

## **SEAGRASS ECOSYSTEMS, THEIR CARBON STORAGE, AND POTENTIAL FOR REDUCING CARBON EMISSIONS**

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### **ABSTRACT**

Seagrass ecosystems are highly productive coastal habitats that play a vital role in maintaining marine biodiversity, supporting fisheries, and regulating global carbon cycles. As marine angiosperms inhabiting shallow coastal waters, seagrasses form extensive meadows that provide essential ecosystem services, including sediment stabilization, nutrient cycling, and habitat for diverse marine organisms. Increasing attention has been given to their role as blue carbon ecosystems, capable of capturing and storing atmospheric carbon dioxide in both biomass and underlying sediments over long timescales. Despite occupying less than 0.2% of the global ocean floor, seagrass meadows contribute significantly to oceanic carbon burial. However, these ecosystems are experiencing rapid global decline due to coastal development, eutrophication, sedimentation, and climate-related disturbances, leading to biodiversity loss and carbon release. This review synthesizes current knowledge on seagrass diversity, distribution, ecosystem functions, and blue carbon potential, with a particular focus on Southeast Asia. It further examines the environmental and biological factors influencing carbon storage, major anthropogenic threats, and emerging restoration strategies, highlighting key knowledge gaps and future research directions to support effective conservation and climate mitigation efforts.

**Key words:** carbon sequestration; coastal resilience; climate change mitigation; ecosystem services; restoration ecology

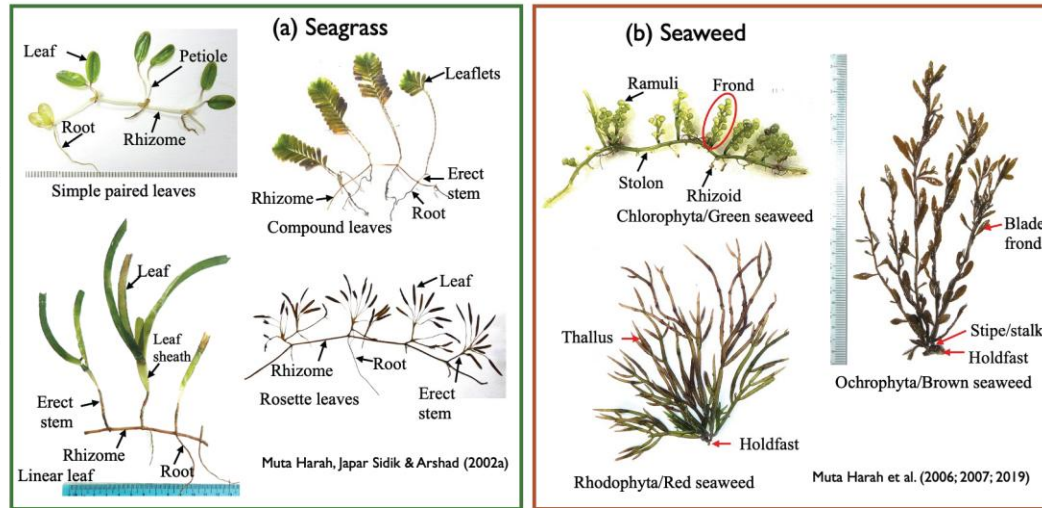
### **INTRODUCTION**

Seagrasses are underwater marine angiosperms from the class Monocotyledoneae. They are the only group of flowering plants (monocotyledonous angiosperms) that have successfully adapted to life in marine and estuarine environments. Unlike algae, seagrasses have true vascular tissues, including roots, stems, and reproductive organs such as flowers and seeds, allowing them to complete their entire life cycle submerged in seawater (Fig. 1).

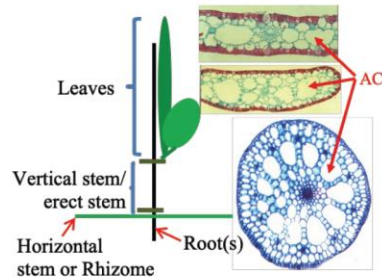
Seagrass ecosystems are some of the most productive and ecologically important coastal habitats in the world. These marine angiosperms form extensive underwater meadows in shallow coastal waters where enough light penetrates the seabed, enabling photosynthesis and primary production. Seagrasses possess well-developed root and rhizome systems that anchor them within sediments and facilitate nutrient uptake, allowing them to thrive in a variety of marine environments ranging from sheltered lagoons and estuaries to open coastal shelves (Green and Short 2003; Orth et al. 2006). Globally, approximately 72–80 seagrass species have been identified, distributed across tropical and temperate regions and forming important ecological links between mangroves, coral reefs, and open marine systems (Green and Short 2003; Orth et al. 2006; Short et al. 2011).

Seagrass ecosystems, their carbon storage.....

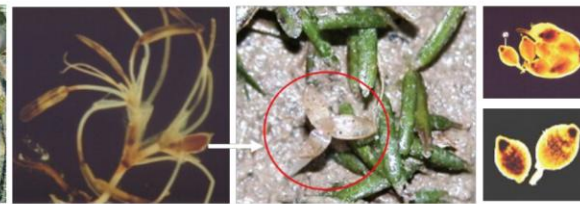
- Angiosperms (flowering plants)
- With a vascular system inter-connecting all organs (stem, leaves and roots), well developed air channel (AC) system
- Leaves generally green
- Produce flowers, fruits and seeds



- Multicellular macroscopic marine algae
- Prostrate axis or stolon, rarely extensive
- Rachis bearing thallus/lamella
- Thallus green, brown, and red
- Produce sporangium and spores



Dioecious *Enhalus acoroides*



Monoecious *Halophila beccarii*

Figure 1. Characteristics of seagrass and seaweeds and their differences

Beyond their biological diversity, seagrass meadows provide a wide array of ecosystem services that support both marine biodiversity and human livelihoods. These ecosystems serve as essential nursery and feeding grounds for numerous fish and invertebrate species, including commercially important fisheries, while also supporting megafauna such as sea turtles and dugongs (Orth et al. 2006; Unsworth et al. 2019). Dense seagrass canopies reduce wave energy, stabilize sediments, and improve water clarity by trapping suspended particles, thereby contributing to shoreline protection and coastal resilience (Koch et al. 2009; Orth et al. 2006). In many tropical coastal regions, particularly within Southeast Asia, seagrass meadows also play a significant role in sustaining local fisheries and food security for coastal communities (Nordlund et al. 2016).

In recent decades, seagrass ecosystems have gained increasing scholarly attention due to their vital role in global carbon cycling. These meadows are now recognized as a key type of blue carbon ecosystem, alongside mangroves and salt marshes, that can capture and store large amounts of atmospheric carbon dioxide (CO<sub>2</sub>) (Duarte et al. 2013; McLeod et al. 2011). Through photosynthesis, seagrasses convert dissolved inorganic carbon into organic matter, which is stored in plant biomass and buried in underlying sediments (Duarte et al. 2013; Fourqurean et al. 2012). Because seagrass sediments are often low in oxygen, decomposition slows down, allowing organic carbon to remain stored for centuries or even thousands of years (Duarte et al. 2013; McLeod et al. 2011). Despite covering less than 0.2% of the global ocean floor, seagrass ecosystems play a significant role in marine carbon sequestration and are estimated to contribute about 10% of the ocean's annual carbon burial (Fourqurean et al. 2012).

