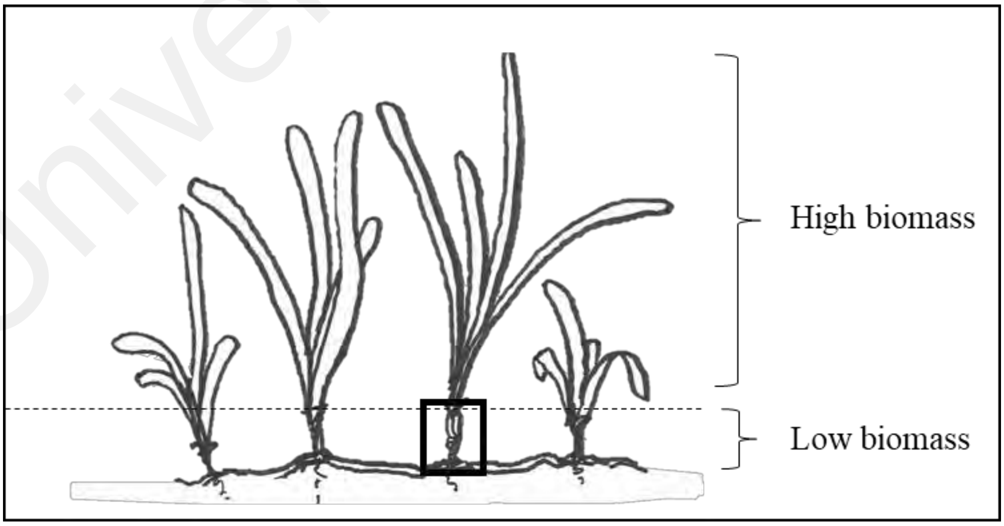


**Figure 2.5: Illustration of the uneven vertical distribution of aboveground biomass in monospecific seagrass. Seagrass blades that are held in sheath (square box) gives high biomass at canopy top and low biomass at the bottom canopy. Greater biomass creates more drag that causes more flow reduction.**

### 2.4.2. Seagrass in Eco-Engineering

The capability of seagrass to reduce currents, dampen waves and stabilize the sea bed (Fonseca, 1989; Fonseca & Cahalan, 1992; Fonseca & Fisher, 1986), makes it a good potential candidate for eco-engineering. Mitsch & Jorgensen (2003) defined ecological engineering as “the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both”. Its main goal “involves restoration of ecosystems and development of new sustainable ecosystems that benefits both human and ecological value”. Despite being a key ecosystem that provides various ecosystem services with value to both human and ecology, seagrass receives little acknowledgment, and conservation of seagrass is not sufficiently reflected in decision making for sustainable coastal management (Unsworth et al., 2018). Threatened by coastal expansion and anthropogenic activities, seagrass continues to decline at a global rate of approximately 7% (Waycott et al., 2009). Hence, incorporating seagrass as a ‘soft’ or ‘hybrid’ structure for coastal protection will achieve the main goal for eco-engineering and will serve to highlight its value to us.

As an ecosystem engineer, the ability of seagrass to modify its abiotic environment seems to give more pros than cons with reference to engineering and ecology in eco-engineering. Compared to hard grey wall structures such breakwaters and seawalls, seagrass is adaptive to sea-level rise, is less costly to build and maintain, causes less damage in case of failures in extreme events, has the capacity for self-recovery and gives ecological benefits as it grows into a healthy meadow over time (Moosavi, 2017). However, designing seagrass for eco-engineering may not be the same for all regions. Extensive local studies are required and the designs need to consider time and space for seagrass to grow for it to play its part as eco-engineering structures (Moosavi, 2017).

## 2.5. Towards Sustainable Coastal Development

### 2.5.1. Sustainable Development Goals

Application of seagrass in eco-engineering is considered to be one of the pathways towards achieving the UN 2030 Agenda for Sustainable Development. This Agenda is a global action plan for our people, planet, and prosperity (UN, 2016). There are 17 Sustainable Development Goals (SDG) under this Agenda that include three dimensions of sustainable development; economic, social, and environmental (UN, 2016). Among these 17 SDGs, utilising seagrass for coastal protection fits within Goal 13 (climate change) and Goal 14 (life below water).

Goal 13 for climate change is to "to take action to combat climate change and its impact" (UN, 2016). The impact of expected sea-level rise in 2011 (UN, 2017) on coastal communities calls for quick action on possible solutions that are more resilient and adaptive, and seagrass as a soft engineering structure seems to fit the requirement through sediment stabilization and carbon sequestration.

Goal 14 for life below water is to "conserve and sustainably use the oceans, seas, and marine resources for sustainable development" (UN, 2016). Much of seagrass decline may lead to a substantial impact on our food security and the loss of endangered species such as dugong and sea turtles (IUCN, 2020) that depends on seagrass for their dietary supplements (Hughes et al., 2009). Hence, exploring the potential use of seagrass via eco-engineering for sustainable development is one of the ways to conserve our remaining seagrass meadows, which is vital for our future living and our planet.

### 2.5.2. Case Study Site: Penang Island

Penang is one of the fastest-growing and most densely populated places in the world. Rapid urbanisation, land reclamation, and extend of artificial shoreline are the choice of solutions to support the increase of population in Penang Island. Between 1960 to 2015, urbanised area of Penang Island has increased from 10.2% to 37.4%, while the reclaimed land increased from 0.1% to 3.2% (Chee et al., 2017). At the time of writing, one of the five proposed artificial islands in Penang Island as part of Penang Transport Masterplan was on-going, and when all artificial islands complete, the reclaimed land will be 10% (Chee et al., 2017). These developments concentrated at the east coast of Penang Island, where sensitive marine ecosystems such as coral reefs and seagrass meadows reside (Anisah Lee & Anscelly, 2016; Chee et al., 2017; Phang, 2000). Anisah Lee & Anscelly (2016) found seagrass density at Pulau Gazumbo significantly decreased due to the reclamation of Light Waterfront near the meadow. This means, the mega-reclamation projects will give big impacts on the marine ecosystems, and incorporating seagrass as eco-engineering into the design may help to reduce the ecological footprints (SDG-14). Besides that, with the risk of sea-level rise, designing an eco-engineering structure that is adaptable to climate change will be beneficial for sustainable coastal protection (SDG-13).

# CHAPTER 3: METHODOLOGIES

## 3.1 Study Area

The study site is an intertidal seagrass bed that lies at the east coast of Penang Island (Figure 3.1). Although this meadow has been around since the 19th century (Chee et al., 2017), it has no official name other than "Middle Bank" or "Beting Tengah" (Chee et al., 2017; Phang, 2000), which is a common name to refer to a shoal in the Penang Strait. Hence, this study site was labelled as Middle Bank Shoal for spatial referencing. There is also another intertidal seagrass bed in Penang Island located less than 2km south of the study site known as "Pulau Gazumbo" (Anisah Lee & Anscelly, 2016).

Middle Bank Shoal is found to be a habitat for many organisms such as fishes, crabs, clams and sea anemones, making the location to be economically important to fishermen and the ecosystem. According to Phang (2000), *Enhalus* sp. and *Halophila* sp. can be found at the meadow. Generally, Middle Bank Shoal is fully submerged throughout the day, but it will be exposed during spring low tide for at least three hours, and the presence of a sandbank at the northern part of the meadow gives us easy access and opportunities for field study.

Fieldwork was conducted during spring low tide in July 2017, October 2017, and February 2018 where 13 stations of seagrass patches were randomly selected within the visible part of the meadow. Locations of the sampling stations are shown in Figure 3.1 and GPS coordinates information can be referred to in Appendix A (Table A1).

