

Carbon Sequestration Potential of Mangroves in Southeast Asia

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1 Introduction

Mangrove forests are considered to be a unique and complex major component of coastal zones in the tropical and sub-tropical regions. They represent transitional ecosystems where the ocean, land, and freshwater meet. Their main vegetation components are generally evergreen trees or shrubs that grow along coastlines, brackish estuaries or delta habitats. Mangrove habitats are easily recognized as they are located at tideland mud or sand flats inundated daily with sea water. They not only play critical roles in ensuring sustainability of coastal ecosystems, but also in fulfilling important socio-economic benefits to coastal communities.

Mangroves are formed in swampy areas with low oxygen conditions prevailing below the first few centimeters. Mangrove trees produce aerial roots that have the three functions of providing gas exchange, water uptake, and support to older trees. To overcome the low amount of oxygen, many mangrove trees including *Sonneratia* spp., *Avicennia* spp., *Brugueira* spp., *Ceriops* spp., and *Rhizophora* spp. develop aerial root systems above the anaerobic substrate to allow gas exchange through the lenticels of the roots (Tomlinson, 1986). These roots also provide lateral support for the trees permitting them to withstand waves and winds in the environment (Lugo, 1990). Many mangrove species, such as those listed above, produce seeds that germinate and develop into seedlings while still attached to the parent tree known as vivipary (Duke, 1992; Abbott, 1994). Viviparity allows propagules to root more rapidly after dispersal when lodged in the mud. This is an important adaptation for propagules establishing themselves in tidal environment (Lugo, 1990).

Mangrove forests' latitudinal distributions are correlated with sea-surface temperature, and tend to mirror coral reef and sea grass bed conditions (Duke, 1992). Optimal growth conditions for mangroves are high humidity, high year-round

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rainfall, a large intertidal range, and a moderate amount of land runoff (Clough, 1993). With many areas containing these conditions, Southeast Asia contains the richest species composition and more than one-third of the world's mangroves (FAO, 1985). Mangrove ecosystems may provide important nutrients and organic carbon to tropical coastal oceans (Alongi, 1996). In addition, they may intercept terrestrial-derived nutrients, pollutants and sediments before they reach the coastal ocean, alleviating problems due to high loading of these anthropogenic constituents (Valiela & Cole, 2002).

Similar to the tropical rainforests, mangrove forests continue to be degraded at rapid rates through different types of human activities (Saenger et al., 1983; Hamilton & Snedaker, 1984). In contrast to tropical rainforests, however, mangroves lack high level of research and conservation efforts, which result in limited understanding of these ecosystems. As mangrove ecosystems represent substantial connections between coastal habitats and terrestrial systems, their degradation could affect the ecological stability of coastal zones.

The purpose of this chapter is to provide an overview of the potential roles of mangroves in sequestering carbon from the atmosphere. The potential importance of mangroves in the global carbon cycle and in offsetting global climate change is highlighted. Specifically, this chapter describes the distribution and abundance of mangroves, discusses the major ecological and economical roles, and highlights the contribution of mangroves for conservation of biodiversity. In addition, the major threats to these ecosystems and their rates of destruction are also discussed. Finally, the potential of mangrove biomass to offset carbon emission in contributing carbon content stabilization in the atmosphere is discussed.

2 Distribution and Abundance

2.1 *Global*

While there are general estimates available on total area of mangrove forests in the world, the extent on the globe is not exactly known. This could be due to differences in assessment methods, definitions, or inconsistent sources of statistics in different countries. Table 1 presents a global extent of mangrove area estimates derived from various published sources.

The first attempt to provide global mangrove area estimates was undertaken in 1980 by FAO as part of Tropical Forest Resource Assessment initiatives (FAO, 1981). The total of mangrove areas in that year was estimated to be 15.6 million hectares, based on data sets collected from a total of 51 countries (Table 1). More recent attempts showed that the estimates of world mangroves are found to be vary, which could partly be due to the different numbers of countries included in the estimates.

Table 1 Global extent of previous mangrove area estimates (FAO, 2003)

Reference	Reference year ^a	Number of countries included	Estimated total area (ha)
FAO/UNEP (1981)	1980	51	15,642,673
Saenger et al. (1983)	1983	65	16,221,000
FAO (1994)	1980–1985	56	16,500,000
Groombridge (1992)	1992	87	19,847,861
ITTO/ISME ^b (1993)	1993	54	12,429,115
Fisher and Spalding (1993)	1993	91	19,881,800
Spalding et al. (1997)	1997	112	18,100,077
Aizpuru et al. (2000)	2000	112 ^c	17,075,600
FAO (2003)	2003	112	14,653,000

^aExcept for FAO/UNEP (1981) and Aizpuru et al. (2000), the reference year is the year of the publications in which the estimate is cited, not the weighted average of all the national area estimates

^bCombined figure from three publications by Clough (1993), Diop (1993), and Lacerda (1993)

^cNew estimates were provided for 21 countries, and for the remaining countries the study relied on Spalding et al. (1997)

The most recent estimates by FAO, taking into account a total of 112 countries, indicated that the current mangrove area is 14.6 million hectares world wide (FAO, 2003). This figure suggests that the world extent of mangrove areas decreased about 1 million hectare or 6.4% in two decades. This estimate was undertaken based on a collection of more than 2,800 national and sub-national data sets, that covered all included countries and areas where mangroves are known to exist, with the earliest estimates dating back to 1918. This is followed by a compilation of an updated list of the most recent, reliable estimate for each country. Regression analyses were performed using existing reliable data over time for each country, which provided estimates for 1980 and 1990 and an extrapolated estimate for 2000 for each country.

2.2 Southeast Asia

Southeast Asia covers an area of about 4,100,000 km². It is a sub-region of Asia, consisting of eleven countries that are geographically located at south of China, east of India and north of Australia. This sub-region consists of two geographic regions: the mainland and maritime. The mainland consists of Cambodia, Laos, Myanmar, Thailand and Vietnam whereas the maritime section consists of the Brunei, Timor Leste, Indonesia, Malaysia, Philippines and Singapore.

Southeast Asian mangroves recorded the highest diversity of all the world's mangroves (Fig. 1). An estimate of the spatial extent of mangroves in Southeast

Asia reported that the region contains over 6.1 million hectares of mangroves, approximately 35% area of global mangrove vegetation. In terms of species diversity, Southeast Asia holds nearly 75% of the world's mangrove species with the highest species diversity found in Indonesia with 45 species, followed by Malaysia (36 species) and Thailand (35 species) (Table 2). A list of plants commonly found in mangrove forests in Malaysia is presented in Appendix.

The global distribution of mangroves stretches into the higher latitudes to about 40° north and south with the main distribution in the tropical and sub-tropical areas, and the majority of mangrove areas in Southeast Asia (Ong et al., 1995; FAO, 2003). The largest area of mangrove occurs in the zone from 0° to 10° of both north and south latitudes (Twilley et al., 1992). As can be seen in Table 2, the most extensive area of mangroves in Southeast Asia found is Indonesia, followed by Malaysia and Myanmar. These three countries account for about 86% of all mangroves in Southeast Asia.

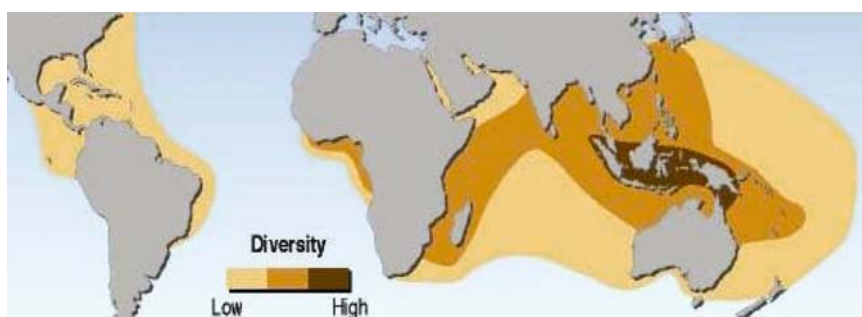


Fig. 1 Global distribution of mangrove diversity (UNEP, 2002)

Table 2 Mangrove area estimates for Southeast Asia (FAO, 2003)

Country	Mangrove area (ha)	Reference year	No. of mangrove species
Brunei	17,100	1992	29
Cambodia	72,835	1997	5
Indonesia	3,493,110	1988	45
Laos	N/A	N/A	N/A
Malaysia	587,269	1995	36
Myanmar	452,492	1996	24
Philippines	127,610	1990	30
Singapore	500	1990	31
Thailand	244,085	2000	35
Timor Leste	3,035	2000	N/A
Vietnam	252,500	1983	29

3 Mangrove Forest Destruction

Despite a better understanding towards their diversity and multiple roles, mangrove ecosystems are identified as among the most threatened habitats on Earth. Mangrove habitat destruction through human encroachment has been the primary cause of mangrove loss. Findings from mangrove resource assessments revealed alarming levels of mangrove destruction. Although scientists cannot determine exactly how extensive mangroves were before people began to alter coastlines, based on historical records, anywhere from 5% to nearly 85% of original mangrove areas in various countries is believed to have lost (World Resources Institute, 2000). Over the last 50 years or so, mangroves have disappeared and continued to be degraded by many activities such as land reclamation, sedimentation, pollution, extraction, conversion, prolonged flooding, and freshwater intrusion.

Tabuchi (2003) estimated that on a global scale, the area under mangroves is shrinking by 100,000 hectares annually due to clear cutting of timber and conversion into aquaculture projects. The loss of mangroves in Gili Petagan, Indonesia occurred as a result of intensive extraction of fuel-wood during 1970s. In Thailand, about 65% of the area of mangroves was lost during 1976–1991 due to an expansion of shrimp farming in the central, east coast, and south east regions of the country (Aksornkoae et al., 1993); MacKinnon (1997) estimated that by the early 1990s, Myanmar had lost almost 75% of the original extent, Vietnam had lost 37%, and Thailand 84%. By the mid of 1980s, Brunei and Philippines had lost 20% and 67% of their original mangrove cover, respectively. Earlier estimates suggested that by early 1980s, Indonesia had lost 55% of its mangroves. Chan et al. (1993) estimated that Malaysia had lost 12% of its mangrove forests between 1980 and 1990. According MacKinnon (1997), by 1993, about 74% of mangrove area in Malaysia was lost from their original extent. In a few regions (i.e., Latin America and the Caribbean), however, the mangrove area is increasing as a result of plantation forestry and natural regeneration. The lack of adequate data on changes in mangrove for some Southeast Asian countries prevents efforts to report trends for the region as a whole.

In the most recent study, Ahmad and Suratman (2007) conducted a change detection analysis of mangrove forests utilizing a time series of Landsat TM imagery in Pulau Indah (literally translated means “Beautiful Island”) and its vicinity, Malaysia. This analysis was focused on determining mangrove reduction rates and identifying their spatial patterns within two interval periods, 1995 to 1999 and 1999 to 2005 (Fig. 2). Results from the analysis suggested there has been a decline in mangrove forests during both intervals at the rates of 14.1% and 1.9%, respectively. The higher declining rate during the first interval was primarily due to expansion and land development for building seaport infrastructures on this island. The estimated reduction rate of mangrove forests for the 10 year-period was 1.6% per year, which is slightly higher that reported nationally by Ong (1982) over the past 20 years (i.e., 1% per year).



Fig. 2 Decline of mangrove forests in Pulau Indah, Malaysia. Area in dark green represents mangrove forests (Ahmad & Suratman, 2007)

4 Services and Functions Provided by Mangroves

4.1 Resources and Socio-economic Contribution

In terms of area, mangrove forests only occupy about 8% of the world's coast (World Resources Institute, 2000). However, despite their small proportion, they play important roles in global ecosystem. In many developing nations in the tropics, mangrove forests have been traditionally utilized by the indigenous and local people for a variety of purposes. They have been dependent on mangrove waters for centuries for fishes, shrimps, crabs, and mollusks and will continue to rely on these products from mangrove habitats. It has been estimated that 60% of the commercial catch in Fiji depends on mangroves (Hamilton & Snedaker, 1984). Along the Caribbean coast of Colombia, approximately 70% of the local fisheries are dependent on mangrove swamps in the Cienaga Grande (Bossi & Citron, 1990).

Mangroves also provide local people with a large variety of timber for construction, firewood, charcoal, poles, fishing gear, and etc. Other products collected from mangrove include fruit, honey, pulp, tannin, (Hamilton & Snedaker, 1984) and traditional medicines from many parts of the plants (Bandaranayake, 1998).

4.2 Ecological and Biodiversity Conservation

The important ecological functions and conservation of biodiversity of mangroves are being recognized in a number of studies. Among the most commonly known and discussed roles of mangroves are those of providing coastal protection against storms, waves and water currents, thus reducing erosion and flooding (Othman, 1994). Mangroves also perform an important function in impeding saltwater intrusion. The ability of mangrove forests to provide shoreline stabilization and storm protection are due to their location in hurricane and typhoon-prone tropical areas

(Primavera, 1995). Prop roots, deeply anchored in mud, help enhance soil consolidation and stability, which provides a good form of natural coastal protection (Siddiqi, 1993). A number of studies have confirmed the function of mangroves in terms of a green belt (Ruitenbeek, 1992; Janssen & Padilla, 1999; Suthawan, 1999; Danielsen et al., 2005; IUCN, 2005). According to Danielsen et al. (2005), an area of mangroves, 100 m wide, with a mangrove density of two or three trees every metre could decrease the height of waves by an estimated 70%. Although some young mangroves may be destroyed by natural disasters, some mature mangroves can survive due their complicated root systems (IUCN, 2005).

There have been several studies showing the beneficial role of mangrove natural features that can help reduce the damage caused by extreme natural phenomena such as tsunamis. Many articles highlighted mangrove ecosystems, because they are one of the most dominant ecosystems in coastal areas, particularly those located in the tsunami-impacted regions. For example, according to Dahdouh-Guebas (2006), the areas covered with mangroves in the Andaman Islands received only 7% of damage, while the areas of the Islands where mangrove had been degraded had an estimated 80% to 100% of the damage. Ghosh (2005) reported that in the southern part of India, with dense mangroves, fewer people suffered from a tsunami and less property was destroyed compared to the areas without mangroves. In Malaysia, Emmanuel and John (2005) reported that Penang Island showed less effect from the waves since the presence of mangrove forests acted as riparian buffers.

The importance of mangrove ecosystems in conservation of biodiversity continues to be a topic of interest. Mangroves provide protective habitat for spawning, nursery, and feeding ground for juvenile fish and crustacean species that spend part of their lives in these habitats (Sasekumar et al., 1994). Mangroves contribute many different functional ways to fisheries. These include contributing nutrients to support an elaborate food web within the mangroves, exporting-derived nutrients offshore to enhance fisheries, or providing habitat to fauna for shelter and nursery grounds (Robertson et al., 1992; Clough, 1993; Marshall, 1994). Mangroves also provide shelter to a wide variety of mammals, amphibians and reptiles. Many other animals such as birds, marine and terrestrial mammals use or visit the mangroves for roosting, nesting, or feeding on a daily or seasonal basis (Hamilton & Snedaker, 1984).

The flora and fauna diversity in mangrove ecosystems provide scientific study and offer tourism opportunities. For example, in Malaysia, Kampung Kuantan is well known for its unique twinkling fireflies (*Photuris lucicrescens*) that live on *Sonneratia caseolaris* trees growing gregariously along river banks. Fireflies are found in marshes or in wet areas where their larvae have more abundant sources of food. The diet of adult fireflies feed on nectar from *S. caseolaris*.

Mangroves also play important roles in creating healthy coastal ecosystems. Adeel and Pomeroy (2002) reported that leaf litter from mangroves provides a principal source of nutrients for the trophic food as the ecosystems produce high productivity of organic matter. For example, the average of leaf litter input rate is 100 g m⁻² year⁻¹ despite relatively low standing biomass accumulation averaged at 1,500 g m⁻². The high productivity is often attributed to high litter degradation rates and efficient recycling of nutrients (Bouillon et al., 2002).

5 Carbon Sequestration in Mangrove Forests

The essential elements of the carbon cycle are shown in schematic diagram of Fig. 3. The carbon budget is closely linked to three major components: terrestrials, coastal and oceans (Twilley et al., 1992). Coastal ecosystems are narrow transition zones between terrestrial and ocean areas, dominated by mangroves, shallow submerged coral reefs and sea grasses coastal oceans. The rate at which carbon cycles through the ecosystem is determined by a number of processes, particularly the rates of primary productivity and decomposition. Both processes are strongly influenced by environmental conditions such as temperature and precipitation. As part of the carbon cycle, autotrophs from terrestrial and coastal ecosystems acquire CO_2 in the atmosphere from photosynthesis by diffusion through leaf stomata, thereby incorporating the CO_2 into their biomass. Some of biomass becomes a carbon source for consumers and respiration returns CO_2 to the atmosphere. Photosynthesis and respiration form a link between terrestrial and coastal ecosystems and the atmosphere (Fig. 3). Carbon loss by photosynthesis is balanced by carbon release during respiration. Photosynthesis and respiration form a link between terrestrial and coastal ecosystems and the atmosphere (Fig. 3). Carbon loss by photosynthesis is balanced by carbon release during respiration.

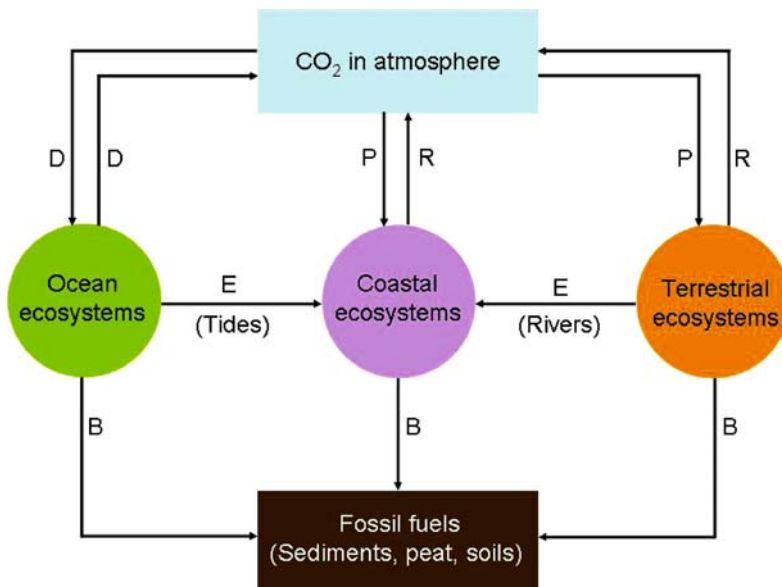


Fig. 3 A simple model for the carbon cycle as it occurs in ocean, coastal and terrestrial ecosystems. D = diffusion, P = photosynthesis, R = respiration, E = exchange, B = burial (Adapted from Twilley et al., 1992; Smith & Smith, 2003)

In ocean ecosystems, photosynthesis and respiration are also important but carbon cycling is more complex due to interaction of CO_2 with water. As the oceans contain more CO_2 than atmosphere and the land biosphere, CO_2 moves between the atmosphere and the ocean by molecular diffusion when there is a

difference in CO_2 gas pressure between the atmosphere and oceans. If CO_2 concentrations in the atmosphere and the surface water are in equilibrium, the net exchange would stop. However, this does not seem to occur, because the concentration of CO_2 in the atmosphere continues to rise as a result of fossil fuel combustion (Smith & Smith, 2003).

Dissolved CO_2 reacts with water to form carbonic acid, which reacts with limestone to form bicarbonates and carbonate ions. As CO_2 is used in photosynthesis, bicarbonates are reconverted to CO_2 . Thus bicarbonates serve as a CO_2 reservoir and some aquatic autotrophs can use dissolved bicarbonates directly as a carbon source.

Being strategically located between land and sea, mangroves in the coastal ecosystems are important interfaces in the exchange of sediment, organic materials and gasses between coastal and both terrestrial and ocean ecosystems. In coastal ecosystems, where dead material from mangrove forests fall into the water, organic material does not completely decompose. Carbon is stored as formed fossil fuels, which are created by the burial of raw humus, partially decomposed organic matter and peat. This potential for storage of carbon in peat may be an important carbon sink and will be discussed later in this chapter.

Mangrove forests may play an important role in the carbon cycle in removing CO_2 from the atmosphere and storing it as carbon in plant materials and soils in a process called sequestration. As about half of mass in trees is carbon, large amounts of carbon are potentially stored in mangrove forests and they may be the largest stores of carbon in coastal zones. To better understand the dynamic of organic matter cycling in mangroves, it is important to know the productivity of mangrove forests mainly in terms of primary production, biomass, litter production, carbon accumulation, and burial.

5.1 Primary Production

Primary production refers to the amount of material produced. It occurs through photosynthesis whereby mangrove plants convert solar energy, carbon dioxide, and water to glucose and eventually plant tissue. In coastal wetlands, this process is affected by changes in the physical and chemical environments, including the amount of solar radiation, water, nutrients, temperature, tides, soil type, oxygen concentration and pH (Twilley et al., 1992). In a study of tree growth and productivity in mangrove forests in Matang, Malaysia, Putz and Chan (1986) monitored the growth of *Rhizophora apiculata* trees from 1920 through 1981. They found that the net primary productivity rate of *R. apiculata* averaged $177 \text{ g m}^{-2} \text{ year}^{-1}$. The mean mortality rate for trees more than 10 cm dbh was 3% per year. In another study, Ong et al. (1979) reported that the net productivity rate of a managed mangrove forest in Malaysia ranged from 118 to $241 \text{ g m}^{-2} \text{ year}^{-1}$. In a study of the same tree species in Thailand, Aksornkoae (1975) estimated that the total net production of trees 11 to 14 years old was $24 \text{ g m}^{-2} \text{ year}^{-1}$. Christensen (1978) found that primary production rate for this species in mangrove forests of Phuket Thailand was 200 g m^{-2}

year⁻¹. In another study, Ong et al. (1995) estimated the biomass productivity rate in terms of above-ground (AB) net productivity for *R. apiculata* from Matang mangrove forest in Malaysia was 1,224 g m⁻² year⁻¹.

5.2 Biomass

In many cases, estimates of mangrove biomass are usually restricted to AB structures. There are only a few studies of estimation of both AB and below-ground (BG) biomass productions have been reported in Southeast Asia. For example, Komiyama et al. (2000) estimated that the total of AB and BG biomass accumulation of *Ceriops tagal* in southern Thailand was 1,798 g m⁻². The components of biomass accumulation, including the stem, branch, leaf, prop root and BG root were estimated as 534, 236, 133, 20, and 875 g m⁻², respectively. BG biomass of *C. tagal* was found to be higher than AB biomass which gave an AB:BG ratio of 1:05. In contrast, Twilley et al. (1992) found that the AB was higher than that of BG biomass in their global estimate of mangrove biomass. The AB and BG accumulation were 1,782 and 1,463 g m⁻², respectively, which gave the AB:BG ratio of 0.82. In Malaysia, AB biomass accumulation for *R. apiculata* ranged from 2,700 to 4,600 g m⁻² with a mean of 4,090 g m⁻² (Putz & Chan, 1980).

According to Twilley et al. (1992), the distribution of biomass accumulation throughout the tropical regions indicated that higher values occur at lower latitudes. Biomass production of mangrove decreased with latitude and a model was fit to the data resulting in: $Y = -7.29(X) + 298.5$ ($R^2 = 0.75$), where X is latitude and Y is predicted biomass (g m⁻²). This model was used to estimate the distribution of AB biomass of mangrove forests in latitudinal zones.

5.3 Litter Production and Decomposition

Mangroves are widely recognized as productive sources of plant debris which enters estuaries in the form of fallen leaves, twigs, and reproductive structures (May, 1999). Litter production is a commonly measured functional aspect of mangrove forests. It is an important component of the cycling of carbon and nutrients in mangrove ecosystems (Roderstein et al., 2005) and contributes to the food chains, through a leaf-detritus pathway, in the benthic coastal systems (Snedaker, 1978). The dissolved organic carbon (DOC) and particulate organic matter (POM) derived from this pathway becomes an important contributor to estuarine secondary productivity (Twilley, 1982); Snedaker (1978) reviewed important aspects of mangrove ecosystems and suggested that “the value of mangroves is accepted and based largely on the production of organic matter as leaf litter fall that enters the estuarine system, where it forms the basis of a complex food web”. Based on this information, global or local patterns of AB dynamics in mangrove ecosystems can be described.

The rate of litter decomposition can be affected by a number of factors, including species, tidal height, rainfall, feeding activities of marine invertebrates, temperature, which in turn affects the rates of organic carbon export from mangrove ecosystems (Twilley, 1982; Camilleri, 1992; Mackey & Smail, 1996; Wafar et al., 1997; Woitchik et al., 1997). As an example, litter decomposition rates vary between mangrove species. Kristensen et al. (1995) found that *Avicennia* spp. leaves decompose faster than those of *Sonneratia* spp. and *Rhizophora* spp. because they are thinner, contain lesser tannins, and sink faster. Lu and Lin (1990) found that litter of *Bruguiera* spp. decomposes quickly, in contrast, *Aegiceras* spp. decomposes slowly (Tam et al., 1990).

Twilley et al. (1992) reported that values of litter productivity from mangrove forests world-wide range from 20 to 160 g m⁻² year⁻¹. In Tritih, central Java, Indonesia, Sukardjo and Yamada (1992) estimated that the litter production rate of *R. mucronata* plantations ranged from 71 to 104 g m⁻² year⁻¹ of dry weight with leaf litter making up 73–84% of the total. Litter fall, leaf production, and propagule production were measured by Clough et al. (2000) in monocultures of the mangrove *R. apiculata* aged from 6 to 36 years in Ca Mau Province, southern Vietnam. They found that total annual litter fall ranged from 94 to 188 g m⁻² year⁻¹ of dry weight. They observed a similar trend as Sukardjo and Yamada's where leaf litter was the main component of litter fall in all stands studied.

The variability of export of leaf litter and detritus from mangrove zones has been attributed to the differences in hydrology, mangrove types, dominant species and stages of development (Odum et al., 1982; Day et al., 1996; Chen & Twilley, 1999). Twilley et al. (1992) estimated that export of organic carbon from mangrove forests ranges from 10% to 50% of litter production. In Malaysia, Gong and Ong (1990) determined the quantitative relationship between the export of material and the areal extent of mangroves in Matang mangrove forest reserve. Using the figure of 50% export, the export of biomass through leaf litter was estimated as 193.5 g C m⁻² year⁻¹. This information supports the importance of mangroves in the export of organic carbon, and also their role as carbon sinks.

Many studies have estimated the total carbon and nutrient accumulation in mangrove forests but limited studies have been conducted for Southeast Asia. BG carbon accumulation was examined for mangrove forests in Pohnpei Island, Micronesia by Fujimoto et al. (1999). They estimated that carbon accumulation rate was 93 g C m⁻² year⁻¹ in conjunction with a sedimentation rate of 2 mm year⁻¹ during sea-level rise phases, but may be higher in other sites where higher accretion rates have been observed. In western Australia, Alongi et al. (2003) estimated that the BG (in soil, live and dead roots) carbon accumulation for *R. stylosa* and *Avicennia marina* forests ranged between 1,400 to 3,300 g C m⁻² and 1,200 to 3,600 g m⁻², respectively.

In subtropical mangrove forests, senescent leaves of *R. mucronata* and *C. tagal* decomposed substantially faster during rainy season (Woitchik et al., 1997). Mackey and Smail (1996) found significantly faster decomposition of *A. marina* debris in lower intertidal zones with greater inundation. They also found an exponential relationship between leaf decomposition rate and latitude. Leaves

decomposed more rapidly at lower latitudes. They attributed the pattern to temperature differences, and concluded that seasonality may have important effects on organic cycling and nutrient export from mangrove ecosystems.

According to Camilleri (1992), feeding activities of marine invertebrates have important effects on decomposition rates of mangrove litter. Marine invertebrates may process large volume of the litter, therefore contributing to nutrient dynamics. For example, in Ao Nam Bor mangrove forest in Thailand, the analysis of foregut contents of sesamid crabs indicated that their diets contained 55–82% of mangrove plant matter (Poovachiranon & Tantichodok, 1991).

The function of mangroves as carbon storage ecosystems has been further reviewed based on published information on the accumulation of organic matter as peat. Mangrove peat has been reported to vary from 2 m to over 9 m depth (Fujimoto et al., 1999; Macintyre et al., 2004), which suggests large stores of plant biomass beneath some mangrove forests. Golley et al. (1962) examined the partition of the total biomass (AB and BG) contained in a mangrove tree and found that peat and fine rots (<0.5 cm diameter) exceeded all other biomass components combined by 5:1. This accumulation of organic material as peat in mangrove soils serves as a sink for carbon and other nutrients.

Mangrove forests are usually characterized by sediment accretion (Woodroffe, 1992). This fact, combined with the high productivity and low ratio of sediment respiration to net primary production, gives mangrove sediments the potential for long-term sequestration of organic carbon. Thus, these systems may play an important role in global carbon cycle (Jennerjahn & Ittekkot, 2002).