The blue carbon potential of seagrass ecosystems is especially important in Southeast Asia, which hosts one of the highest diversities of seagrass species worldwide (Fortes et al. 2018; Short et al. 2011). The region features extensive tropical coastlines and shallow-water habitats that support a variety of seagrass species across diverse environmental conditions, including estuaries, lagoons, coral-reef flats, and subtidal shoals (Fortes et al. 2018; Green and Short 2003). Countries like Indonesia, Malaysia, the Philippines, and Thailand are home to large seagrass meadows that play vital roles in regional biodiversity, fisheries productivity, and coastal ecosystem stability (Fortes et al. 2018; Japar Sidik et al. 2006; Nordlund et al. 2016; Prathep 2003; Unsworth et al. 2019). These ecosystems also serve as important carbon sinks in tropical coastal environments, thereby enhancing their role in climate change mitigation and sustainable coastal management (Duarte et al. 2013; Fourqurean et al. 2012). The assessments have further emphasized the large carbon storage capacity of tropical seagrass sediments, showing their importance as natural climate solutions in global efforts to reduce carbon (Alongi 2014; Fourqurean et al. 2012).

Nevertheless, despite their ecological and climatic significance, seagrass ecosystems are undergoing a rapid global decline. The loss of seagrass habitats has been estimated at approximately 7% annually in certain regions, predominantly due to anthropogenic disturbances such as coastal development, eutrophication, sedimentation, dredging, and climate-related stressors (Waycott et al. 2009). The deterioration of seagrass meadows not only results in biodiversity loss and diminished fisheries productivity but may also release stored sediment carbon, thereby potentially transforming these ecosystems from long-term carbon sinks into sources of greenhouse gas emissions (Macreadie et al. 2017; Fourqurean et al. 2012; Pendleton et al. 2012).

Given the increasing recognition of seagrass ecosystems as vital components of coastal resilience and climate mitigation, there is an urgent need to synthesize current knowledge on their ecological functions, carbon sequestration capacity, and conservation challenges, especially in Southeast Asia. This review aims to provide a comprehensive overview of seagrass ecosystems, with particular emphasis on their distribution, ecological roles, and blue carbon potential in Southeast Asia. Furthermore, the review examines the environmental and biological factors influencing carbon storage, identifies major human threats to seagrass habitats, and discusses emerging restoration and

conservation strategies to enhance their contributions to climate change mitigation and sustainable coastal management.

## SEAGRASS DIVERSITY AND DISTRIBUTION IN SOUTHEAST ASIA

Southeast Asia is widely recognized as a global hotspot for seagrass biodiversity, supporting a significant portion of the world's seagrass species within its tropical coastal waters (Short 2025; Fortes et al. 2018; Short et al. 2011). The region is part of the Indo-Pacific, which has the greatest diversity of seagrass species worldwide. This high diversity results from the presence of various coastal environments, including estuaries, lagoons, coral reef flats, intertidal mudflats, and shallow continental shelves, all of which provide suitable conditions for seagrass establishment and growth (Green and Short 2003; Short et al. 2007). These habitats are typically characterized by warm tropical temperatures, relatively stable salinity levels, and shallow water depths that allow enough light penetration for seagrass photosynthesis and productivity (Orth et al. 2006; Hemminga and Duarte 2000).

Seagrass species richness in Southeast Asia varies among countries, ranging from 7 to 19 species (Table 1), with the highest diversity observed in the Philippines, Indonesia, and Malaysia (Zakaria et al. 2025; Salim et al. 2025; Kurniawan et al. 2024; Che Alias et al. 2024; Fortes et al. 1998). Throughout the region, seagrass meadows are found in diverse coastal environments, reflecting the influence of environmental factors such as sediment type, hydrodynamic conditions, and nutrient levels (Kilminster et al. 2015; Green and Short 2003; Hemminga and Duarte 2000). Dominant genera in the area include *Enhalus*, *Thalassia*, *Halophila*, *Halodule*, *Cymodocea*, and *Syringodium*, each exhibiting unique morphological traits and ecological adaptations that enable them to thrive in various habitats. Larger, canopy-forming species such as *Enhalus acoroides* and *Thalassia hemprichii* are typically found on more stable substrates, while smaller, fast-growing species such as *Halophila* spp. and *Halodule* spp. are more common in dynamic or disturbed environments (Kilminster et al. 2015; Hemminga and Duarte 2000).

Several Southeast Asian countries, including Indonesia, Malaysia, the Philippines, Thailand, and Vietnam, support extensive seagrass meadows that greatly contribute to marine biodiversity and ecosystem productivity (Fortes et al. 2018; Short et al. 2007). These habitats serve as vital nursery grounds for fish, crustaceans, and other marine organisms while also supporting artisanal fisheries and coastal livelihoods in tropical communities (Nordlund et al. 2016; Unsworth et al. 2019). In Malaysia, at least 17 seagrass species have been recorded across coastal regions in Peninsular Malaysia, Sabah, and Sarawak, representing some of the highest national diversities in the region (Zakaria et al. 2025; Fortes et al. 2018; Bujang et al. 2006). These meadows occur across diverse habitats, including estuarine systems, coastal lagoons, intertidal mudflats, and reef-associated shoals (Zakaria et al. 2025; Bujang et al. 2018), with species composition reflecting local environmental factors such as sediment type, hydrodynamic exposure, and nutrient availability (Kilminster et al. 2015; Yaakub et al. 2014).

Notably, the recent discovery of *Halophila nipponica* in Malaysian waters highlights the evolving understanding of seagrass diversity in the region and emphasizes the importance of ongoing monitoring and taxonomic refinement (Zakaria et al. 2025; Che Alias et al. 2024).

Despite their ecological importance, the spatial distribution of seagrass ecosystems in Southeast Asia is only partially documented due to limited long-term monitoring and inconsistent regional mapping efforts (Fortes et al. 2018; Short et al. 2011). Recent advances in remote sensing technologies and geographic information systems have improved the ability to map and monitor seagrass habitats; however, additional efforts are needed to create comprehensive baseline data on seagrass distribution, habitat characteristics, and ecosystem functions to support effective conservation and management strategies throughout the region (McKenzie et al. 2020; Phinn et al. 2012).

**Table 1.** Seagrass species distribution in Southeast Asia by country/territory.+

No.	Family and species	BN	ID	CM	MM	MY	PH	SG	TH	VN	AN <sup>+</sup>
	<b>Seagrass area (km<sup>2</sup>)</b>	<b>1.5</b>	<b>8,812.9</b>	<b>324.9</b>	<b>4.3</b>	<b>16.3</b>	<b>27,262.2</b>	<b>0.3</b>	<b>148.5</b>	<b>157.4</b>	<b>8.3</b>
	<b>1. Family Hydrocharitaceae</b>										
1.	<i>Enhalus acoroides</i> (L. f.) Royle	•	•	•	•	•	•	•	•	•	•
2.	<i>Thalassia hemprichii</i> (Ehrenb.) Aschers.	•	•	•	•	•	•	•	•	•	•
3.	<i>Halophila beccarii</i> Aschers.	•	•	•	•	•	•	•	•	•	
4.	<i>Halophila decipiens</i> Ostenfeld		•	•	•	•	•	•	•	•	
5.	<i>Halophila gaudichaudii</i> J. Kuo						•				
6.	<i>Halophila major</i> (Zoll.) Miq.		•		•	•	•		•	•	
7.	<i>Halophila minor</i> (Zoll.) den Hartog		•	•	•	•	•	•	•	•	
8.	<i>Halophila ovalis</i> (R. Br.) Hook. f.	•	•	•	•	•	•	•	•	•	•
9.	<i>Halophila ovata</i> Gaudich. and in Freycinet						•				•
10.	<i>Halophila nipponica</i> J.Kuo					•					
11.	<i>Halophila spinulosa</i> Aschers.	•	•		•	•	•	•			
12.	<i>Halophila sulawesii</i> J. Kuo		•								
13.	<i>Halophila</i> sp. 1						•				
14.	<i>Halophila</i> sp. 2 ( <i>Halophila tricostata</i> Greenway)					•	•				
	<b>2. Family Cymodoceaceae</b>										
15.	<i>Cymodocea rotundata</i> Ehrenb. et Hempr. ex Aschers.	•	•	•	•	•	•	•	•	•	•

*Seagrass ecosystems, their carbon storage.....*

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	<b>Seagrass area (km<sup>2</sup>)</b>	<b>1.5</b>	<b>8,812.9</b>	<b>324.9</b>	<b>4.3</b>	<b>16.3</b>	<b>27,262.2</b>	<b>0.3</b>	<b>148.5</b>	<b>157.4</b>	<b>8.3</b>
16.	<i>Cymodocea serrulata</i> (R. Br.) Aschers. et Magnus		•	•	•	•	•	•	•	•	•
17.	<i>Halodule pinifolia</i> (Miki) den Hartog	•	•	•	•	•	•	•	•	•	•
18.	<i>Halodule uninervis</i> (Forssk.) Aschers.		•	•	•	•	•	•	•	•	•
19.	<i>Syringodium isoetifolium</i> (Aschers.) Dandy		•	•	•	•	•	•	•	•	•
20.	<i>Thalassodendron ciliatum</i> (Forssk.) den Hartog		•			•	•			•	
	<b>3. Family Ruppiaceae</b>										
21.	<i>Ruppia maritima</i> L.		•	•		•	•		•		
22.	<i>Ruppia brevipedunculata</i> Shuo Yu & den Hartog		•								
	<b>4. Family Zosteraceae</b>										
23.	<i>Zostera japonica</i> Aschers. et Graebn.									•	
	<b>Total number of species</b>	<b>7</b>	<b>17</b>	<b>12</b>	<b>13</b>	<b>17</b>	<b>19</b>	<b>12</b>	<b>13</b>	<b>14</b>	<b>9</b>

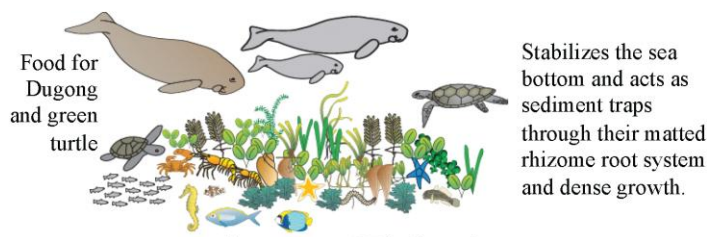
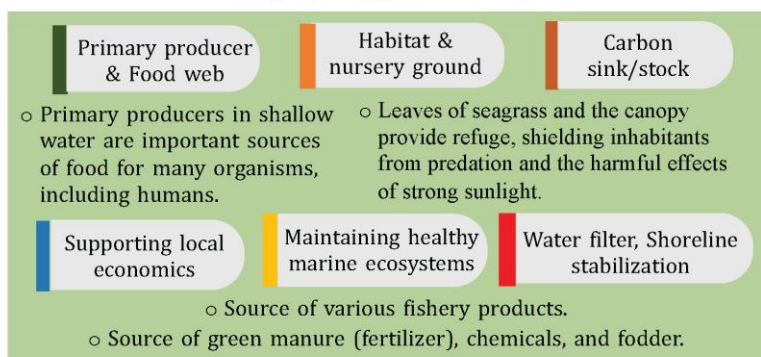
Country codes and references used to compile this list as follows: BN, Brunei (Lamit et al. 2017; Fortes 1988); ID, Indonesia (Salim et al. 2025; Kurniawan et al. 2024; Tuntiprapas et al. 2015; Wawan 2011; Kuo 2007); CM, Cambodia (Vibol et al. 2010; UNEP 2008); MM, Myanmar (BOBLME 2015; Nguyen et al. 2014; Novak et al. 2009; Soe-Htun et al. 2009); MY, Malaysia (Zakaria et al. 2025; Che Alias et al. 2024; Nguyen et al. 2014; Japar Sidik and Muta Harah 2011); PH, Philippines (Kim et al. 2017; Fortes 2013; Waycott et al. 2002; Fortes 1989); SG, Singapore (Yaakub et al. 2013); TH, Thailand (Tuntiprapas et al. 2015; Nguyen et al. 2014); VN, Viet Nam (Nguyen et al. 2014; 2013); AN, Andaman and Nicobar Islands (Tangaradjou et al. 2010; Jagtap et al. 2003), the “+” denoting this is a union territory of India.