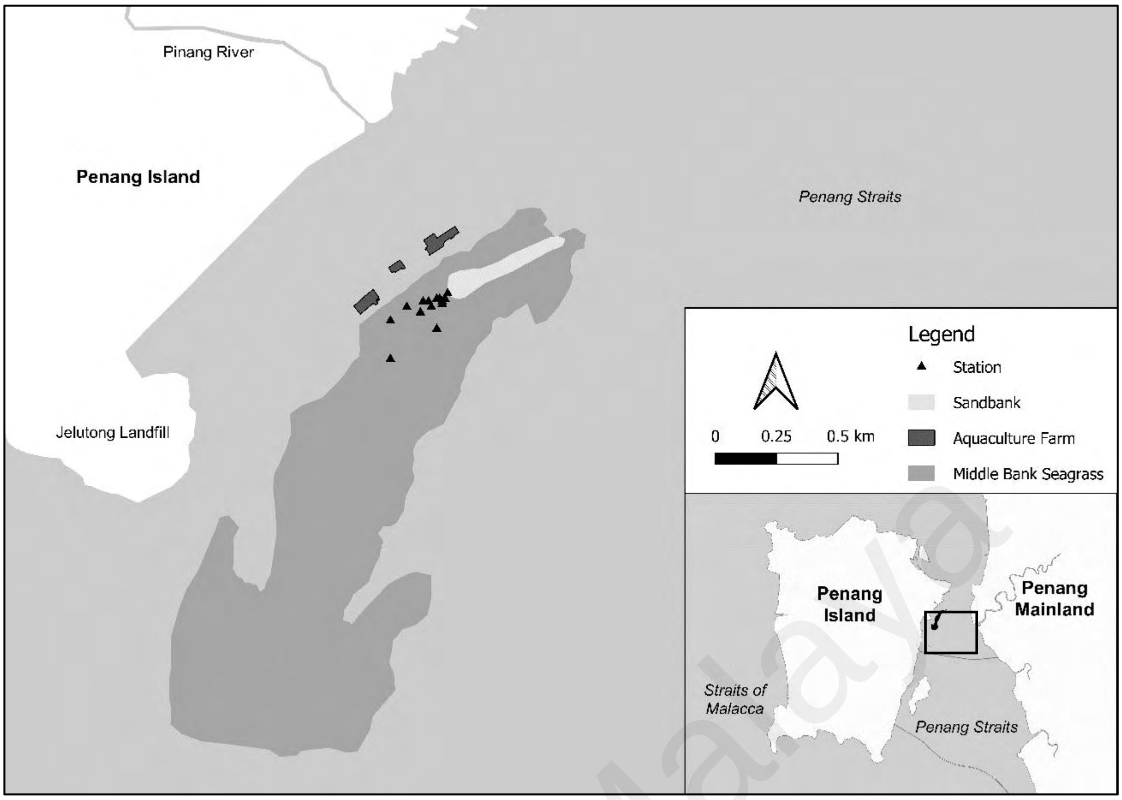


**Figure 3.1: Map showing the location of Middle Bank Shoals at Penang Straits. Sampling stations were randomly chosen within seagrass patches that were exposed during the sampling period.**

## 3.2 Characterization of Seagrass Meadow Structures

Seagrass samples were randomly collected within exposed seagrass patches during the sampling period, approximately within a 1m radius of the sampling stations, using a metal corer of 11 cm internal diameter. The corer was pushed into the seabed and whole plants were uprooted and carefully sealed into plastic bags. Samples were collected in triplicates for every species found at a sampling station.

Seagrass samples were rinsed with freshwater and epiphytes were carefully scrapped off from their leaves using a razor blade. The plants were then separated into aboveground and belowground parts. The aboveground part was kept for biomass quantification.

Seagrass aboveground parts were air-dried followed by oven drying at 60°C for 48 hours and weighed to their constant value (Gacia et al., 1999). Total aboveground biomass ($gDW.m^{-2}$) of sampling station was calculated by dividing seagrass dry weight with the corer surface area as per Eq 3.1 below:

$$Aboveground\ biomass = \frac{\begin{array}{c}Dry\ weight\ of\\ aboveground\ biomass\ (gDW)\end{array}}{Corer\ surface\ area\ (m^2)} \tag{3.1}$$

For shoot density (no. of $shoot.m^{-2}$), the number of shoots for every species of a sampling station was counted, summed, and divided by the corer surface area as shown in Eq 3.2 (Duarte & Kirkman, 2001).

$$Shoot\ density = \frac{Number\ of\ shoot\ counted\ in\ corer}{Corer\ surface\ area\ (m^2)} \tag{3.2}$$

As for LAI ($m^2.m^{-2}$), it is a value derived from the total leaf surface area (LSA) per ground area (Gacia et al., 1999). LSA was measured by scanning and tracing leaf blades using CPCe software. Because to trace surface area of all leaf blades for all species in every sampling station was very time consuming, LSA from three to five shoots of each species found were measured. Mean LSA per number of shoot traced was calculated (Eq 3.3), and LAI was extrapolated by multiplying LSA to shoot density of sampling station (Gacia et al., 1999).

$$Leaf\ Area\ Index\ (LAI) =$$

$$\frac{LSA\ (m^2)}{Number\ of\ shoot\ traced}\ X\ shoot\ density\ (from\ Eq\ 3.2) \qquad (3.3)$$

Many of the previous studies included leaf length or canopy height as one of the factors that influence sediment deposition (Gacia et al., 2003, 1999; Paladini de Mendoza et al., 2018; Panyawai et al., 2019). However, including this factor is considered reasonable if we were to study and compare the effect of seagrass on sedimentation within a monospecific stand. In Middle Bank meadow, it was multispecific and well-mixed, and their size spectrum ranged from the smallest understory species to the biggest tropical canopy former species. This means averaging the canopy height of a sampling station will give a high deviation and may not represents the structure of the meadow accurately. Furthermore, our study focused on the influence of meadow structure as a whole, and we believed using LAI (total leaf surface area per ground area) as a predictor was enough to represent meadow structure in the context of seagrass shape and size.

### 3.3 Quantification of Total Sediments Deposition

Sediment trap was used to collect deposited sediments, and it was designed as recommended by Schiel et al. (2006) for intertidal sampling to reduce loss of particles and to minimize the risk of losing traps during flooding and ebbing. It is a j-shaped tube trap, 5.5 cm internal diameter (ID), 82 cm long, with height-to-mouth diameter (H/D) ratio of 15 cm (Figure 3.2). In every sampling station, three sediment traps, tied together as one set unit to represent the triplicates, were mounted level on the seabed with the mouth facing the seaward end (Schiel et al., 2006). Traps were left at the stations to collect sediments and retrieved on the following day. They were sealed and taken to the laboratory for further analysis.

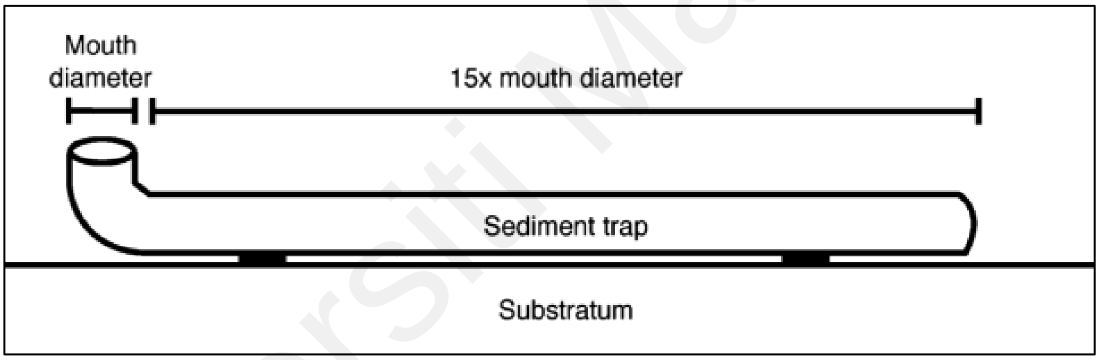


**Figure 3.2: Diagram of sediment trap used by following the design for intertidal sampling, with height-to-mouth diameter (H/D) ratio of 15cm (Schiel et al., 2006).**

Total weight of sediment deposited was determined via the evaporation method based on the procedure in the ASTM Standards (2002) designation D 3977-97 (Reapproved 2002). This method is applicable to highly turbid water samples that range from 0.2 to 20 L in volume, in which the standard filtration method is no longer practical. In a natural ecosystem, sediment composition includes both organic and inorganic particles. Because this study was looking at the effect of seagrass on total sediment deposition that represents the real meadow ecosystem regardless of the source of the sediment, hence organic matter removal was not performed.

