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Effect of hydrology on the structure and function of mangrove ecosystems in the Can Gio Mangrove Biosphere Reserve, Vietnam

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EFFECT OF HYDROLOGY ON THE STRUCTURE AND FUNCTION OF MANGROVE ECOSYSTEMS IN THE CAN GIO MANGROVE BIOSPHERE RESERVE, VIETNAM

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ABSTRACT

The influence of hydrology on the mangrove forests of Vietnam has received little scientific attention, even though hydrology is recognized as the primary forcing function in mangrove ecosystems worldwide. The purpose of this dissertation research was to determine the effects of hydrology on specific structural attributes and functional processes within the mangrove forests of Can Gio, a province in southeastern Vietnam. Khe Vinh (KV) and Mui O (MO), two locations within compartment 17 of the Can Gio Mangrove Biosphere Reserve, were chosen as study sites. This research addressed two questions: (1) What are the characteristics of the hydrological regime at the Can Gio mangrove forest? and (2) How does the hydrological regime in the Can Gio mangrove forest affect soil properties, sedimentation, litter decomposition, primary production and species distribution.

Tidal effects of the China Sea and the Saigon and Dong Nai Rivers affected the hydrological regime of the Can Gio mangrove forests. Average high tide and low tide were higher in the dry season than in the wet season. The different mangrove vegetation zones had different flooding frequencies at the KV and MO study sites. Zone 1 (nearest to the shoreline) at the KV site had a lower elevation than the other, more inland, mangrove zones at both the KV and MO sites. Overall, flooding frequency and elevation affected various soil properties. Low elevation zones had the highest sedimentation rates and flooding frequency. No sedimentation occurred at the MO site.

Litter decomposition at the KV and MO study sites was dependent on the tissue structure of the species and the zones in which they occurred. Species that had thin and soft tissues had a higher decomposition rate than species with thick and hard tissues. The decomposition process was affected by vegetation zone, elevation, and flooding frequency. Flooding frequency and elevation affected primary production and species distribution at the study sites. More species were found in the higher elevation zones, which had dry,

compacted soil. However, zones with a single dominant species, such as *Rhizophora apiculata* or *Avicennia alba,* had the greatest amount of litter fall.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Mangroves of the World

The beautiful, but eerie, intertidal tropical forests are known in general as “mangals,” “mangrove swamps” or “mangrove forests”. Such ecosystems are found along intertidal, coastal shorelines of the tropical and sub-tropical regions of the world. Mangrove ecosystems are an interest to the people who live in coastal zones and to scientists who study these wetlands and their ecology. Mangrove forests have been described as highly productive ecosystems, consisting of species that occur either in monospecific zones (Patterson and Mendelssohn 1991) or in mixed zones that occur parallel to the shoreline within the intertidal zone. Some mangrove species are tall trees, some are shrubs, and others are lianas. Their roots can grow above the soil surface and grow into the soil (stilt roots and drop roots, buttress roots), or protrude from the soil into the air with structure such as with knee roots, plank roots, and pneumatophores (Nam and Thuy 1999). Some species can grow in relatively deep water, but others cannot survive in such conditions. Their development is maximized in riverine conditions where sedimentation and nutrient conditions are favorable.

Mangroves cover about 22 million ha globally, but their area has been decreased by human activity in the last several decades (Snedaker 1993, Tuan et al. 2002) report about 15 million ha of mangrove forests remain worldwide. They are distributed along muddy and sandy seashores, estuaries, shallow bays and swamps adjacent to the sea in tropical and subtropical regions (Figure 1.1). Mangrove forests are generally located between latitudes 32^{o}N and 28^{o}S. However, the occurrence of mangrove forests in the Northern Hemisphere from latitudes 24^{o}N to 32^{o}N depends on the local water and air temperature (Mendelssohn

and McKee 2000). The number of mangrove species varies according to the geographical location, position within an estuary, and the position along the intertidal profile.

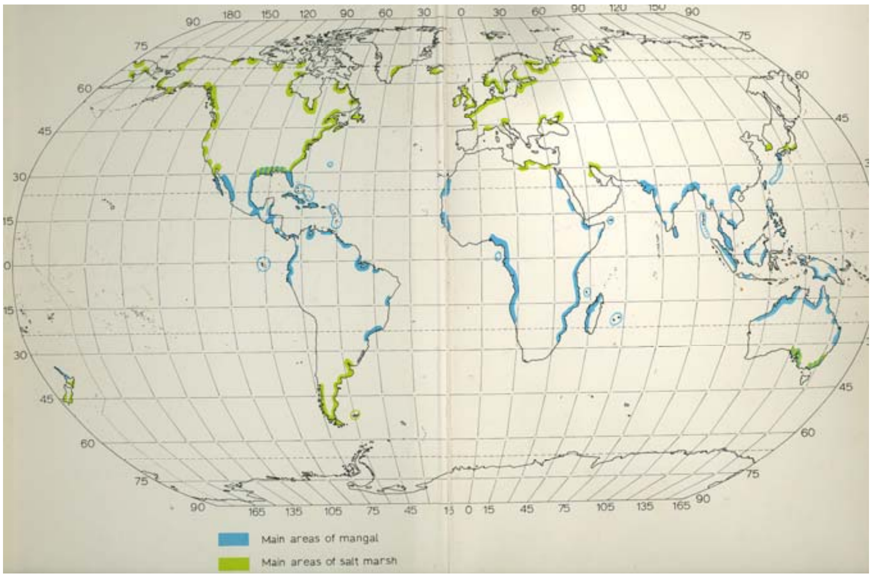

Figure 1.1: The distribution of mangroves forests in the world (Chapman 1977).

Mangroves species worldwide, comprise approximately 14-16 families and 54-75 species (Tomlinson 1986). The greatest biodiversity occurs in Southeast Asia (Tomlinson 1986), consequently, these forest communities are often complex (Bunt 2000). Vietnam, where this dissertation research takes places, lies in an area with a rich and diverse number of species that includes 36 true mangrove species – 33 species belonging to 19 genera and 15 families (Hong 1993).

Contrary to Southeast Asia, only 12 mangrove species occur in the New World. These species are dominated by the genera *Rhizophora* and *Avicennia.* Only four species of mangroves exist along portions of the southern USA. Florida has approximately 187,000 ha of mangrove forests with the red mangrove, *Rhizophora mangle*, dominating (Duke 1992). Latin America mangrove forests are species poor with only 11 species dominated by the genera *Rhizophora* (4 species) and *Avicennia* (4 species).

1.2 Mangrove Forests in Vietnam

Vietnam is located in southeast-Asia, between 23^{o}22’ to 8^{o}30’ north latitude and 102^{o}10’ to 109^{o}24’ east longitude. Vietnam is bordered to the north by China, to the east and the south by the South China Sea, and to the west by Laos and Cambodia. The total area of land is approximately 320,000 km^2, and the coastline length is 3,260 km (Hong et al. 2005). Vietnam contains two major river systems, the Red River that forms the Red Delta in the north, and the Mekong River that forms the Mekong Delta in the south. A number of smaller rivers also occur. Annually, they supply large amounts of fluvial material to their river mouths and along the coastal zone, thereby providing the substrate for mangrove forest development in Vietnam.

Mangrove forests in Vietnam are not extensive in area, but they play an important role in environmental protection. They also support the economy of farmers who live in coastal and estuarine regions. From the north to the south, mangroves occur in four geographic zones: zone 1 from Mon Cai to Do Son, zone 2 from Do Son to Lach Tuong, zone 3 from Lach Tuong to Vung Tau and zone 4 from Vung Tau to Ha Tien (Hong 1993) (Figure 1.2). The area of Vietnamese mangrove forests in 1943 included about 408,500 ha (Hong and San 1993) throughout the country. The most extensive mangrove development was in the southern part of Vietnam. However, during the war (1962-1971), approximately 200,000 ha of Vietnamese mangrove forests were destroyed by chemical warfare (Hong and San 1993). In addition, after the war (1975) large areas of the mangrove forests were converted to support aquaculture. As a result, mangrove forest area decreased to 156,608 ha in 1999, consisting of 38,100 ha of natural forest and 97,019 ha of planted forest (Hong et al. 2005). The remaining 21,489 ha were developed for aquaculture. The Mekong Delta located in southern Vietnam (Figure 1.2) originally had about 250,000 ha of mangrove forest. This area decreased to 80,000 ha in 1992 and then to 51,000 ha in 1995 (EPFM 1995). The main cause

Figure 1.2: The distribution zones (zone 1, zone 2, zone 3 and zone 4) of mangrove forests in Vietnam. The figure was modified from Hong (2005)

of this decline were herbicide spraying during the war and clearing of mangrove forests for aquaculture (Minh et al. 2000). Immigration of landless people from other parts of the country in combination with weak governmental control posed additional problems that led to excessive lumbering of mangrove forests to provide timber, fuel, charcoal, and building materials.

Prior to 1975, the Can Gio mangrove forest, where this research was conducted, covered an area of 40,000 ha with a dense canopy and mature trees over 25 m tall and 25 - 40 cm in diameter. From 1965 to 1970, this area was almost completely destroyed due to chemical warfare. However, after 22-years of afforestation, a project that began in 1978, under the support of the government and with the sustained efforts of many people, the Can Gio mangrove forest has become one of the largest replanted mangrove areas in Vietnam (with a beautiful natural landscape and a high diversity of both flora and fauna). On January 21st, 2000, the Can Gio mangrove forest was recognized by the MAB/UNESCO committee as an International Mangrove Biosphere Reserve. This is the first biosphere reserve in Vietnam (Tri et al. 2000). The Can Gio mangrove forest is located entirely in the fourth mangrove zone and is adjacent to Ho Chi Minh City. It has 77 plant species, divided as follows: 24 species of true mangroves in 13 genera, 16 species of salt resistant plants in 11 genera, and 37 species of upland species in 24 genera (Nam et al. 1994).

Mangrove forests play a number of important roles. They provide environmental protection and supply food for humans. Mangrove forests protect coastlines from erosion, storm damage, wave action, and act as buffers that catch alluvial materials, thus promoting positive elevation-change and shoreline progradation. Mangrove ecosystems also play a significant role as nurseries and food sources for many marine species. The local people in the coastal zone also acquire food from these systems. They are also important for the recycling of organic matter and nutrients (Chapman 1974). People in developing countries

use the resources available in mangrove forests for many purposes such as the production of mats, paper, housing, baskets, boats, textiles, and as a source of staple food. In Australia and Sri Lanka, local people use extracts from mangrove plants as valuable dyes. Nowadays, mangroves are also used as a place for sightseeing and recreation.

1.3 Research on Mangrove Forests

Because of the importance of mangrove forests, many scientists have conducted extensive research on different aspects of mangrove forest ecology. Some studies have emphasized the effects of hydrology on the structure and function of mangrove forests and the relationship between the hydrological regime and soil biogeochemistry and factors that affect the geographical range, zonation, succession and productivity of mangrove forests.
In 1974, Lugo and Snedaker classified mangrove ecosystems into six types according their physical-hydrologic condition: Overwash, Fringe, Basin, Riverine, Dwarf, and Hammock. Subsequently, Critrón et al. (1985) suggested a simplified version of the classification scheme with four major types: Fringe Mangrove which includes Overwash Islands, Riverine Mangroves, Basin Mangroves, and Dwarf (or scrub) Mangroves. However, Lugo et al. (1989), based on the original types, proposed an even simpler classification of three basic categories: Riverine, Fringe (including overwash islands) and Basin (including dwarf and hammock) mangrove forests (Mendelssohn and McKee 2000). Mangrove forests occur in different topographic and hydrodynamic conditions. Based on protection from high-energy wave action, five geomorphologic settings were developed by Thom (1982): (1) Protected shallow bays, (2) Protected estuaries, (3) Lagoons, (4) the leeward sides of peninsulas and islands, (5) Protected seaways and areas behind spits and behind offshore shell or shingle islands.

Mangrove forests occur in the intertidal zone. The specific hydrological regime of this area has a considerable effect on the system, not only on mangrove species, but also on soil

biogeochemistry. Gosselink and Turner (1978) considered hydrology as the most important factor controlling ecological processes in wetlands. In addition to hydrology, the structure of mangrove forests is also affected by the geomorphic and geophysical characteristics of the coastal zone (Thom 1982). Twilley (1998) and Twilley et al. (1999) proposed that mangrove ecology is influenced by local hydrologic factors that are controlled by micro-topography. They used a simulation model of hydrology to demonstrate the relationship between water budget and the inputs of precipitation and tides. This hydrologic model indicated that the ecological properties of mangroves in the upper intertidal zone of lagoons in southwest Florida were sensitive to changes in rainfall deficiency.

Patterson et al. (1997) showed that tidal inundation and predation affects seedling establishment and survival of *Avicennia germinans* in a sub-tropical salt marsh. Also, elevation and tidal regime affects seed dispersal and germination of *Avicennia germinans.* Salinity and sulfide are stress factors that affect growth rates (McKee 1995b, Clarke and Allaway 1993).

Mendelssohn and McKee (2000) stated that physiography and hydrology are important factors which influence both mangrove ecosystems and salt marshes. They indicated that the hydrological regime has a strong effect on the structure and function of wetlands by influencing abiotic factors such as salinity, soil moisture, soil oxygen, and nutrient availability, as well as biotic factors such as the dispersal of seeds and propagules. These factors directly affect the distribution and condition of species and ecosystem productivity.

The inundated condition in wetlands influences soil redox potential and pH, and, in turn, soil biogeochemical processes (Patrick and Delaune 1977, Gambrell and Patrick 1988, Delaune and Pezeshki 1991, Gambrell 1994). These biogeochemical processes affect the function and structure of mangrove ecosystems. For example, sulfide concentration and redox

potential affect the species distribution and growth of mangrove seedlings (McKee et al. 1998, McKee 1993, McKee 1995a).

Mostafa (2001) evaluated the growth and establishment ability of *Avicennia marina* propagules under the effects of an intertidal environment in the coastal zone of Kuwait. Above ground biomass and production of mangrove communities of Biscayne National Park and Taylor River Slough National Park, Florida (USA) were quantified by Ross et al (2001). They used allometric equations to estimate the total above-ground biomass of three mangrove species (*Rhizophora mangle*, *Laguncularia racemosa* and *Avicennia germinans*). Hsueh and Lee (2000) and Tuffers et al. (2001) demonstrated the adverse effects of low salinities on the photosynthetic performance of *Avicennia marina.* Khan and Aziz (2001) studied the salinity tolerance of mangrove species in Pakistan, and Dinesh et al. (2004) compared soil biogeochemistry properties in undisturbed and disturbed mangrove forests of South Andaman, India.

In contrast to much of the rest of the world, the ecology of the mangrove ecosystems in Vietnam has received little attention. The first studies began in 1990 and concentrated on biodiversity surveys, biomass measurements, primary production, soil properties, and some studies related to mangrove restoration. Hong et al. (1997) evaluated the factors that affect the development and distribution of mangrove forests in Vietnam, the components and characteristics of the mangrove flora, and the factors that lead to mangrove degradation. Tri (1996) also surveyed and described the characteristics of flora in Vietnamese mangrove forests. His study focused on the Ca Mau Province, Mekong Delta and Can Gio, HCM City, where the richest species in Vietnam is found. Tuan et al. (2002) provided a general description of the Can Gio Mangrove Biosphere Reserve. Other studies such as Hong's (1993) on the flora of mangrove forests in Vietnam, Nam and My (1992) on mangrove protection, Nam et al. (1996) on biomass of *Rhizophora apiculata* in the Can Gio forest and

Nam (2003) on biomass of *Avicennia abla* in the Can Gio forest have been conducted. In addition, the biomass and soil characteristics of *Rhizophora apiculata* mangroves in Ca Mau (Loi et al. 2002) and on the interaction between post-larvae and *Rhizophora apiculata* (Nga 2004) were investigated. However, a better understanding of the hydrology, biochemistry, and the effects of both biotic and abiotic factors on the stability and development of mangrove ecosystems needs further investigation. Therefore, this study was carried out to determine the effects of hydrology on specific structural attributes and functional processes within the Can Gio mangrove ecosystem.

1.4 The Aims of the Dissertation

The overall goal of this research was to elucidate the effects of hydrology on the mangrove forests of Can Gio, Vietnam. Especially to:

(1) Determine the structure of mangrove ecosystems under different elevations and resulting hydrologic regimes.

(2) Determine the structure and function of restored mangroves in different hydrologic conditions.

(3) Determine the effect of hydrology and resultant biogeochemistry on species composition.

These objectives will be addressed in the following chapters:

Chapter 2 provides a review of recent literature on mangrove forests with an emphasis on distribution, classification, and definition. It also reviews the structure, function, soil properties, and topography of mangrove forests. The hydrology of mangrove ecosystems is also emphasized. Chapter 3 describes the study area, surveying methods, and experimental design used in the research. Chapter 4 emphasizes the hydrological regime of the study sites at the Can Gio Mangrove Reserve. Chapter 5 shows the effect of hydrology on soil composition and soil nutrients. Chapter 6 investigates the effects of hydrology on

sedimentation. Chapter 7 discusses the response of litter decomposition on the hydrological regime and how decomposition differs among species. Chapter 8 explains the effect of hydrology on species distribution and primary production. Chapter 9 provides overall conclusions and suggestions for future research.

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CHAPTER 2

LITERATURE REVIEW

2.1 Mangrove Forests

2.1.1 Definition

The terms ‘mangrove forest’ and ‘mangrove swamp’ are used to describe areas with a profuse community of plants such as trees, shrubs, palms, and ground ferns (Duke 1992, Mendelssohn and McKee 2000), that can adapt to anaerobic and saline conditions. The term mangrove originated from the Portuguese word “mangue” meaning “tree”, and in English, the word “grove” means “a stand of trees” (Dawes 1981, Mitsch and Gosselink 2000). The word “mangrove,” or ‘manggi’ in Malaysia, has been used to describe two genera of Rhizophora (i.e. Rhizophora acupilata and Rhizophora mucronata). These species live in the muddy shores of the tropical regions where they distribute their seeds and emit aerial roots that fasten into the saline mire to eventually become new stems. Their seeds also establish a root system while still being attached to the parent plants (Mendelssohn and McKee 2000).

In ecological terms, mangrove community, mangrove ecosystem, mangrove forest, and mangrove swamp are synonymously used to indicate a biodiverse community of species, to describe specific individual plants that can adapt to saline environments (Mitsch and Gosselink 2000) or to indicate salt-tolerant trees and shrubs that are native to the intertidal zones (Mendelssohn and McKee 2000). Duke (1992) described mangroves as a biodiversity of trees and shrubs that pre-dominate the tropical region and, in general, exceeds one half meter in height and normally grows above the mean sea level in the intertidal zone of the marine coastal environment or in the estuarine margin, where the environment is harsh, restrictive, and dynamic. Therefore mangrove forests or mangrove swamps are easily

recognized not only by the congregation of a specific community of species, but also by the characteristics of the region in which these species prosper. Mangrove forests can usually be found in the coastal zones and large estuaries of sub-tropical and tropical regions with intertidal gradients, mudflats, and sediment. Mangrove forests are composed of two taxonomies: true mangroves and plant associations. True mangroves need intertidal gradients, mudflats, and sediment to develop and can be recognized by dominant structure in the intertidal gradient. Plant associations do not need the same environmental conditions to develop and can grow in a wide range environmental conditions (Bunt et al. 1982). Full knowledge of mangrove species classification is essential in differentiating between plant associations and true mangroves (Hong and San 1993).

2.1.2 Distribution

Mangrove forests are generally distributed along the tropical and subtropical coastlines between latitudes 32^{o} N and 28^{o}S. However, mangrove distribution is mainly concentrated from 25^{o} N to 25^{o} S (Mitsch and Gosselink 2000) because local climate conditions, such as air and water temperature, allow for it (Mendelssohn and McKee 2000, Mitsch and Gosselink 2000). Frequent and extreme frost is also a major factor preventing mangrove extension into tropical and subtropical regions (Twilley 1998). Mangroves develop prosperously on fine-grained sediment and in active deltaic plains with abundant fresh water supply. However they can also grow on a variety of substrates including sand, volcanic lava, and carbonate sediments (Taal 1994). Mangrove forests in the sub-tropical region can develop on loamy or sandy soil where they are protected by sand banks. In the delta regions, mangrove forests grow best along the river bands and creeks where there are intertidal gradients and salt or brackish water. