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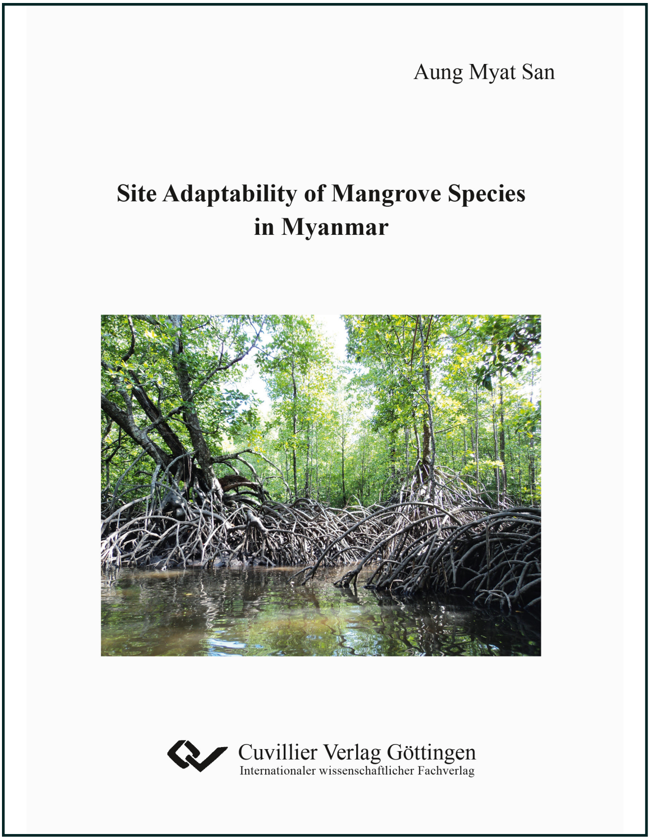

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1 Introduction

1.1 Mangroves and their benefits

Mangrove forests are economically and biologically important both at local and global scales (Alongi, 2014). Mangroves are the world's dominant coastal ecosystems comprising flowering trees and shrubs which are adaptable to marine and estuarine tidal conditions (Alappatt, 2008). Mangrove forests occur in the inter-tidal region between the sea and the land of tropical and subtropical regions, with distribution approximately between 30° N and 30° S latitude (Giri *et al.*, 2011). Mangroves grow along with shallow-waters of coastal areas and tidal mudflats extending inland along brackish rivers, streams and their tributaries (Melana *et al.*, 2000). Mangroves can be found in 124 countries from five regions: Asia, Africa, North and Central America, South America and Oceania. Globally, the total mangrove area is 15.2 million hectares which is equivalent to one-quarter of Madagascar's land area, demonstrating mangroves as a rare forest type (Spalding *et al.*, 2010; Kathiresan, 2011b).

Mangrove ecosystems provide a variety of direct and indirect economic and environmental services (Spaninks and Van Beukering, 1997). Mangrove trees serve as the primary producer in the ecosystem, they provide habitat for aquatic fauna and they play a role in the livelihoods of local populations (Melana *et al.*, 2000). Mangrove forests function as breeding, spawning, hatching and nursing grounds for marine species, and provide services for the subsistence and livelihood of local communities (Dahdouh-Guebas *et al.*, 2005). Mangroves also provide wood products for housing, fuelwood for energy, tannins, medicines, food and fodder. Mangroves are important habitats for marine and coastal fisheries and supporting the development of on-site and off-site fisheries (Spaninks and Van Beukering, 1997; Spalding *et al.*, 2010).

Moreover, mangroves are at the higher level of primary production compared to other tropical or temperate forests, as the total above-ground biomass of the world's mangrove forests was estimated to be over 3700 Tg of carbon (Spalding *et al.*, 2010). According to Alongi, 2009 and Reef *et al.*, 2010, the average estimates of net primary productivity (NPP) for mangrove range from 2 to 50 Mg C ha^{-1} year^{-1}. Mangroves store atmospheric carbon and contribute significant benefits to control global climate change (Panneerselvam, 2008). The mangrove ecosystem plays an important role in reducing carbon emissions as mangrove vegetation can absorb quantities of atmospheric carbon between 75 to 150 Tg C ha^{-1} yr^{-1} (Eong, 1993; Martuti *et al.,* 2017)