At the laboratory, traps were emptied into a 3L volumetric flask. Each trap was rinsed with distilled water until the contents were completely removed. The volumetric flasks were then covered with aluminium foil to avoid any biological activities that could affect the samples and were left on bench for the sediments to settle. Once settled, most of the supernatant water was carefully siphoned without disturbing the bottom sediment. The samples were then rinsed a few times using distilled water to remove salts until it reached 0% salinity. A refractometer was used to confirm zero salinity before proceeding to the next step.

Samples were then poured into pre-weighed evaporating dishes and oven-dried at 60°C for 2 to 3 days (ASTM Standards, 2002). Then they were transferred into a desiccator to cool down to room temperature. Dry weight was measured using an analytical balance to constant value. Usually a single drying cycle is adequate to obtain a constant weight. If weight shifts occur, the sediments were dried for another 24 hours and weighed a second time to ensure the weights are stable. Dry weight of deposition rate ($gDW.m^{-2}.day^{-1}$) was then calculated by dividing the sediments dry weight per day to the area of the mouth traps as shown in Eq 3.3 below.

$$Sediment\ deposition = \frac{\begin{array}{c}Dry\ weight\ of \\ trapped\ sediments\ per\ day\ (gDW.day^{-1})\end{array}}{Area\ of\ mouth\ trap\ (m^2)} \qquad (3.3)$$

### 3.4 Evaluation of Meadow Structures and Sediments Deposition

Multiple linear regression analysis using R Studio software was conducted to establish the relationship between Middle Bank seagrass meadow structures and sediment deposition. Prior to that, exploratory data analysis was performed to get an overview of the relationship between predictors and response variables, and to identify the presence of collinearity, if any, among the potential predictors (Steel et al., 2013).

High correlation coefficient between the predictors suggests multicollinearity is present, which can adversely affect the precision of regression analysis (Montgomery et al., 2012). To confirm, a Variance Inflation Factor (VIF) test was used to measure the magnitude of collinearity and to determine if the VIF was within the acceptable limit (Montgomery et al., 2012). If VIF was more than 5, it means one of the predictors should be removed from the model (Boslaugh, 2013). VIF (Eq 3.4) is defined as reciprocal of tolerance; 1-$R^2$, where $R^2$ is calculated from the regression of correlated predictors (Montgomery et al., 2012).

$$Variance\ Inflation\ Factor\ (VIF) = \frac{1}{1 - R^2} \tag{3.4}$$

Before proceeding to regression analysis, a global validation of linear model assumption test (Pena & Slate, 2006) was performed on R Studio Software using "*gvlma*" package to determine if the response variable of the model met the assumptions of the linear regression model, which include; (1) linearity, (2) normal distribution, (3) uncorrelatedness, and (4) constant variance or homoscedasticity (Pena & Slate, 2006). Then, multiple linear regression analysis was performed, and residual plots from the regression model were diagnosed to assess for potential outliers and best fit model (Teetor, 2011). Cook's Distance analysis was used to identify the most influential observations to be removed from this model (Cook, 1977).

# CHAPTER 4: RESULTS

In this chapter, results shown in chapter 4.1 and chapter 4.2 are for objective 1 and objective 2, respectively. Chapter 4.3 presents results for the data exploration and final regression analysis for objective 3, which will also answer the research questions by testing the hypotheses of this study.

## 4.1 Middle Bank Meadow Structures

The meadow structure variable with their value range (mean ± SE) in the Middle Bank were as follows; (1) shoot density, range: 140-6181 (3250±431) shoot.$m^{-2}$; (2) total aboveground biomass, range: 26.28-295.79 (141.01±28.18) gDW.$m^{-2}$; and (3) LAI, range: 1.60-10.03 (4.81±0.96) $m^2.m^{-2}$. Meadow structure was very dynamic and varied between sampling stations, especially for shoot density (Figure 4.1).

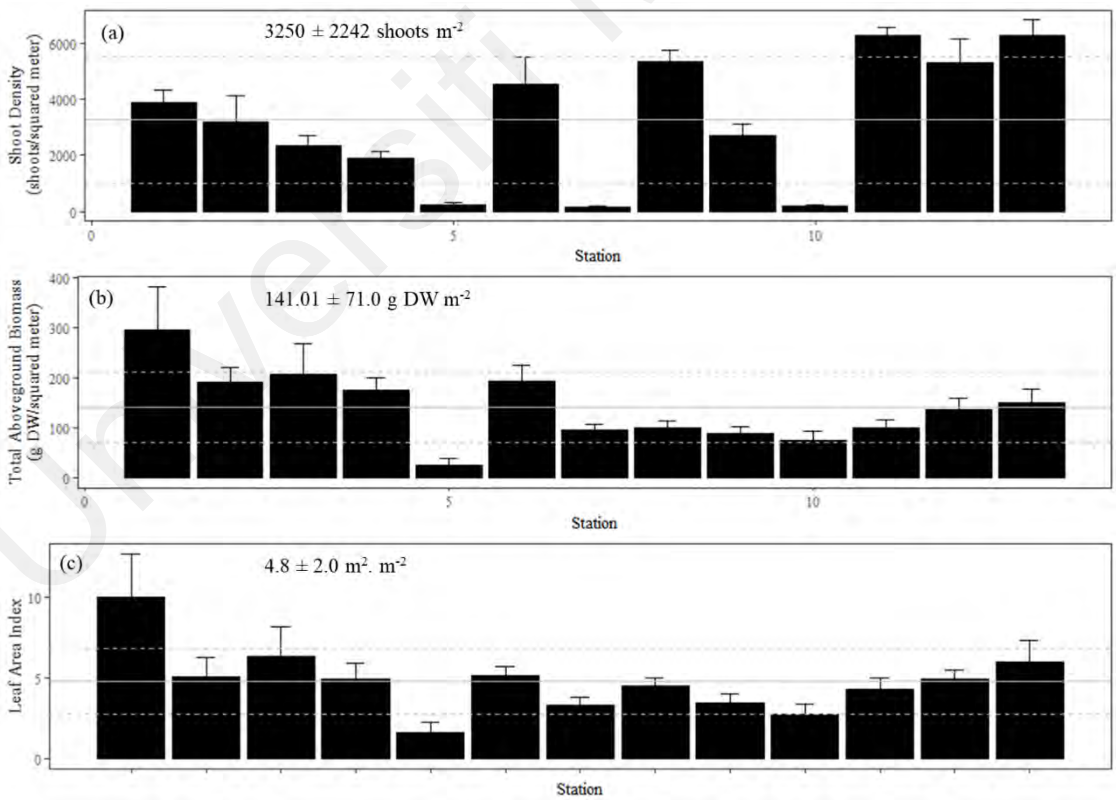


**Figure 4.1: Mean of shoot density (a), total aboveground biomass (b) and Leaf Area Index, LAI (c) of sampling stations in Middle Bank Shoal. *Solid (dashed) grey horizontal lines represent the mean (mean ± SD) of the respective meadow structure variable.**

Three seagrass species were found at Middle Bank Shoal. They were *Enhalus acoroides* (L. *f.*) Royle, *Thalassia hemprichii* (Ehrenberg) Ascherson, and *Halophila ovalis* (R. Br.) Hooker *f.* Seagrass patches were not uniform across the meadow, and the composition varied from monospecifc stands of *E. acoroides* to multispecific patches of two to three seagrass species (Table 4.1). *E. acoroides* was the most common species in Middle Bank as it was present in all sampling stations, whereas *T. hemprichii* and *H. ovalis* were mostly found in less muddy areas and with more compact seabed.

**Table 4.1: Seagrass species recorded (+) at sampling stations. EA = *Enhalus acoroides,* TH = *Thalassia hemprichii,* HO = *Halophila ovalis*.**

| Species | Station | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| EA | + | + | + | + | + | + | + | + | + | + | + | + | + |
| TH | + | | | + | | + | | + | + | | + | + | + |
| HO | + | + | + | | | + | | + | + | | + | + | + |

Although only three species were recorded in this study, Table 4.2 shows they were very distinctive in terms of biomass and LAI (*E. acoroides* > *T. hemprichii* > *H.* ovalis), and shoot density (*H. ovalis* > *T. hemprichii* > *E. acoroides*). Because of this, the presence or absence of a seagrass species gave variation to the total shoot density, aboveground biomass and LAI of a sampling station (Figure 4.1). Factors that drive these variations and distribution were not assessed in this study. Results of these variables for each seagrass species in every sampling station are reported in Appendix B (Table B1).