Several methods have been used to measure sedimentation rates, including the use of natural and man-made radionuclides, such as ^{137}Cs and ^{210}Pb . Alongi et al. (2001) used these methods to estimate mass sediment accumulation in four mangrove forests in Ao Sawi, Thailand. The mass sediment accumulation rate was rapid at all forests studied, ranging from 2,900 to 7,600 g m⁻² year⁻¹. Using the same method, a higher rate of mass sediment accumulation rate was recorded (2,200–11,400 g m⁻² year⁻¹) for Matang mangrove forests in Peninsular Malaysia (Alongi et al., 2004). In Ba Lat estuary, Vietnam, sediment rates were compared between dry and wet seasons by Van Santen et al. (2007) using sediment traps in a bare mudflat containing a vegetation gradient from pioneering mangroves to 5- to 7-year-old mangroves. As expected, the sedimentation rate recorded in the wet season was higher than in the dry season (34,600 g m⁻² year⁻¹ versus 29,400 g m⁻² year⁻¹).

Alongi et al. (2001) also examined rates of carbon mineralization and burial in sediments accumulation in Ao Sawi, Thailand and found that the thickness of mixed layer sediments in all forests ranged from 16 to 38 cm. Total inputs of organic carbon ranged from 26.4 to 40.9 mol C m⁻² year⁻¹ and burial rates ranged from 15.3 to 23.4 mol C m⁻² year⁻¹. Total rates of carbon mineralization ranged from 7.0 to 16.4 mol C m⁻² year⁻¹.

Chmura et al. (2003) studied the component of the terrestrial biological carbon pool by compiling data sets for 154 sites in mangroves and salt marshes from the western and eastern Atlantic and Pacific coasts, as well as the Indian Ocean, the

Mediterranean Ocean, and the Gulf of Mexico. They found that the average carbon density of mangroves (0.055 g cm^{-3}) is significantly higher than salt marshes (0.039 g cm^{-3}), and the carbon accumulation rate for both wetlands is about $210 \text{ g m}^{-2} \text{ year}^{-1}$. Considering global estimates of mangrove coverages, they calculated that carbon sequestration in mangroves is about $38 \text{ Tg C year}^{-1}$, which suggests that mangroves sequester carbon faster than terrestrial forests. Also, they suggested that the role of mangrove as carbon sinks may be ecologically important since decomposition in mangrove soils occurs mainly through sulphate reduction, which would contribute less to greenhouse gases.

5.4 Methane Emissions from Mangroves

One of the important greenhouse gases that contribute to a rise in global mean surface temperature is methane (CH_4). Wuebbles and Hayhoe (2002) reported that the current globally-averaged mixing ratio of methane concentration is 1,750 parts per billion, which is more than double that of pre-industrial times. The concern over the increasing rate of methane concentration has stimulated the effort to develop policies for controlling its emission.

Methane emissions from mangroves show large variability due to the complexity of environmental factors that affect the production of methane. These include salinity, soil texture, temperature and nutrient, transport of organic sediments, vegetation types and morphology, chemical characteristics of organic materials, topography and geomorphology (Dunfield et al., 1992; Lindau et al., 1993). The supply of organic materials is important for methane production and emission (Wang et al., 1987); Bartlett et al. (1983) reported that salinity and sulphate are the major inhibitors of methane production by stimulating activity of sulphate reducing bacteria, which compete with methanogens for the reduced substrates. Soil texture is involved with transferring and trapping methane produced in the reduced soil and thus affects the net production of methane emission (Le Mer & Roger, 2001). According to Dunfield et al. (1993), soil temperature is critical in determining the production and emission of methane from the subsurface to the atmosphere with optimum temperature between 25°C to 30°C .

There are only a few investigations on methane emissions from mangroves in Asia (e.g., Alongi et al., 2001; Purvaja & Ramesh, 2001; Lekphet et al., 2005; Krupadam et al., 2007). Methane emissions from various mangrove areas have estimated with a wide range of emissions. Some studies found that methane emissions from mangrove were considered to be negligible (Giani et al., 1996; Alongi et al., 2001). In South India, Purvaja and Ramesh (2001) estimated the methane emission rate from mangrove forests ranging from 0.0473 to $0.3245 \text{ g m}^{-2} \text{ day}^{-1}$. In Ranong Province, Thailand, Lekphet et al. (2005) reported that emission rates were found to vary seasonally with the highest rate in the rainy season, followed by summer and cold seasons, during which the values were 0.00052 , 0.00027 , and $0.00019 \text{ g m}^{-2} \text{ day}^{-1}$, respectively. They reported that these seasonal variations were

as a result from several factors in field conditions such as water conductivity, soil temperature, and water level. In southeastern coast of Puerto Rico, Sotomayor et al. (1994) estimated the methane emission rate from mangroves ranging from 0.0004–0.0082 g m⁻² day⁻¹. Lyimo et al. (2002) found that the methane emission rate in Mtoni mangrove sediments Tanzania were at the range of 0–0.0192 g m⁻² day⁻¹.

6 Conclusions

The main objective of this chapter was to review the roles of mangrove primary production in the carbon cycle of mangroves and in the coastal ecosystems, which continues to be an issue of interests. Studies have shown that mangrove ecosystems contribute to primary productivity of the coastal ecosystems and indirectly increasing secondary productivity of adjacent habitats. Published data compiled from differing mangrove ecosystems shows that organic carbon in mangroves and marine sediments contribute immensely in providing source of carbon. This information supports the importance of mangroves in the cycling of nutrients, and also their role in carbon sequestration.

Degradation of mangrove ecosystems through a variety of human activities has been the primary cause of mangrove loss. These impacts are likely to continue as human populations and land development activities expand further into mangrove ecosystems. Therefore, reducing mangrove degradation, reforestation of mangroves, and sustainably managed existing mangroves, can provide a cost-effective way of increasing their capacity in the carbon and nutrient cycles. However, to accurately calculate how much carbon can be stored and how to maintain them as sinks will be critical for those making decisions related to mangrove rehabilitation and reforestation. Hence, a better understanding on how mangrove plants and soils absorb, store, and release carbon, also how these activities will affect the carbon cycle, is essential in order to better understand of how mangrove ecosystems function, especially in their role in stabilizing carbon content in the atmosphere.

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Appendix A list of plant species found in the mangrove forests in Malaysia (Saenger et al., 1983; Ashton & Macintosh, 2002; MOSTI, 2003)

No.	Family	Species	Category ^a	Life-form	Common name (in Malay)
1	Acanthaceae	<i>Acanthus ilicifolius</i>	MA	Shrub	Jeruju puteh
2	Arecaceae	<i>Nypa fruticans</i>	MA	Palm	Nipah
3	Asteraceae	<i>Pluchea indica</i>	MA	Shrub	Beluntas
4	Avicenniaceae	<i>Avicennia alba</i>	M	Tree	Api-api puteh
5	Avicenniaceae	<i>A. lanata</i>	M	Tree	Api-api bulu
6	Avicenniaceae	<i>A. marina</i>	M	Tree	Api-api jambu
7	Avicenniaceae	<i>A. officinalis</i>	M	Tree	Api-api ludat
8	Combretaceae	<i>Lumnitzera littorea</i>	M	Shrub/tree	Teruntum merah
9	Combretaceae	<i>L. racemosa</i>	M	Shrub/tree	Teruntum putih
10	Euphorbiaceae	<i>Excoecaria agallocha</i>	M	Tree	Buta-buta
11	Meliaceae	<i>Xylocarpus granatum</i>	M	Tree	Nyireh bunga
12	Meliaceae	<i>X. meluccensis</i>	M	Tree	Nyireh batu
13	Myrsinaceae	<i>Aegiceras corniculatum</i>	M	Shrub	Kachang-kachang
14	Myrsinaceae	<i>A. floridum</i>	M	Shrub	Kachang-kachang
15	Pteridaceae	<i>Acrostichum aureum</i>	M	Fern	Piai raya
16	Pteridaceae	<i>A. speciosum</i>	M	Fern	Piai lasa
17	Rhizophoraceae	<i>Bruguiera cylindrica</i>	M	Tree	Berus
18	Rhizophoraceae	<i>B. gymnorrhiza</i>	M	Tree	Tumu merah
19	Rhizophoraceae	<i>B. parviflora</i>	M	Tree	Lenggadai
20	Rhizophoraceae	<i>B. sexangula</i>	M	Tree	Tumu putih
21	Rhizophoraceae	<i>Ceriops decandra</i>	M	Tree	Tengar
22	Rhizophoraceae	<i>C. tagal</i>	M	Tree	Tengar
23	Rhizophoraceae	<i>Rhizophora apiculata</i>	M	Tree	Bakau minyak
24	Rhizophoraceae	<i>R. mucronata</i>	M	Tree	Bakau kurap
25	Rubiaceae	<i>Scyphiphora hydrophyllacea</i>	M	Shrub	Chigam
26	Sapotaceae	<i>Planchonella obovata</i>	MA	Tree	Menasi
27	Sonneratiaceae	<i>Sonneratia alba</i>	M	Tree	Perepat
28	Sonneratiaceae	<i>S. caseolaris</i>	M	Tree	Berembang
29	Sonneratiaceae	<i>S. ovata</i>	M	Tree	Gedabu
30	Sterculiaceae	<i>Heritiera littoralis</i>	MA	Tree	Dungun
31	Leguminosae	<i>Caesalpinia crista</i>	MA	Tree	Unak
32	Leguminosae	<i>Derris trifoliata</i>	MA	Tree	Tuba laut
33	Leguminosae	<i>D. uliginosa</i>	MA	Tree	Setui
34	Malvaceae	<i>Thespesia populnea</i>	MA	Tree	Bebaru
35	Pandanaceae	<i>Pandanus odoratissimus</i>	MA	Palm	Pandan
36	Tiliaceae	<i>Brownlowia argentata</i>	MA	Shrub/tree	Kiei

^aM: true mangrove; MA: mangrove associate