In addition to productive functions, mangrove forests serve as natural barriers, mitigating the risk of catastrophic storms and tsunamis by protecting the lives and property of coastal communities (Badola and Hussain, 2005). The mangrove root systems lower the velocity of tidal flow, resulting in a less turbulent environment, which encourages sedimentation, and sediment stabilization and protects shorelines and shore-based activities (Gilbert and Janssen, 1998). The capture of sediments by mangroves plays an important role in land forming processes to address the issue of sea-level rise by global climate change (Hoque *et al.*, 2015).

Mangroves serve as natural water filters by removing organic wastes from water which benefit associated ecosystems such as coral reefs, which are the most biologically diverse marine ecosystem on the earth (Panneerselvam, 2008). Mangroves are also important hotspots for migratory birds during their migratory season, and the number of supported bird species is directly related to the structure of mangroves and diversity of plant species (Ambuel and Temple, 1983; Azimah and Tarmiji, 2018). Moreover, sustainably managed mangroves can provide sites for eco-tourism (Kathiresan, 2011b)

Although the mangroves are tolerant to the extreme environment and are highly productive ecosystems, their existence is threatened throughout the world (Lagomasino *et al.*, 2016). Globally, developing countries contribute the highest mangrove coverage (90%); however, mangroves are at risk for extinction in 26 countries (Kathiresan, 2011b). The mangrove areas are disappearing at a rate of 1-2% annually, and the world's mangrove experts estimate that the ecosystem services of mangroves will cease within 100 years (Duke *et al.*, 2007).

Nowadays, the benefits of mangroves are well recognized, and the conservation of mangrove ecosystems has become a global concern. Restoration of mangroves in tropical countries under the Bonn Challenge, the forest landscape restoration (FLR) approach, is one of the global efforts to conserve this unique ecosystem (IUCN, 2017; Besseau, 2018; Gómez, 2018).

1.2 Mangrove forests in Myanmar

The Republic of the Union of Myanmar, formerly known as Burma, is the second largest country of Southeast Asia and occupies a total area of 65.66 million hectares. It is situated in a tropical region within the latitudinal range of 9°32' and 28°31' North and longitudinal range of 92°10' and 101°11' east. Myanmar is bordered by China in the northeast, India and Bangladesh in the northwest, Laos and Thailand in the southeast.

The total forest cover in Myanmar is 29 million hectares and roughly 43% of the country's area is covered by natural forests (FAO, 2015). Due to diverse microclimates and topographic conditions, six major types of forest can be defined as shown in Figure 1.1. Among those, mangrove forests play a unique and important role for socioeconomic development of local communities as well as for the country as a whole.

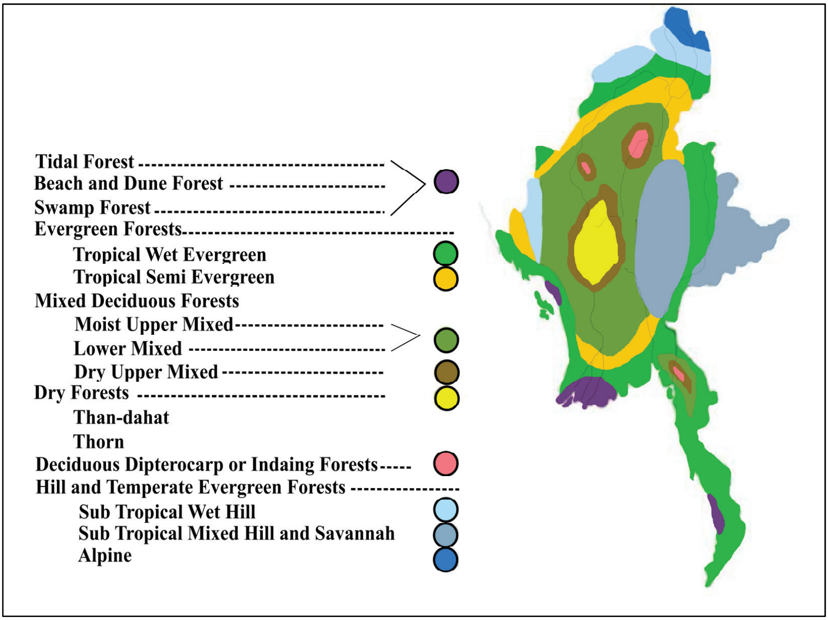


Figure 1.1 Vegetation types of Myanmar. (Source: Forest Department and IUCN, 2015 after Kress *et al.*, 2003)