**Table 4.2: Meadow structure (mean ± SE) of seagrass species in Middle Bank Shoal. EA = *Enhalus acoroides,* TH = *Thalassia hemprichii,* HO = *Halophila ovalis*.**

| Species | Shoot Density (shoots. $m^{-2}$) | Aboveground Biomass (g DW. $m^{-2}$) | Leaf Area Index ($m^2$. $m^{-2}$) |
|---|---|---|---|
| EA | 189 ± 19 | 109.72 ± 11.52 | 3.5 ± 0.3 |
| TH | 846 ± 112 | 43.29 ± 5.77 | 1.6 ± 0.2 |
| HO | 3669 ± 305 | 6.72 ± 0.67 | 0.4 ± 0.1 |

### 4.2 Sediment Deposition Rate on Middle Bank Shoal

The rate of total sediment deposition ranged from 3956 to 13237 gDW.m$^{-2}$.day$^{-1}$. The mean (± SE) of total sediment deposition rate was 7554.12±856.64 g DW.m$^{-2}$.day$^{-1}$ (Figure 4.2). From observation, sediment load on the Middle Bank Shoal may have come from the ongoing reclamation project at Seri Tanjung Pinang (northeast coast of Penang Island), urban run-off discharge from the Pinang River, effluent discharge from the adjacent aquaculture farm, and erosion from the Jelutong Landfill.

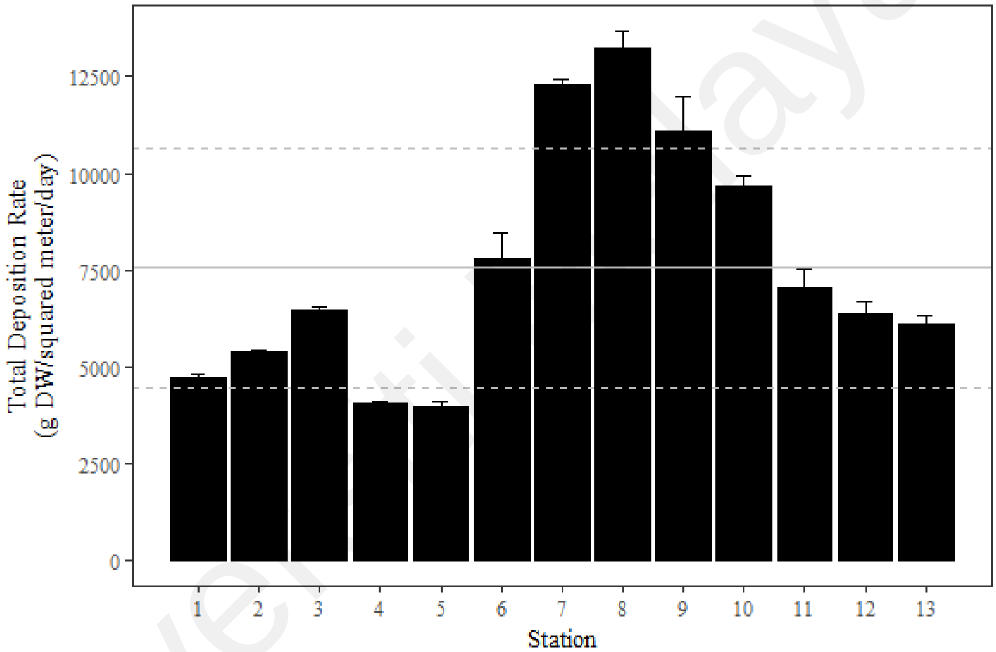


**Figure 4.2: Sediment deposition rate at Middle Bank Shoal. Solid (dashed) grey horizontal line represents the mean (± SD) of the total deposition rate.**

### 4.3 Meadow Structure and Sediment Deposition Rate

Based on the correlation matrix in Figure 4.3, it shows that (1) deposition rate had a negative relationship with all predictors, and (2) aboveground biomass and LAI were highly correlated. VIF 8.13 implies strong collinearity (Montgomery et al., 2012) between aboveground biomass and LAI, and one of these predictors had to be removed from the regression model. Although previous studies showed strong relationship between LAI and deposition rate (Gacia & Duarte, 2001; Gacia et al., 1999), measured LAI in this study may not be equal to field LAI as leaves may overlap, hence reducing contact surface area with water flow. This suggests LAI may vary from time to time depending on the movement of leaf blades, whilst aboveground biomass of a seagrass patch remains the same. Because of this variation, we removed LAI from the model.

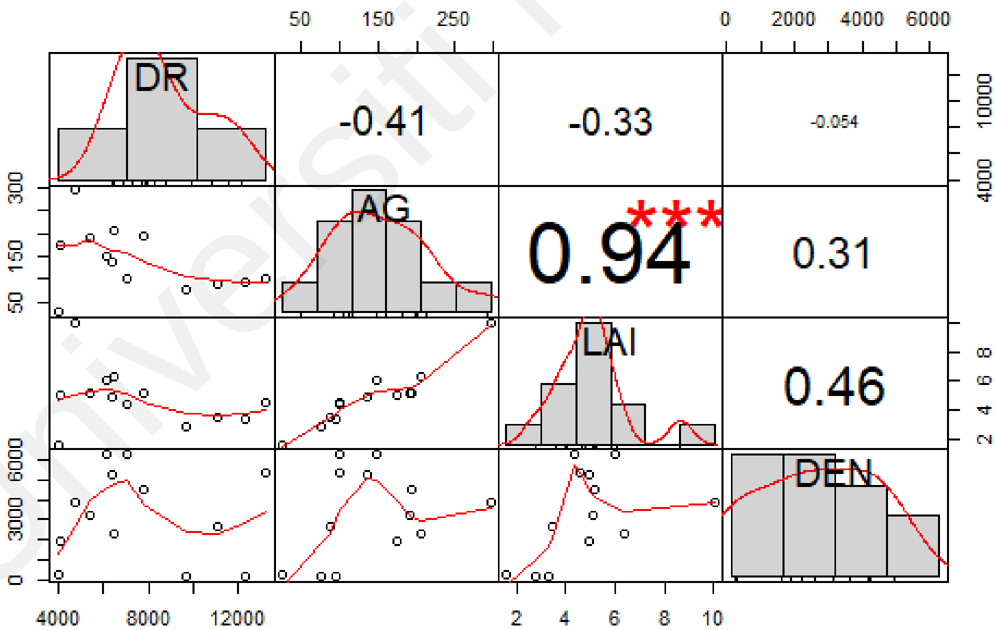


**Figure 4.3: Correlation matrix for all variables. The numbers represent the correlation coefficient, R. Deposition rate (DR) is the response variable, while aboveground biomass (AG), Leaf Area Index (LAI) and shoot density (DEN) are the predictors.**
**Note: *** is the significant p value < 0.0001**

The multiple linear regression model used in this study was as follow:

$$y = \beta_0 + \beta_1(X_1) + \beta_2(X_2) + e \tag{4.1}$$

$y$ refers to response variable (deposition rate), $X$ is the predictor variables (aboveground biomass and shoot density), β is the coefficient and $e$ is the unobserved error of the model.

Figure 4.4 shows the residual plots from the regression model. Station 5, station 7 and station 8 might be outliers (Figure 4.4), which we proceeded to confirm by using Cook's Distance analysis.