## ECOSYSTEM FUNCTIONS AND SERVICES OF SEAGRASS MEADOWS

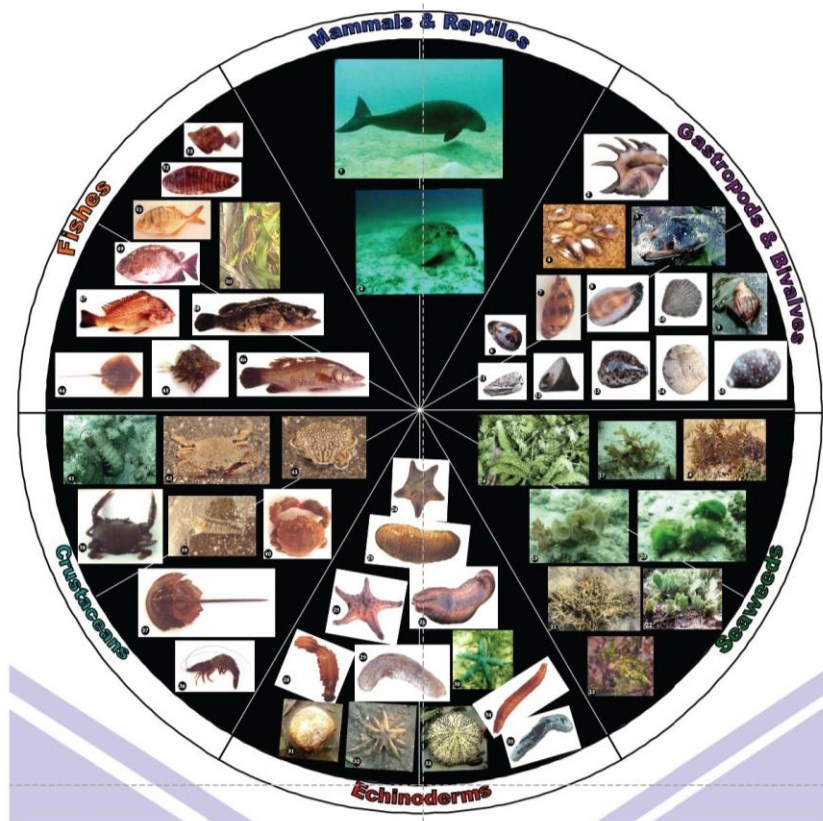
Seagrass meadows provide a wide range of ecological functions that support the stability of coastal ecosystems and marine biodiversity (Fig. 2). As highly productive marine habitats, seagrasses play a major role in primary production in shallow coastal areas and create structurally complex habitats that support numerous marine species (Orth et al. 2006; Hemminga and Duarte 2000). The dense canopy formed by seagrass leaves and rhizomes provides shelter, feeding grounds, and nursery habitats for many fish, crustaceans, and invertebrates, including species of commercial and ecological importance (Unsworth et al. 2019; Heck et al. 2003). A key ecological role of seagrass ecosystems is their function as nursery habitats for juvenile fish and invertebrates. Many marine species rely on seagrass meadows during early life stages because the complex vegetation offers protection from predators and supplies abundant food resources (Unsworth et al. 2019; Heck et al. 2003). Studies have shown that fish abundance and diversity are often significantly greater in seagrass habitats than nearby unvegetated areas, emphasizing the importance of seagrass meadows in supporting coastal fisheries productivity (Nordlund et al. 2016; Orth et al. 2006).

In addition to supporting marine biodiversity, seagrass ecosystems play a crucial role in regulating coastal physical processes. Dense seagrass canopies reduce wave energy and water flow, promoting sediment deposition and stabilizing seabed substrates (Christianen et al. 2013; Koch et al. 2009). The root–rhizome network further binds sediments, reducing erosion and helping to maintain coastal geomorphological stability (Koch et al. 2009; Hemminga and Duarte 2000). By trapping suspended particles and enhancing sediment stabilization, seagrass meadows also improve water clarity and support the conditions necessary for benthic primary producers like corals and other seagrasses (Orth et al. 2006). Seagrasses also play a key part in nutrient cycling and water quality regulation within coastal ecosystems. Through nutrient uptake from sediments and the water column, seagrasses influence the cycling and retention of essential nutrients such as nitrogen and phosphorus (McGlathery et al. 2007; Hemminga and Duarte 2000). The interaction among seagrass plants, sediments, and microbial communities enhances nutrient transformation processes, which can help reduce eutrophication and sustain ecosystem productivity in coastal waters (Waycott et al. 2009; McGlathery et al. 2007).

### Seagrass Ecosystem Benefits



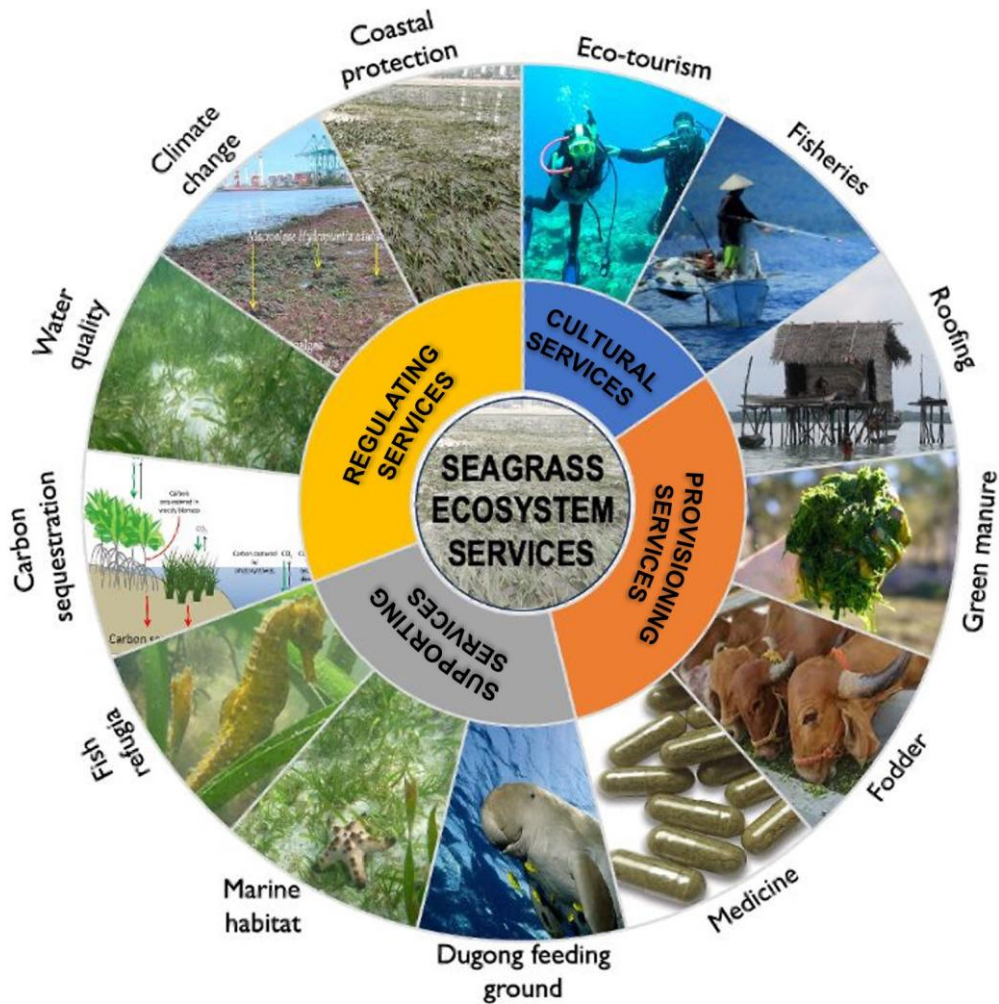
## Seagrass and Biodiversity



**Figure 2:** Importance and biodiversity of seagrass ecosystems

Beyond their ecological significance, seagrass ecosystems offer many socio-economic benefits to coastal communities. Seagrass meadows support fisheries resources, contribute to food security, and provide livelihoods for millions of people worldwide, especially in tropical regions where coastal populations rely heavily on marine resources (Unsworth et al. 2019; Nordlund et al. 2016). Additionally, seagrass ecosystems help stabilize sediments, protect shorelines, and improve water quality, supporting the long-term sustainability of coastal environments and their ecosystem services (Koch et al. 2009; Orth et al. 2006).

Given their multiple ecological and socio-economic roles, conserving and managing seagrass ecosystems is increasingly important for maintaining coastal resilience and supporting sustainable ocean economies. These ecosystem services also provide the foundational basis for the progressive acknowledgment of seagrass meadows as essential blue carbon ecosystems, thereby playing a pivotal role in worldwide carbon sequestration and climate change mitigation (Fig. 3).



**Figure 3:** Seagrass ecosystem services

### **BLUE CARBON POTENTIAL OF SEAGRASS ECOSYSTEMS**

Seagrass ecosystems are increasingly recognized as some of the most vital blue carbon habitats, playing a critical role in the long-term sequestration and storage of atmospheric carbon dioxide in coastal marine environments (Duarte et al. 2013; McLeod et al. 2011). Blue carbon refers to the carbon captured and stored by vegetated coastal ecosystems such as seagrasses, mangroves, and salt marshes, which collectively help combat climate change by removing carbon dioxide from the atmosphere and storing it in plant biomass and marine sediments (Pendleton et al. 2012; McLeod et al. 2011).

Seagrasses absorb carbon through photosynthesis by converting dissolved inorganic carbon into organic matter, which is incorporated into plant tissues such as leaves, roots, and rhizomes (Duarte et al. 2013; Hemminga and Duarte 2000). A large portion of this organic carbon is subsequently transferred to surrounding sediments via plant litter deposition, root turnover, and sediment trapping processes linked to the seagrass canopy structure (Duarte et al. 2013; Kennedy et al. 2010). Over time,

the accumulation of organic matter in anoxic sediments creates long-term carbon reservoirs beneath seagrass meadows.

One of the key features of seagrass ecosystems is their remarkably ability to store carbon in sediments over extended periods. Seagrass sediments often contain large amounts of organic carbon that can remain buried for centuries or even thousands of years because of slow decomposition rates under low-oxygen conditions (Duarte et al. 2013; Fourqurean et al. 2012). Although seagrass meadows cover less than 0.2% of the global ocean floor, they are responsible for about 10% of the ocean's annual carbon burial, highlighting their important role in global carbon sequestration (Fourqurean et al. 2012).

Global assessments estimate that seagrass ecosystems store significant amounts of carbon in their sediments and biomass, with global seagrass carbon reserves reaching several petagrams of carbon (Macreadie et al. 2017; Fourqurean et al. 2012). Carbon burial rates in seagrass meadows are among the highest observe in marine ecosystems, often surpassing those in terrestrial forests on a per-area basis (Alongi 2014; Duarte et al. 2013). These findings have increased recognition of seagrass ecosystems as valuable natural climate solutions that can aid carbon mitigation. The potential of seagrass ecosystems for blue carbon storage is particularly significant in tropical areas such as Southeast Asia, where high primary productivity and suitable conditions foster the growth of extensive seagrass meadows (Fortes et al. 2018; Alongi 2014). Tropical seagrass systems frequently have high biomass and sediment carbon storage, especially in habitats with fine sediments and stable water movement (Macreadie et al. 2017; Kennedy et al. 2010). Therefore, protecting and restoring seagrass ecosystems in tropical coastal areas is a promising way to boost coastal carbon storage and aid climate change mitigation efforts.

However, the ability of seagrass ecosystems to serve as effective carbon sinks heavily relies on ecosystem integrity and long-term habitat stability. Disturbances such as coastal development, eutrophication, dredging, and physical damage can degrade and loss of seagrass meadows, which may then release stored sediment carbon back into the water column and atmosphere (Macreadie et al. 2017; Pendleton et al. 2012). Therefore, conserving and restoring seagrass habitats are increasingly seen as essential parts of global blue carbon strategies.

## **FACTORS INFLUENCING CARBON STORAGE IN SEAGRASS MEADOWS**

The ability of seagrass ecosystems to store and sequester carbon varies widely across different geographic regions and habitat types, influenced by multiple interacting biological and environmental factors. Carbon stocks within seagrass meadows are affected by elements such as species composition, plant morphology, sediment characteristics, hydrodynamic conditions, and ecosystem productivity, all of which control both the generation of organic carbon and its long-term preservation in the sediments below (Duarte et al. 2013; Fourqurean et al. 2012; Kennedy et al. 2010). Biological traits regulate carbon production, while sediment properties and hydrodynamic conditions influence organic carbon burial and preservation. Both autochthonous and allochthonous inputs contribute to carbon stocks, collectively determining the magnitude and persistence of blue carbon in coastal ecosystems. In tropical coastal systems, especially in Southeast Asia, landscape connectivity to nearby habitats like mangroves and estuaries further influences carbon storage. These habitats supply additional organic inputs and enhance sediment carbon accumulation (Fortes et al. 2018; Rozaimi et al. 2017; Miyajima et al. 2015). Understanding these interactions is essential for accurately estimating blue carbon stocks and identifying habitats with high potential for long-term carbon sequestration.

### **Biological Controls: Species Traits and Morphology**

Species composition and plant morphology are crucial in determining the carbon storage potential of seagrass ecosystems. Large canopy-forming species such as *Enhalus acoroides* and

*Thalassia hemprichii* generally produce more above- and belowground biomass than smaller pioneer species, leading to higher organic carbon inputs into surrounding sediments (Duarte et al. 2013; Hemminga and Duarte, 2000). Their extensive root and rhizome systems improve sediment stability, help trap suspended particles, and support long-term carbon burial by reducing sediment resuspension (Koch et al. 2009; Orth et al. 2006).

In contrast, smaller species such as *Halophila* spp. and *Halodule* spp. typically have lower biomass, shorter life cycles, and faster turnover rates and are often adapted to dynamic or disturbed environments (Kilminster et al. 2015). While these species contribute to primary production and early colonization, their relatively shallow root systems and lower biomass result in smaller sediment carbon pools than those of larger climax species (Duarte et al. 2013; Hemminga & Duarte, 2000). Consequently, variations in species composition and morphological traits across various areas cause variation in carbon storage capacity among seagrass meadows.

### **Sediment Controls on Carbon Retention**

Sediment properties are crucial for organic carbon accumulation and long-term preservation in seagrass ecosystems. Fine-grained sediments, such as silts and clays, generally support higher levels of organic carbon because they can facilitate the deposition and retention of organic particles while restricting oxygen penetration into the sediment column (Fourqurean et al. 2012; Kennedy et al. 2010). Limited oxygen availability slows microbial decomposition, enabling organic carbon to be preserved over longer periods.

In contrast, coarse sandy substrates are more permeable, allowing greater water exchange and oxygen penetration, which can accelerate microbial decomposition and reduce long-term carbon storage capacity (Macreadie et al. 2017). This pattern is especially clear in tropical seagrass systems, where meadows located in muddy, estuarine, or mangrove-influenced environments often have substantially higher sediment carbon stocks than those on exposed sandy substrates (Rozaimi et al. 2017; Miyajima et al. 2015). These results highlight the importance of sediment grain size and depositional environments in regulating carbon retention within seagrass meadows.