Myanmar possesses a coastline of 2800 km in the south-west and northern parts along the Bay of Bengal and the Andaman Sea (Aung and MacDonnell, 2016). The coastline extends from the Naf River, the borderline of Myanmar and Bangladesh, to Kawthaung which borders Thailand in the southern edge of the country. The coastline can be divided into Rakhine Coast (upper coastal region), Ayeyawady Delta (central coastal region) and Tanintharyi Coast (lower coastal region), and natural occurrence of mangrove forests can be found mainly in these three regions. The distribution of mangroves in these three coastal regions is shown in Figure 1.2. The total mangrove forest area of these three coastal regions was 462,954 hectares in 2015 (Forest Department, 2019). According to Spalding *et al.* (2010), Myanmar is ranked seventh out of 12 countries with the largest mangrove area and is ranked third in Southeast Asia after Indonesia and Malaysia. The mangrove forests of Myanmar are unique and do play an important role in the socio-economic development of local dwellers as well as that of the country (Emerton and Aung, 2013). Together with the adjacent coral reefs, they also provide protective and productive functions along the coastline (Forest Department and IUCN, 2015).

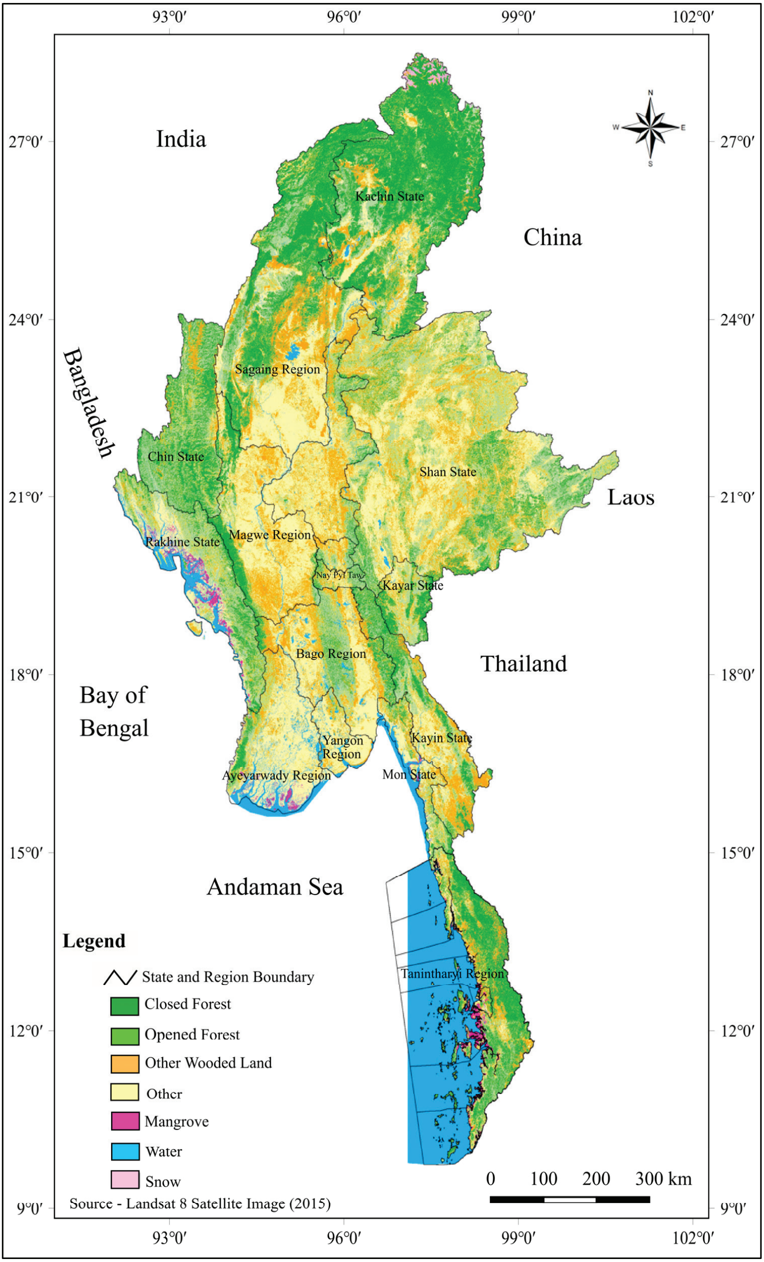
The mangrove forests within the permanent forest estate are under the administration of Forest Department of the Ministry of Natural Resources and Environmental Conservation. They are classified either as Reserved Forests for production, as Protected Public Forests for local supply or as Protected Areas for nature conservation (Forest Department and IUCN, 2015). According to Than (2006), there was no systematic management of mangroves until 1924. From 1924 to 1972, mangrove forests were managed by the forest working plan with proper silvicultural treatment and management prescriptions. A selection system with a fixed felling cycle of 20 to 40 years was applied in the management of mangroves. After 1972, the development of working plans was interrupted due to political and several other reasons. Currently, the Forest Department develops individual working cycles of mangrove forests in the District Forest Management Plans for the intensive management and rehabilitation of mangroves (Than, 2006).