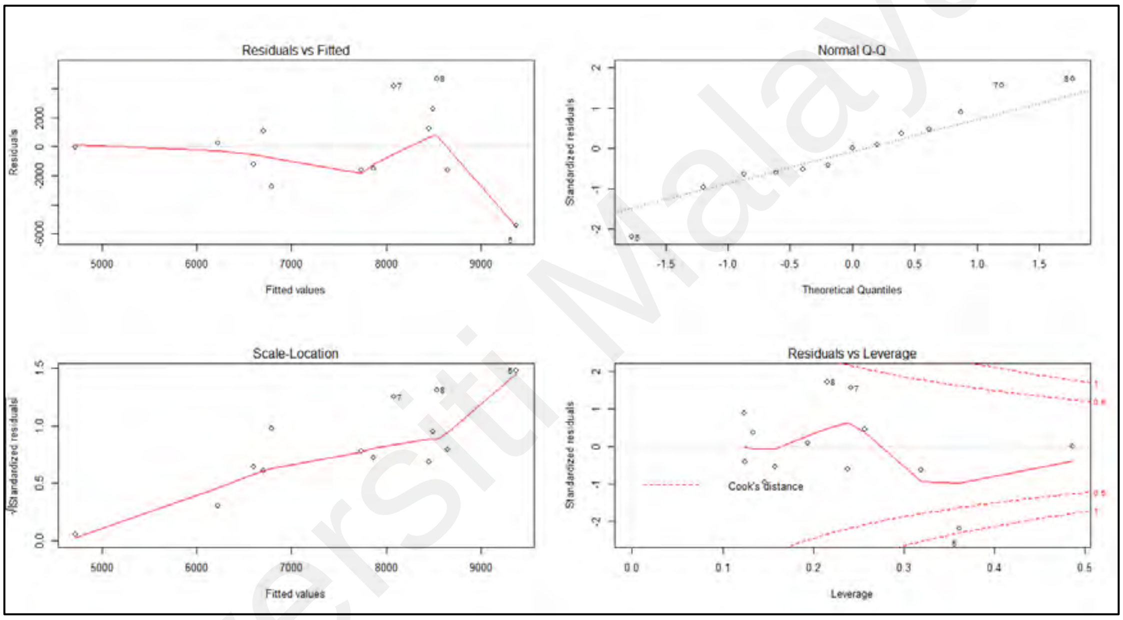


**Figure 4.4: Residual plots from linear regression model. Best fit regression model should have (1) randomly scattered Residual vs Fitted plot, (2) the points on Normal Q-Q plot are more or less on the line, (3) the points on the Scale-Location plot are centralized, and (4) the points on Residual vs Leverage plot are within the Cook's Distance line (Teetor, 2011)**

Cook's Distance analysis was used to assess and identify the most influential observation in this model (Cook, 1977). Observation that has Cook's Distance greater than 4 times the mean is considered to be highly influential, and in this case, station 5 was an influential observation (Figure 4.5).

The analysis was re-run and the regression model was significantly improved with adjusted $R^2$ from 0.0048 (for all sample) to 0.4039 (when excluding station 5). This supported the notion that station 5 was an influential observation. Hence, the data point from station 5 was removed.

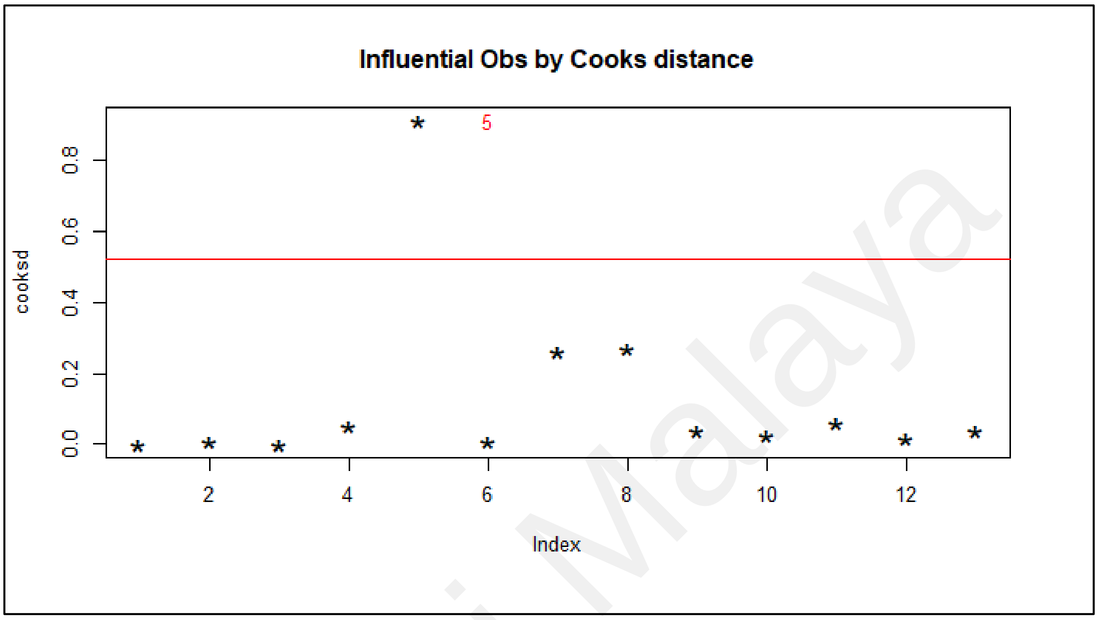


**Figure 4.5: Plot graph shows the index of Cook's Distance calculated from the observed data. Any observation above the red line is considered highly influential to the model.**

Regression model analysis shows meadow structures were significant predictors ($p<0.05$, Adj-$R^2$ = 0.40) for sediment deposition rate on Middle Bank Shoal (Table 4.3). Among the meadow structures evaluated, 49% ($p<0.05$) of the variation of deposition rate on Middle Bank Shoal can be explained by the total aboveground biomass (Table 4.3), where greater aboveground biomass lessened the total deposition rate (Figure 4.6).

**Table 4.3: Summary of multiple linear regression model for sediment deposition by seagrass on Middle Bank Shoal.**

| Source of variation | df | Estimate | F | P (>\|t\|) | % of explained variation | Adj R squared |
|---|---|---|---|---|---|---|
| Model: DR = AG + DEN | | | | | | |
| Full model | | | | | | |
| AG | 1 | -31.91 | 9.13 | * | 49.48 | |
| DEN | 1 | -0.19 | 0.32 | | 1.74 | |
| Residual | 9 | | | | 48.78 | |
| Null | 11 | | | | 100.00 | 0.40 |
| After backward stepwise approach | | | | | | |
| Best-fit model | | | | | | |
| AG | 1 | -32.79 | 9.80 | * | 49.48 | |
| Residual | 10 | | | | 50.52 | |
| Null | 11 | | | | 100.00 | 0.49 |

* = significant p < 0.05, AG = total aboveground biomass, DEN – shoot density

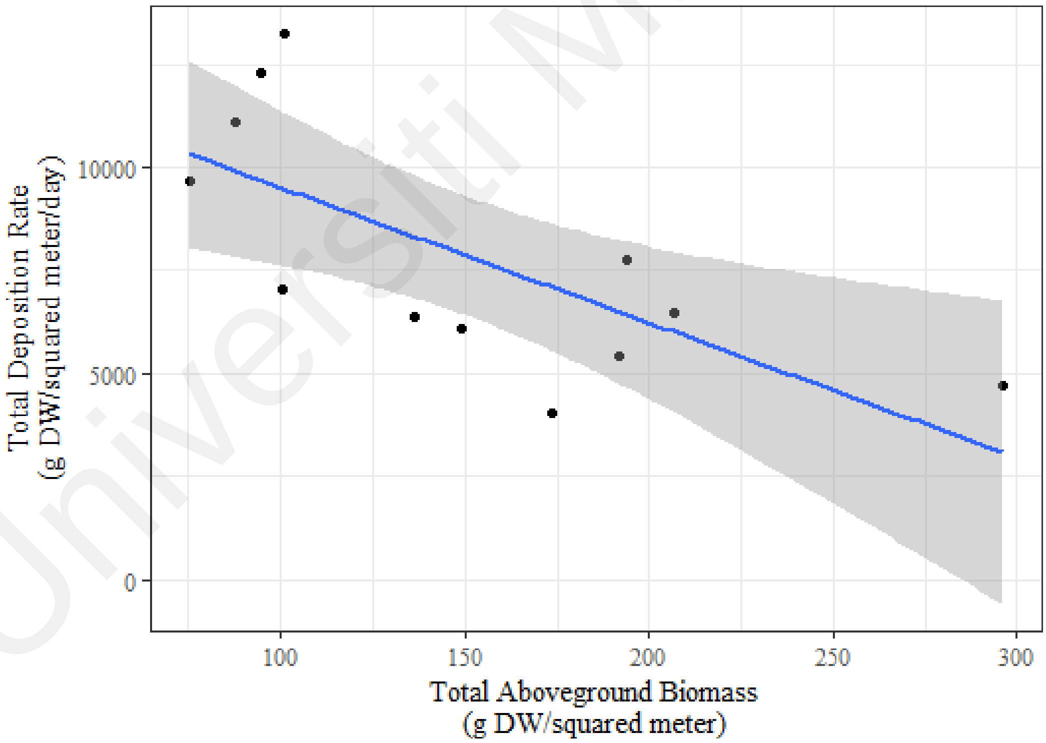


**Figure 4.6: Deposition rate with 95% confidence interval (grey shade) against total aboveground seagrass biomass on Middle Bank Shoal.**

# CHAPTER 5: DISCUSSION

## 5.1 The Architecture of Middle Bank Seagrass

Middle Bank Shoal is a simple meadow with the least diverse seagrass communities amongst the shallow/intertidal meadows in Peninsular Malaysia. Compared to them, they have more than four seagrass species (Anisah Lee & Anscelly, 2016; Japar Sidik et al., 2006; Sabri et al., 2013), while this study site only has three species. *E. acoroides, T. hemprichii* and *H. ovalis* are the common seagrass species found in shallow/intertidal meadows of Peninsular Malaysia (Japar Sidik et al., 2006; Sabri et al., 2013). It was interesting to note that 10 years ago there was no record of *T. hemprichii* in Penang Island (Phang, 2000), and unlike Middle Bank Shoal, the latest publication still shows no sign of *T. hemprichii* in Pulau Gazumbo (Anisah Lee & Anscelly, 2016). When and how it has appeared requires further study to understand the factors that have led to the presence of *T. hemprichii* in Middle Bank Shoal.

When compared to other shallow meadows in Southeast Asia, the Middle Bank meadow has the low number of species too (Table 5.1). The Ko Talibong meadow in Thailand has six species recorded while both Bolinao and Bacuit Bay-El Nido in Philippines have seven species (Terrados et al., 1998). In spite of that, Middle Bank shoot density and aboveground biomass were relatively high; which was five times denser than Bolinao and almost three times greater than the aboveground biomass of Ko Talibong (Table 5.1). This was most likely because in Middle Bank Shoal, the biggest contributor of shoot density was *H. ovalis* (fast growing species) and aboveground biomass was *E. acoroides* (largest tropical species). While in Thailand and the Philippines, meadows were dominated by either fast growing and small species, or slow growing and medium sized species, which means their contribution to total aboveground biomass and shoot density were relatively modest (Terrados et al., 1998).

**Table 5.1: Mean (minimum-maximum) shoot density and aboveground biomass of selected seagrass meadow with depth less than 3m at high tide in Southeast Asia. All are multispecific meadows, with three or more seagrass species.**

| Location | Middle Bank Shoal (this study) | Ko Talibong, Thai[a] | Bolinao, Phil[a, b, c] | Bacuit Bay-El Nido, Phil[a] |
|---|---|---|---|---|
| *Enhalus acoroides* | | | | |
| Aboveground Biomass (gDW.m$^{-2}$) | 109.7 | 4.9 | 53.7 | 13.9 |
| Shoot Density (shoots.m$^{-2}$) | (105 – 526) | - | (5 – 29) | - |
| *Thalassia hemprichii* | | | | |
| Aboveground Biomass (gDW.m$^{-2}$) | 43.3 | 3.4 | 93.9 | 14.6 |
| Shoot Density (shoots.m$^{-2}$) | (105 – 1786) | - | (65 – 335) | - |
| *Halophila ovalis* | | | | |
| Aboveground Biomass (gDW.m$^{-2}$) | 6.7 | 10.3 | 3.1 | 0.6 |
| Shoot Density (shoots.m$^{-2}$) | (1053 – 6000) | - | (12 – 388) | - |
| Number of species | 3 | 6 | 7 | 7 |
| Total Aboveground Biomass (gDW. m$^{-2}$)* | 141 | 47.5 | 288.2 | 87.9 |
| Total Shoot Density (shoots. m$^{-2}$)* | (140 – 6281) | - | (2 – 1064) | |

* value includes other species recorded at the meadow

[a] Terrados et al. (1998)

[b] Bach et al. (1998)

[c] Gacia et al. (2003)

## 5.2 Sediments Deposition on Middle Bank Shoal

### 5.2.1 Total Deposition Rate

The rate of total sediment deposition on Middle Bank Shoal was extremely high when compared to other sediment deposition studies in shallow meadows within Southeast Asia (Table 5.2). Even its minimum value was 20 times greater than the mean value recorded in the Philippines and Thailand, and 5 times greater than Vietnam (Table 5.2). High sediment deposition on Middle Bank Shoal is probably due to: (1) large sediment influx from the observed anthropogenic activities stated in chapter 4.2; especially the land reclamation, river discharge and aquaculture farm adjacent to the meadow, and (2) high resuspended sediment in the intertidal meadow (discussed in the next chapter).

**Table 5.2: Mean (± SE) of deposition rate of shallow Southeast Asia seagrass meadow.**

| Location | Total Deposition Rate ($gDW.m^{-2}.day^{-1}$) | |
|---|---|---|
| | Mean | ± SE |
| Philippines[a] | | |
| Silaqui | 18.8 | 2.01 |
| Pislatan | 38.5 | 2.85 |
| St. Barbara | 175.3 | 16.09 |
| Buenavista | 154.4 | 3.57 |
| Umalagan | 105.8 | 9.22 |
| Vietnam[a] | | |
| Bay Tien | 681.1 | 102.40 |
| Dam Gia Bay | 76.2 | 3.72 |
| My Giang I | 266.5 | 18.43 |
| My Giang II | 122.5 | 9.53 |
| Thailand[b] | | |
| Tangkhen Bay | 47.35 | 18.99 |
| Penang, Malaysia (This study) | | |
| Middle Bank Shoal | 7554.1 | 856.64 |

[a] Gacia et al. (2003)
[b] Panyawai et al. (2019)

### 5.2.2 Possibility of Resuspended Sediment Dominating Total Deposition

There is a high possibility that the resuspended sediment dominated the total deposition on Middle Bank Shoal. Studies of sediment flux in shallow depth have shown the contribution of resuspended sediment could be more than 70% of total deposition (Gacia & Duarte, 2001; Ganthy et al., 2013; Paladini de Mendoza et al., 2018). This means that resuspended sediment may cause variation in total deposition (Gacia & Duarte, 2001; Gacia et al., 1999; Paladini de Mendoza et al., 2018). In other words, the increase of resuspended sediment could increase the total deposition.

As an intertidal seagrass meadow, Middle Bank Shoal may have high sediment resuspension because of its shallow water depth. Resuspension happens when hydrodynamic energy that acts on sediment surface exceeds the critical bed shear threshold and causes sediment movement/erosion (Madsen et al., 2001). Strong positive relationship between resuspended sediment and hydrodynamic energy has been observed in both shallow and intertidal meadows (Gacia & Duarte, 2001; Koch, 1999; Paladini de Mendoza et al., 2018; Panyawai et al., 2019). Because hydrodynamics was not measured in this study, their effects on resuspension in Middle Bank Shoal would be generally discussed based on observation and references from previous studies to strengthen this suggestion.

Situated in the middle of a busy Penang Strait (Figure 3.1), Middle Bank Shoal is likely subjected to strong hydrodynamic energy. From observation, the currents are generally driven by tides, winds, and waves (especially from external forces such as generated from boat traffic). The sampling stations in this study were located close to sandbank (Figure 3.1); the upper intertidal zone, where they were most probably exposed to high flow velocity and wave breaking, especially during flooding. This is because hydrodynamic energy intensifies with the onset of incoming tides (Koch, 1999). Turbulence from high surface current and wave energy could reach the seafloor and disturb bed sediment in shallow depth (Madsen et al., 2001; Paladini de Mendoza et al., 2018; Schiel et al., 2006), and increase bed shear stress that may lead to sediment resuspension (Fonseca & Cahalan, 1992; Koch, 1999; Paladini de Mendoza et al., 2018). Hence, being shallow and intertidal, Middle Bank Shoal might experience high resuspension that occurs throughout the tidal phase (flooding and ebbing).