### **Sources and Inputs of Organic Carbon**

Although seagrasses produce organic carbon through their own primary production, much of the carbon stored in seagrass sediments originates from external sources. Many studies have shown that sediment carbon pools can include contributions from mangroves, phytoplankton, macroalgae, and terrestrial organic matter transported from nearby ecosystems (Duarte and Krause-Jensen 2017; Howard et al. 2017; Oreska et al. 2017; Miyajima et al. 2015; Kennedy et al. 2010).

Seagrass canopies reduce current flow and enhance the capture of suspended particles, causing the accumulation of allochthonous organic matter in meadow sediments (Duarte and Krause-Jensen, 2017). As a result, seagrass ecosystems act not only as sources of carbon but also as effective sediment traps that collect and hold organic material from surrounding areas. This process is especially important in tropical coastal systems where seagrass meadows are located near mangrove forests. Organic matter exported from mangroves can be transported into nearby seagrass habitats and later buried in sediments, greatly contributing to overall carbon stocks (Miyajima et al. 2015; Kennedy et al. 2010). In Southeast Asia, research indicates that a significant portion of carbon in seagrass sediments may originate from mangroves, underscoring the role of cross-ecosystem carbon transfer in coastal blue carbon dynamics (Fortes et al. 2018; Rozaimi et al. 2017).

### **Hydrodynamic and Environmental Conditions**

Hydrodynamic conditions and environmental gradients further affect carbon storage by affecting sediment stability and organic matter accumulation. Seagrass meadows in sheltered areas, such as lagoons, estuaries, and enclosed bays, typically experience lower wave energy and increased sediment deposition, which promotes organic carbon accumulation and long-term storage (Kennedy et al. 2010; Koch et al. 2009). Conversely, meadows exposed to strong currents and wave action face higher sediment resuspension, which can reduce carbon retention.

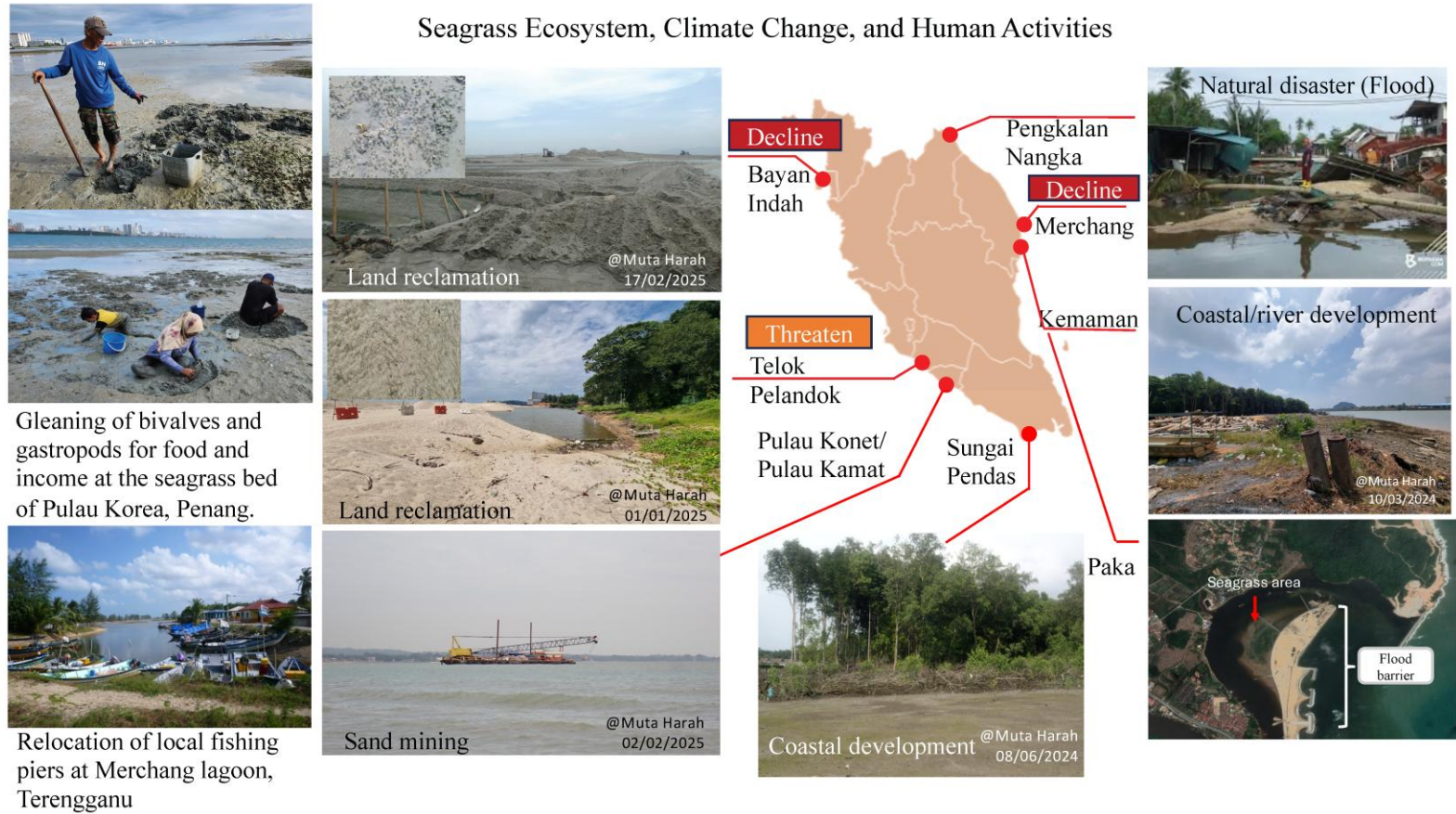
Environmental factors such as water depth, light availability, and nutrient levels also affect seagrass productivity and its ability to sequester carbon. High primary productivity boosts the input of organic material into sediment carbon stores through litter deposition and root turnover (Duarte et al. 2013). However, excessive nutrient enrichment can destabilize seagrass habitats by encouraging algal overgrowth and reducing light availability, which can lead to meadow degradation and potential carbon loss (Waycott et al. 2009).

### **THREATS TO SEAGRASS ECOSYSTEMS AND IMPLICATIONS FOR CARBON LOSS**

Despite their ecological importance and significant role in carbon sequestration, seagrass ecosystems are declining globally. Human activities such as coastal development, eutrophication, sedimentation, destructive fishing practices, and climate change have sped up the deterioration and loss of seagrass habitats in many regions (Waycott et al. 2009; Orth et al. 2006). These threats not only reduce seagrass coverage and biodiversity but also affect the stability of carbon stored in seagrass sediments. Coastal development and land reclamation are especially major threats in rapidly growing coastal areas like Southeast Asia. Activities such as dredging, port construction, and shoreline modification can directly remove seagrass beds or disturb sediment dynamics and water quality, leading to habitat loss (Fortes et al. 2018; Unsworth et al. 2018). Increased sedimentation related to coastal development can decrease light penetration in the water, limiting photosynthesis and ultimately causing seagrass decline (Orth et al. 2006). In Malaysia, human activities like coastal development, land reclamation, and natural phenomena (e.g., climate change) pose major threats in fast-growing coastal regions (Fig. 4).

Eutrophication caused by nutrient runoff from agriculture, sewage discharge, and aquaculture is another major factor in seagrass loss. Elevated nutrient levels can promote the growth of phytoplankton and epiphytic algae, thereby reducing light available to seagrass leaves and hindering plant growth (Waycott et al. 2009; Burkholder et al. 2007). Long-term eutrophication can lead to widespread meadow degradation and ecosystem collapse. Physical disturbances like boat anchoring, trawling, and coastal construction can also harm seagrass beds by uprooting plants and disrupting sediment stability (Waycott et al. 2009; Burkholder et al. 2007). These activities often fragment seagrass meadows and weaken their role as sediment stabilizers and carbon sinks (Unsworth et al. 2018; Orth et al. 2006). The decline of seagrass ecosystems has serious implications for blue carbon storage.

### Seagrass Ecosystem, Climate Change, and Human Activities



**Figure 4.** Rapid coastal development and rising pollution threaten to erode seagrass habitats. Once the root mat is disturbed, centuries of stored carbon can be released within years

When seagrass meadows are disturbed or destroyed, organic carbon buried in sediments can become exposed to oxygen, speeding up microbial decomposition and releasing stored carbon into the water or atmosphere (Macreadie et al. 2017; Pendleton et al. 2012). In such situations, seagrass ecosystems may change from long-term carbon sinks to sources of greenhouse gases.

Previous studies have shown that the loss of vegetated coastal ecosystems, including seagrasses, mangroves, and salt marshes, may significantly contribute to global carbon emissions associated with coastal habitat degradation (Pendleton et al. 2012). As a result, protecting existing seagrass meadows and restoring degraded habitats have become key priorities in blue carbon conservation efforts to combat climate change. Given the rapid coastal development across much of Southeast Asia, conserving seagrass ecosystems is especially crucial in this region. Improving coastal management policies, enhancing environmental monitoring, and promoting ecosystem-based management approaches will be vital to reducing human pressures and maintaining the carbon sequestration capacity of seagrass ecosystems.

### **SEAGRASS RESTORATION AND CONSERVATION FOR BLUE CARBON**

The growing recognition of seagrass ecosystems as key blue carbon sinks underscores the need to protect existing meadows and restore degraded habitats. Seagrass meadows store large amounts of organic carbon in both plant biomass and underlying sediments, making them key players in long-term coastal carbon storage (Duarte et al. 2013; Fourqurean et al. 2012). Efforts focused on conserving and restoring seagrass ecosystems are increasingly valued as nature-based solutions that help mitigate climate change while also boosting coastal biodiversity, fisheries productivity, and ecosystem resilience (Unsworth et al. 2019; Macreadie et al. 2017).

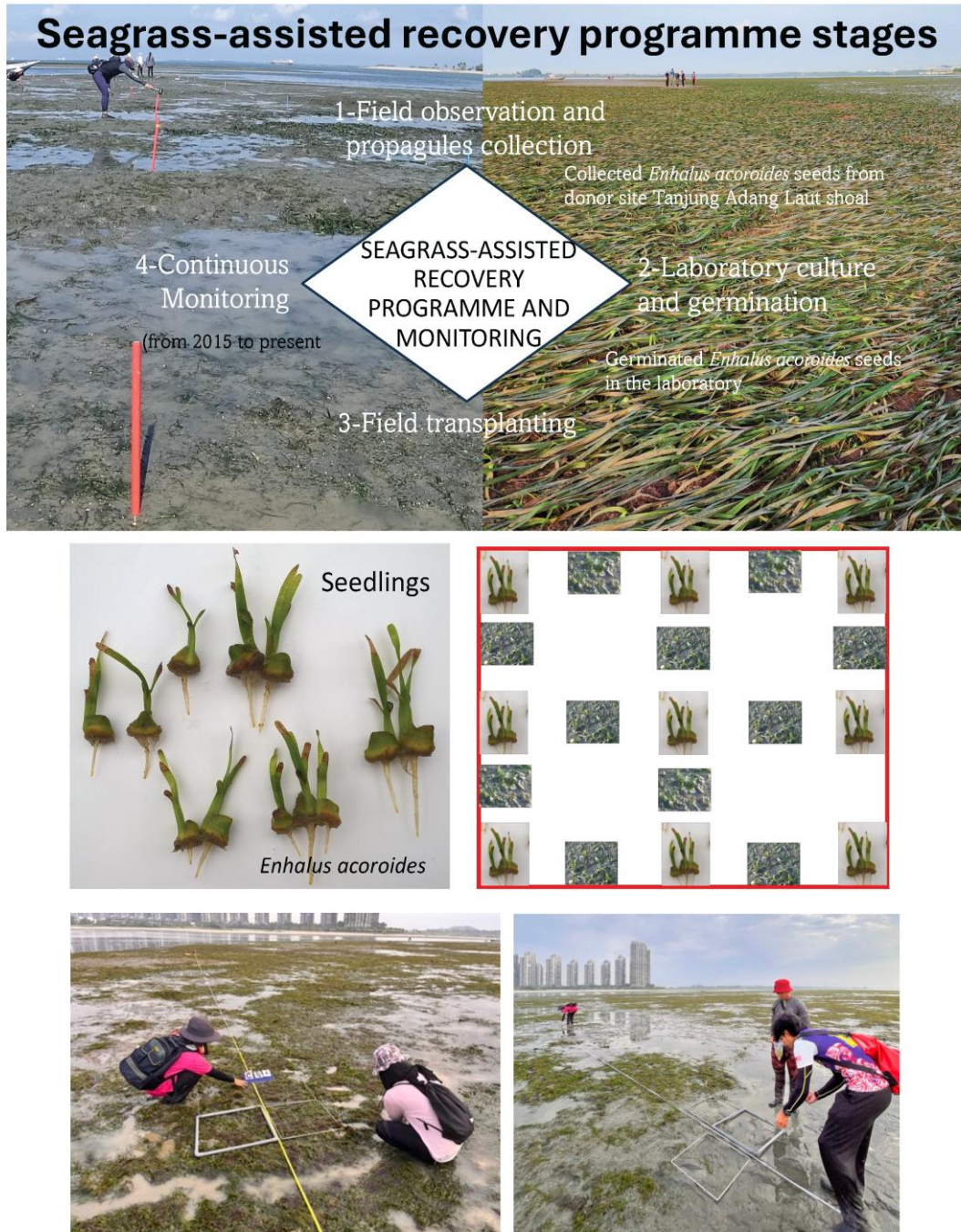
Various restoration methods have been developed to help the recovery of degraded seagrass habitats. Among these, transplanting vegetative shoots or sods from donor meadows has historically been one of the most commonly used techniques, especially for species that spread through rhizome growth (Orth et al. 2006; Fonseca et al. 1998). The success of vegetative transplantation mainly depends on environmental factors like sediment stability, water clarity, and hydrodynamic conditions, which influence the survival and growth of transplanted shoots (van Katwijk et al. 2016).

In Southeast Asia, restoration research has been vital in developing seagrass transplantation methods and improving ecological understanding of meadow recovery. Early restoration efforts in the Philippines demonstrated the possibility of reestablishing tropical seagrass species in disturbed coastal areas (Fortes et al. 2018; Fortes 1990). In Indonesia, studies by Kiswara and Rappe further advanced restoration techniques by evaluating transplantation methods and community-based programs aimed at restoring seagrass in degraded coastal ecosystems (Rappe et al. 2013; Kiswara 2004). These regional efforts have helped create practical restoration strategies suited to tropical coastal environments.

Recently, seed-based restoration methods have gained more attention as alternative strategies for seagrass rehabilitation. Unlike vegetative transplantation, seedling-based restoration can enhance genetic diversity while reducing pressure on donor meadows. Studies in Malaysia have shown that transplanting seedlings of tropical species such as *Enhalus acoroides* can successfully support meadow recovery under suitable environmental conditions. Long-term monitoring in the Sungai Pulai estuary has revealed that seedling transplantation helps establish stable seagrass patches and aids sediment stabilization in disturbed coastal habitats (Zakaria et al. 2025, Fig. 5). These results suggest that seed-based approaches could be a promising option for restoring large tropical seagrass species that produce viable seeds and seedlings.

Despite advances in restoration techniques, conserving existing seagrass ecosystems remains the most effective way to protect blue carbon stocks. Mature seagrass meadows store organic carbon in

sediments for long periods, and disturbance or removal of these habitats can release this stored carbon into the environment (Macreadie et al. 2017; Pendleton et al. 2012).



**Figure 5:** Long-term monitoring in the Sungai Pulai estuary has shown that seedlings of *Enhalus acoroides* and mixed transplants with *Halophila ovalis*/*H. major*/*H. spinulosa*

Therefore, protecting healthy seagrass habitats through marine protected areas, integrated coastal management, and enhanced environmental monitoring is crucial for maintaining their long-term carbon storage capacity (Unsworth et al. 2019).

Given the rapid coastal development across Southeast Asia, enhancing conservation and restoration efforts will be crucial for maintaining the ecological functions of seagrass ecosystems. Integrating seagrass conservation and restoration into blue carbon management and coastal planning strategies can provide valuable opportunities to boost climate mitigation while maintaining coastal ecosystem resilience.

## **KNOWLEDGE GAPS AND FUTURE RESEARCH DIRECTIONS**

Although there is growing recognition of the ecological and climate-regulating importance of seagrass ecosystems, many knowledge gaps still exist in understanding their role in global blue carbon dynamics. While significant progress has been made in quantifying carbon stocks in temperate seagrass ecosystems, data from tropical regions, especially Southeast Asia, remains limited (Miyajima et al. 2015; Fourqurean et al. 2012). Since Southeast Asia has one of the highest diversities of seagrass species and expansive shallow coastal habitats, improving regional carbon stock assessments is essential for developing more accurate global blue carbon estimates (Unsworth et al. 2019; Fortes et al. 2018).

Another significant research gap involves the impact of species-specific traits and habitat variability on carbon sequestration potential. Seagrass species vary greatly in morphology, growth strategies, and biomass allocation patterns, which can affect sediment stabilization and organic carbon accumulation (Duarte et al. 2013; Hemminga and Duarte 2000). However, comparative studies examining how morphological plasticity and habitat adaptation influence carbon storage remain limited, particularly for tropical species. Understanding these connections is crucial for identifying species and habitats with the highest carbon sequestration potential and for enhancing restoration efforts.

Furthermore, the role of external carbon sources in seagrass sediment carbon pools needs further research. While past studies indicate that a large portion of sediment carbon in seagrass meadows may come from mangroves, phytoplankton, or terrestrial sources, the contributions of these sources can vary greatly across regions and environments (Duarte and Krause-Jensen 2017; Kennedy et al. 2010). Understanding of how carbon is transferred between mangroves, seagrasses, and nearby coastal habitats is crucial for improving blue carbon accounting methods.

Another emerging field of research involves combining genetic and ecological studies to better understand the resilience and adaptive capacity of seagrass populations. Genetic diversity affects the ability of seagrass populations to respond to environmental stressors, including climate change, coastal development, and habitat fragmentation (Unsworth et al. 2019; Orth et al. 2006). However, studies linking genetic variation to habitat characteristics and ecosystem functioning remain limited, particularly for tropical seagrass species.

Finally, although restoration efforts have increased in recent years, many projects still have limited spatial scope and lack long-term monitoring. Better assessment of restoration outcomes, including survival, meadow growth, and carbon accumulation, is essential to evaluate the effectiveness of different restoration methods (Macreadie et al. 2017; van Katwijk et al. 2016). Integrating long-term ecological monitoring with blue carbon assessments is essential for measuring how restoration programs contribute to climate mitigation and ecosystem recovery.

Addressing these research gaps is vital for improving our understanding of seagrass ecosystem functions and highlighting the significance of seagrass meadows in global blue carbon efforts. Future research should emphasize interdisciplinary approaches that combine ecological, biogeochemical, and genetic insights to better understand the resilience and carbon storage potential of seagrass ecosystems.

## CONCLUSION

Seagrass ecosystems are among the most vital coastal habitats for supporting biodiversity, stabilizing sediments, and regulating carbon processes in marine environments. As a crucial part of global blue carbon systems, seagrass meadows play an important role in capturing and storing atmospheric carbon dioxide in both plant biomass and sediments below. Their ability to function as long-term carbon sinks depends on various interacting factors, including species composition, plant morphology, sediment properties, water movement, and the degree to which the landscape is connected to neighboring coastal habitats. In Southeast Asia, seagrass meadows exist across diverse coastal environments and significantly contribute to regional ecological productivity and coastal resilience. However, these ecosystems face increasing threats from coastal development, sediment accumulation, eutrophication, and climate-related disruptions. These threats not only endanger seagrass biodiversity and ecosystem functions but may also disrupt long-term sediment carbon storage, potentially transforming seagrass meadows from carbon sinks into sources of greenhouse gases.

Restoration and conservation efforts are crucial for preserving the ecological and climate-regulating functions of seagrass ecosystems. Recent studies show that both vegetative transplantation and seedling-based restoration can help recover degraded seagrass habitats when environmental conditions are appropriate. Specifically, restoration projects involving tropical species like *Enhalus acoroides* demonstrate the potential of assisted recovery techniques to enhance sediment stabilization and improve long-term ecosystem resilience.

Despite growing scientific interest, several research gaps remain in understanding the carbon dynamics and ecological roles of tropical seagrass ecosystems. Future studies should focus on improving regional carbon stock assessments, examining how species traits and habitat variability influence carbon sequestration, and utilizing ecological, genetic, and biogeochemical methods to better evaluate seagrass resilience and restoration success.

Strengthening conservation policies, increasing restoration efforts, and expanding scientific research are essential for protecting seagrass ecosystems and maintaining their vital role in coastal climate mitigation strategies. Protecting and restoring seagrass beds will not only preserve biodiversity and ecosystem services but also contribute significantly to global efforts to fight climate change and ensure coastal ecosystems remain healthy.

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