Since mangrove degradation is a global issue, there is no exception within Myanmar. Due to the lack of clearly defined land-use systems, mangrove forests in Myanmar are subjected to severe degradation and denudation. Until today, the major causes of mangrove forest losses are over-exploitation of resources, conversion to agricultural land, and other development activities (Giesen *et al*., 2007). Mitra (2013) discovered that the main causes of mangrove degradation in Myanmar are clear-felling for the expansion of aquaculture and agriculture, urban development, excessive siltation and other pollution. Due to all those anthropogenic pressures, mangroves in Myanmar are reported as part of the most degraded mangrove systems in the Indo-Pacific (Giesen *et al.*, 2007). The changes of mangrove forest areas in the three main coastal regions are specified in the following table.

Table 1.1 The distribution of mangroves in three coastal regions of Myanmar and the changes of areas from 1980 to 2015 (Forest Department, 2019).

	Coastal Region	**Areas in year** (ha)		**Remaining mangroves areas** (%)
		1980	**2015**	
1.	Rakhine Coast	168,000	126,988	76
2.	Ayeyarwady Delta	275,000	78,883	29
3.	Tanintharyi Coast	262,000	257083	98
	Total	**705,000**	**462,954**	**66**

Among the three coastal regions, the degradation of mangroves in the Ayeyarwady Delta is the most serious. In addition to anthropogenic impacts, a category four tropical cyclone, Nargis, which was the most brutal and worst natural disaster in the history of Myanmar, hit the Ayeyarwady Delta in 2008. The cyclone swept down homes and infrastructure along its path and destroyed the mangrove forests of the Ayeyarwady Delta (TCG, 2008). After the Nargis, the productive and protective functions of the mangroves was recognized and afforestation and reforestation programs were initiated by the Forest Department of the Ministry of Natural Resources and Environmental Conservation, NGOs and INGOs with the involvement of local communities, to restore healthy mangrove ecosystems in Ayeyarwady Delta, but also in Rakhine State and Tanintharyi Region. In the National Biodiversity Strategy and Action Plan (2015-2020), Myanmar set a strategic goal to conserve 10% of coastal and marine areas to achieve one of the Aichi Biodiversity Targets (Forest Department and IUCN, 2015).



Source - Landsat 8 Satellite Image (2015)

Figure 1.2 Land cover map of Myanmar illustrating the distribution of mangroves along the coastline. (Source: GIS section of Forest Department).

1.3 Adaptation strategies of mangroves

Mangroves are woody halophytes (Ball, 1988a; Kathiresan, 2011b) and grow under harsh environmental conditions including high salinity, high temperature, extreme tides, high sedimentation and muddy anaerobic soil conditions (Giri *et al.*, 2011). Within intertidal zones, mangroves physiologically tolerate the two most important factors, salinity and anoxia or anaerobic soil conditions (Alongi, 2009).

To adapt to the saline environment, mangroves perform several resistance strategies such as salt exclusion, extrusion, storage, succulence, compartmentalization and osmoregulation (Saenger, 2002; Alongi, 2009). All mangroves exclude 80-95% of salt at the root level, and some do have an effective ultrafiltration system within the roots. The salts which pass into the plant tissue after filtration (5 - 20%) are stored in the old leaves which are later shed to release undesirable salt (Saenger, 2002; Panneerselvam, 2008). Based on their salt eliminating characteristics, mangroves can be classified into salt secretors and non-secretors whereas the former secrete salts from the leaves through salt glands or multicellular glands (Tomlinson, 1986). Reef and Lovelock (2015) stated that salt secretion in mangroves could improve the water balance.

Under saline conditions, mangroves possess the ability of high water use efficiency by regulating water transport together with managing ions as solutes (Reef and Lovelock, 2015; Scholander *et al.*, 1962). Mangroves use salt in their tissues for water transport. They keep the internal concentration higher than in the soil since water diffuses from low to high concentration (Kathiresan, 2011b). Similarly, mangroves maintain the concentration of ions in shoots higher than in the roots in order to promote the upward water flow in the plant (Kathiresan, 2011b). In order to take up water from the root system, mangroves maintain water potentials (the combination of pressure and osmotic potential) lower than the growing substrate (Scholander, 1968; Tomlinson, 1986; Mitlöhner, 1998; Khan and Aziz, 2001; Reef and Lovelock, 2015). Mangroves also use ions as solutes to lower the osmotic potential of the cells, regulating the ion concentration of their tissues according to the salinity of surrounding medium (Scholander *et al.*, 1962; Werner and Stelzer, 1990; Reef and Lovelock, 2015).

Since the plants need more energy for water uptake from saline soil, mangroves developed a number of mechanisms to promote water use efficiency in photosynthesis

(Reef and Lovelock, 2015; Munns and Gilliham, 2015). The leaves of mangrove species are composed of thick-walled epidermis, wax-coated upper surface, sunken stomata and a dense layer of variously shaped hairs on the lower surface to reduce the loss of water from transpiration (Saenger, 2002; Reef and Lovelock, 2015; Ariyanto, 2018). Under full sunlight, maintaining leaf posture at an angle up to 75° from horizontal is one of the abilities mangroves use to lower the leaf temperature and avoid excessive transpiration from intense radiation. The higher the leaf angle the smaller the leaf surface exposed to sunlight, explaining the greater salinity tolerance of the species (Ball, 1988a; Reef and Lovelock, 2015). Mangroves also reduce the leaf size in high saline conditions since smaller leaves effectively maintain an equal temperature to the surrounding atmosphere (Reef and Lovelock, 2015).

In addition to the salinity, waterlogged or anaerobic soil conditions are other factors that do limit the growth of mangroves (Alongi, 2009). To facilitate the oxygen uptake in anoxic soil, mangroves developed different types of aerial roots: pneumatophores (e.g. *Avicennia* species), stilt roots (e.g. *Rhizophora* species), knee roots (e. g. *Bruguiera* species) and plank roots (e.g. *Xylocarpus* species) (Tomlinson, 1986; Ball, 1988a; Alongi, 2009). The aerial roots of mangroves are composed of lenticels which allow only air to pass through into the root (Tomlinson, 1986; Ball, 1988a; Panneerselvam, 2008). Additional to the root ventilation function, the pneumatophores of some species (e.g. *Avicennia* species and *Sonneratia* species) possess chlorophyll and perform photosynthesis (Dromgoole, 1988; Saenger, 2002). Moreover, Saenger, 2002 noted that mangroves may perform various metabolic responses to the oxygen-deficient or anoxic site conditions.

The mangrove environment is regularly inundated by brackish water or seawater, and mangroves developed strategies for successful reproduction within such an unstable environment. Most of the mangroves reproduce via vivipary propagules (seedlings), which allows the seeds to readily germinate and receive nutrients while still attached to the mother tree (Panneerselvam, 2008; Kathiresan, 2011b). The seed dispersal is mostly realized by tidal current and the propagules are modified for floating (Tomlinson, 1986). The propagules are also tolerant to salinity (Clarke, 1993) and may survive a longer viable period until they attached to the ground at a favorable site (Kathiresan, 2011b).

1.4 Rationale of the study

Though mangroves have been studied by many researchers in the past, there still remains a poor understanding of mangroves and their eco-biology (Kathiresan, 2011b). In Myanmar, there is a limited amount of research on site adaptability of mangrove species. Four years after the cyclone Nargis in 2012, a research study aimed at observing the status of recovered mangroves in the central coastal region of the Bogalay and Laputta Townships of the Ayeyarwady Delta. The study summarized that the number of stems per hectare was higher and the regeneration status was better in areas experiencing less human influence (Myat San, 2012). Investigating the status and characteristics of mangrove forests of all the coastal regions in Myanmar is of utmost importance to develop silvicultural and management strategies for the restoration of depleted mangroves.

For the restoration of mangrove forests, the Forest Department planned to establish 1200 ha of mangrove plantations annually, according to Myanmar Reforestation and Rehabilitation Program-MRRP (Forest Department, 2017). In the context of forest restoration or plantation forestry, site-species matching is crucial for successful establishment. Since mangrove formation is highly influenced by various site factors, the study on the physiological responses of mangrove species to ecological limiting factors is essential for site-species matching. Myanmar also needs scientific research concerning the adaptability of mangrove species in different coastal regions and the relevance of introducing a species from one coastal region to another.

Salinity is a major abiotic factor limiting the growth and distribution of mangrove species (Wang *et al.,* 2011). Though mangroves grow best under lower salinity, the range of salinity level for the optimal growth varies among the species (Duke *et al.*, 1998). Various mangrove species may have different tolerance levels to the site salinity. Medina and Francisco (1997) stated that the salinity of the growing substrate is strongly and positively related to the osmolality of the cell sap in the leaves. According to Mitlöhner (1997), and inter alia, the internal osmotic potential of a plant reflects the concentration of dissolved salts, sugars, organic acids in the cells. In order to absorb the water from the soil, the plant must have a higher concentration of solutes, following the principle of diffusion. Therefore, the osmotic potential of the cells (in the state of full water saturation of the plant) is directly proportional to the amount of soluble salts in the soil. Accordingly, the osmotic potential could be used to measure the plant adaptability for salinity in different sites either quantitatively or qualitatively. Hence, observing the osmotic potential of plants and their soil substrate at a specific location is one of the gateways to understand response and adaptability of mangrove species to their growing sites.

Thus, one can propose the most appropriate species to be planted in a specific site condition for mangrove restoration by knowing the osmotic properties of different mangrove species. In order to determine the prospect of success of introducing a mangrove species from one coastal region to another, it is necessary to observe the differences in osmotic potential of mangrove species from all coastal regions of Myanmar. Moreover, the comparison of osmotic potentials among different mangrove species can identify the most salt tolerant species for restoration of mangroves coastal areas with higher salinity.

Osmotic stress caused by high salinity can reduce the availability of water and lower the supply of carbon dioxide to a plant (Tanaka *et al*., 1999; Li *et al*., 2008). Higher salinity reduces nitrogen accumulation and inhibits the uptake of K+ in some mangrove species, consequently diminishing the photosynthesis process (Patel *et al*., 2010; Kao *et al*., 2001). In addition to salinity, nutrient deficiency due to prolonged waterlogging is one of the limiting growth factors for mangrove species. Waterlogged sediments of mangrove soils form an anaerobic environment, which causes nitrification and results in low nutrient availability (Whigham *et al*., 2009); Cheng *et al*., 2012). According to Waisel (1972) as cited in (Nasrin *et al.,* 2018) prolong oxygen deficiency in soil may lead to temporary change in metabolic activity or permanent damage of mangroves.

Understanding the nutrient status of plants in response to environmental stresses would thus be one of the approaches to evaluate the best species for planting sites. According to Adams and Grierson (2001), the stable isotope technique has been applied in research on plant ecology to understand response of plants to their growing environment. It can be applied to discover the interaction between limiting ecological factors and the isotopic compositions of essential nutrient elements in the wood tissues.