Besides that, the design of the trap used in this study might also be one of the reasons for high contribution of resuspended sediment in the total deposition. As explained in chapter 2.2.2, total deposition increases exponentially towards the seabed (Figure 2.4) and the amount of sediment trapped at different height is primarily driven by the amount of resuspended sediment in total deposition (Gacia & Duarte, 2001; Gacia et al., 1999; Paladini de Mendoza et al., 2018; Ward et al., 1984). For example, Ward et al. (1984) showed total depositions trapped at 15cm height from seabed were significantly higher than those trapped at 50cm in *Ruppia maritima* meadow. In shallow *Posidonia oceanica* meadow, Gacia & Duarte (2001) found similar findings for total depositions at 20cm height in comparison to 100cm. This is because resuspended sediment constituted a larger percentage of total deposition when trapped closer to the seabed (Gacia & Duarte, 2001; Ward et al., 1984). Meanwhile, the trap used in this study was approximately at 10cm height from seabed, hence suggesting higher contribution of resuspended sediment in the total deposition.

### 5.3 Middle Bank Seagrass for Sediment Entrapment

Towards achieving the aim of this study, this section is to answer the research questions stated in chapter 1.3.1 by discussing the relationship between meadow structure and sediment deposition in chapter 5.3.1, and how Middle Bank seagrass (aboveground biomass) might influence the variation of sediment flux through possible modification of hydrodynamic in chapter 5.3.2. Generally, the functions of seagrass for sediment entrapment are: (1) promote deposition of suspended sediment, and (2) retain sediment from resuspended. Resuspension/erosion is a big issue for the shallow intertidal environment, and the ability of seagrass to tackle this issue is a vital component for coastal stabilization (Ganthy et al., 2013; Koch, 1999; Widdows et al., 2008). Because total sediment deposition on Middle Bank Shoal was relatively high and was most likely dominated by resuspended sediment, the key to a functional seagrass is to reduce resuspension while continue to promote primary deposition.

#### 5.3.1 Relationship of Meadow Structure and Sediment Deposition

All meadow structure variables measured in this study; i.e shoot density, LAI, and aboveground biomass, had negative relationships with total sediment deposition (Figure 4.3). This contradicted the first hypothesis. Both studies by Fonseca & Fisher (1986) and Gacia et al. (1999) found positive relationships between LAI and sediment deposition, where bigger LAI trapped more sediment. Gacia et al. (1999), however, found decreased sediment deposition when LAI was more than 4 $m^2.m^2$, and they believed that in canopies with high density, bending of leaves may interfere with the deposition of suspended particles. This could be one of the reasons for the negative relationship between the meadow structure variables and sediment deposition at the Middle Bank, as the mean LAI was 4.8 $m^2.m^2$. Besides that, assuming resuspended sediment dominated total deposition, Middle Bank seagrass might reduce deposition by retaining sediment from those resuspended. This is similar to a previous study by Ward et al. (1984) where they found the negative relationship between seagrass *Ruppia maritima* and total deposition were due to its ability to buffer resuspension.

The deposition rate in Middle Bank Shoal was best explained by aboveground biomass instead of LAI, as hypothesized earlier (hypothesis 2). Due to high multicollinearity, LAI was not included as a predictor alongside the aboveground biomass in the regression model, but when compared in separate univariate tests, aboveground biomass had a stronger relationship with total deposition ($R^2 = 0.49$) than LAI ($R^2 = 0.37$, results not shown). This could be because in determining LAI, we measured the leaf surface area of every leaf blade of a seagrass plant, but the contact surface area between leaf blades and water (LAI) may vary in the water column. LAI in the water column may vary significantly than measured LAI when leaf blades bend and overlap. Meanwhile, aboveground biomass is not affected by hydrodynamics, i.e. biomass measured in the lab and actual biomass in the water column are likely to be the same. The lack of 'real' LAI representation in the water column compared to aboveground biomass could be the reason for the stronger biomass relationship with sediment deposition than LAI. How aboveground biomass explains the variation of sediment deposition is discussed in the next chapter.

Because both LAI and biomass are highly correlated ($R = 0.94$), to include LAI as part of the meadow structure effects on sediment deposition rate in future studies is questionable. We need to consider the method used to quantify the LAI and its significance to the model. While univariate tests have shown slight differences between aboveground biomass and LAI as a better predictor in this study, it took only two to three days to obtain aboveground biomass data compared to one week or more for LAI (depending on sample size). Although previous studies measured LAI of *Posidonia oceanica* by factoring length and width of leaf blades and extrapolated it with shoot density to expedite the process (Gacia & Duarte, 2001; Gacia et al., 1999; Paladini de

Mendoza et al., 2018), this method is not practical for all seagrass species especially when the leaf shapes are not straight and symmetrical like *Thalassia* sp. and *Halophila* spp. Tracing the leaf perimeter is needed instead to quantify LAI for each sample, which is more time-consuming than quantifying aboveground biomass. Therefore, for future sedimentation studies in intertidal and multispecific meadow, we believe it is more effective to only quantify the aboveground biomass than measure the LAI.

As for shoot density, its relationship with total deposition rate in Middle Bank was very weak ($R^2 = 0.02$). While some previous studies have shown similar findings (Gacia & Duarte, 2001; Gacia et al., 1999; Paladini de Mendoza et al., 2018), Wilkie et al. (2012) gave the opposite results, where they found that shoot density of *Zostera noltii* influenced the trapping of small particles in a flume study. Compared to monospecific meadows in these previous studies, Middle Bank seagrass was multispecific and more than 80% of its total shoot density were contributed by *H. ovalis*, the smallest yet fastest growing species in the meadow. The influence of *Halophila* spp. in reducing current flows and trapping suspended sediment is minimal compared to larger seagrass species (Fonseca, 1989). This could be the reason why shoot density had a very weak relationship with total deposition on Middle Bank Shoal. Although the effect of *Halophila* spp. in controlling erosion via its extensive rhizomes has been shown (Fonseca, 1989), this function was not captured in this study.

### 5.3.2 Influence of Multispecific Intertidal Seagrass on Trapped Sediment

The negative relationship between meadow structure and trapped sediment suggested that Middle Bank seagrass may influence the total sediment deposition by retaining sediment from resuspension more than promoting deposition of primary sediment, as discussed in the previous chapters. We did not quantify the deposition of primary and resuspended sediments in this study; therefore, the following discussion explains possible Middle Bank seagrass-sediment interaction based on previous findings to support this idea.

Being a multispecific meadow, the uneven vertical distribution of aboveground biomass (Figure 5.1) for Middle Bank seagrass (due to its very distinctive species morphologies) might be an important reason for its strong negative relationship with total deposition. With reference to species leaf length and shoot density, akin to a terrestrial forest *E. acoroides* would be the emergent tree, *T. hemprichii* the canopy and *H. ovalis* the understory. This mixture produces meadow with aboveground biomass that is 'heavier' at the bottom than at the canopy top. This is the opposite to monospecific meadows with no understory species, where the leaf blades are held by sheaths and forms greater biomass at the canopy top rather than the bottom (Koch, 1999), as portrayed in Figure 5.1. This large allocation of biomass closer to the seabed suggests that Middle Bank seagrass may buffer sediment resuspension by reducing bed flow (Koch, 1999), while the light canopy top probably had a minimal effect on trapping of suspended particles (Koch, 1999). Hence, this supports the assumption for the negative relationship between meadow structure and total deposition. Because resuspended flux most likely dominates total deposition, high Middle Bank seagrass probably lowers total deposition by reducing resuspension more than promoting primary deposition.

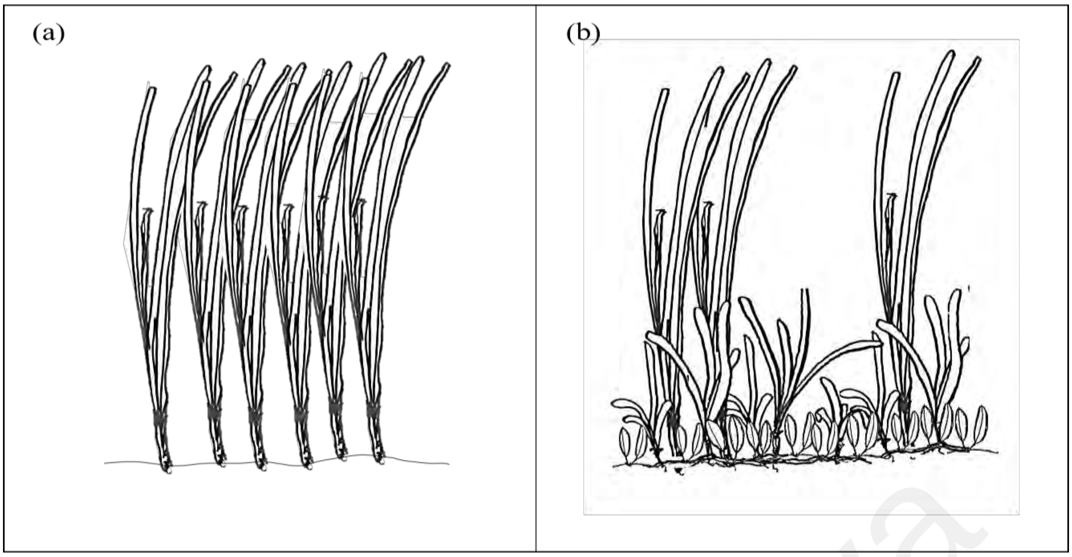


**Figure 5.1: Illustration to compare vertical aboveground biomass distribution between monospecific and multispecific meadow. In monospecific meadow (a) with no understory species and where leaf blades are held in sheath, aboveground biomass is higher at canopy level than near bed, while in multispecific meadow (b), the combination of different leaf length with smaller species being denser than bigger ones give greater clumped aboveground biomass closer to bottom than canopy top, which might play an important role in sediment entrapment.**

As an intertidal meadow, the influence of Middle Bank seagrass on sediment entrapment is expected to be tide-dependent. At low tide, the interweaving of leaves would form a mat that closes the gap between aboveground biomass and bottom sediment (Figure 5.2), and which holds sediments down from being resuspended by deflecting flow over it (Fonseca, 1989). As water floods in, strong flows would compress the seagrass canopy (Figure 5.2) up to half of its leaf length (Ganthy et al., 2013), causing a 'skimming flow' effect - a phenomenon where higher flow is observed above the canopy top than below canopy, serving to seal the below canopy environment and protect the sea bed against erosion (Koch, 1999; Widdows et al., 2008; Wilkie et al., 2012). In dense meadows, the overlap of leaves from the canopy compression could also interfere with deposition of suspended particles (Gacia et al., 1999). When water reaches high slack tide (Figure 5.1), hydrodynamic energy weaken (Koch, 1999) and less force to compress the seagrass canopy and therefore, the canopy height increases (Ganthy et al., 2013). This also increases friction on the hydrodynamic and may further enhance flow reduction within the meadow, thus promoting sediment deposition and preventing resuspension (Paladini de Mendoza et al., 2018; Widdows et al., 2008). However, because Middle Bank seagrass does not occupy the whole water column, the attenuation of hydrodynamic is probably less effective, hence the influence on primary deposition is expected to be modest (Madsen et al., 2001; Paladini de Mendoza et al., 2018).

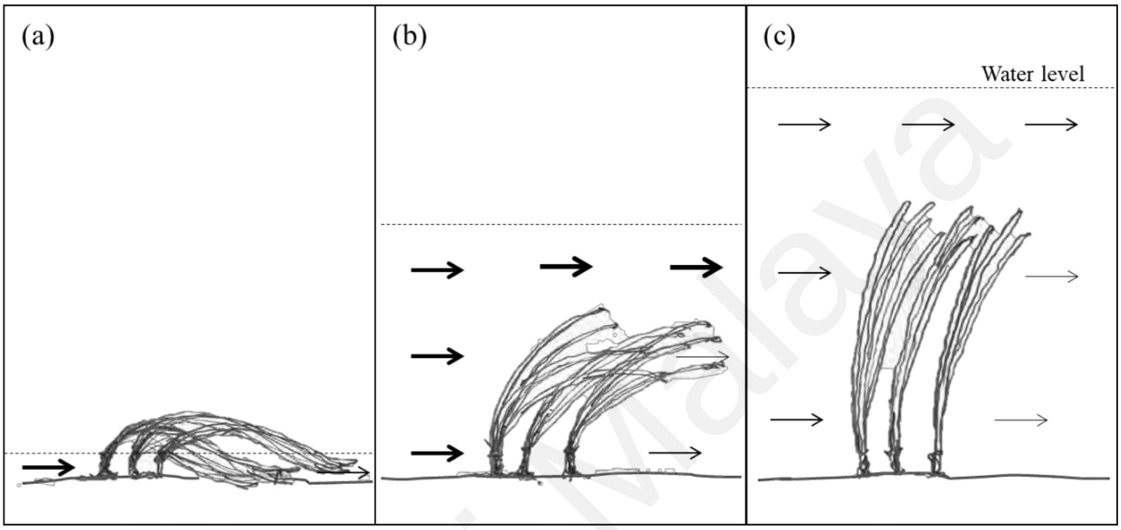


**Figure 5.2: Illustration of intertidal seagrass meadow in different tidal phase. At low tide (a) leaf blades lay flat on sea bed holding sediment down from resuspension during flooding, as water level increase (b) overlapping of leaves from canopy compression sealed below canopy environment and protect bottom sediment from erosion, and at high slack tide (c) flow decreases, seagrass canopy height increases, hence promote sedimentation and reduce resuspension. Arrows represent flow velocity (thicker arrow denotes higher velocity).**

# CHAPTER 6: CONCLUSION

The Middle Bank meadow was made up of three different seagrass species. They are *E. acoroides,* the longest and most common species found in the meadow; *T. hemprichii,* the medium sized seagrass; and *H. ovalis,* the smallest yet most dense species among all. The combination of these seagrass species adds dimension to the meadow's vertical profile.

High sediment deposition on Middle Bank Shoal could be the results of large sediment influx from anthropogenic activities near the meadow and high resuspended sediment in intertidal zone. Meadow structures had negative relationship with total sediment deposition on Middle Bank Shoal, and among them, aboveground biomass was the meadow structure variable that best explained the variation of sediment deposition. Being an intertidal meadow, the function of Middle Bank seagrass for sediment entrapment is tide-dependent. Because high resuspension is expected to occur in the intertidal zone, the influence of Middle Bank seagrass on sediment flux was most likely through retaining sediment from resuspension, whilst the deposition of primary sediment might be modest. The interweaving of bending leaves at low tide and during flooding closes the gap between the seagrass biomass and seabed, sealing off the bottom environment from resuspension. The bending of dense leaves might also interfere with primary deposition. At high tide, seagrass plants occupy a small percentage of water column, and gives minimal effect on primary deposition too. Besides that, as a multispecific meadow with dense understory species, greater allocation of aboveground biomass at the bottom than the canopy top could decrease near bed flow and prevent bed resuspension. The ability of seagrass to retain sediment from resuspension will stabilize the bed sediment, hence supports seagrass potential for natural coastal protection, parallel to the UN 2020 Agenda for Sustainable Development. We also hope that this study will add value to the importance of seagrass and the ecosystem services it provides, leading to more effort in protecting and conserving the seagrass meadow.

## 6.1. Way Forward: For Future Studies

The strong relationship between Middle Bank seagrass and sediment deposition strengthens the possibility of incorporating intertidal seagrass as a soft approach in eco-engineering. It is important for the potential "green wall" to provide not just coastal protection by damping waves and flow velocity, but also to provide coastal stabilization (Borsje et al., 2011; Chee et al., 2017; Mitsch & Jørgensen, 2003; Perkins et al., 2015). This preliminary study showed that intertidal seagrass would fit the requirement for erosion control, though more in-depth studies are needed to support this argument.

Moreover, it is interesting to discover the significant role of aboveground biomass for sediment entrapment when previous studies used canopy height, LAI and density to understand the influence of seagrass meadow on sediment flux (Fonseca, 1989; Fonseca & Fisher, 1986; Fonseca & Koehl, 2006; Gacia & Duarte, 2001; Gacia et al., 1999; Koch, 1999; Paladini de Mendoza et al., 2018; Wilkie et al., 2012). This means that when designing an eco-engineering structure with seagrass, considering the distribution of biomass should not be ignored as it is just as equally important as other meadow structures. However, there are no universal functions for all seagrass species, and seagrass-sediment interactions are very dynamic and site-specific. Hence, more studies are required to explore the ecosystem services provided by intertidal seagrass. For future studies, we should also explore the effect of intertidal seagrass on fluid motion and sediment accretion/erosion to further understand the ecological function of intertidal seagrass for sediment entrapment for future sustainable coastal development.

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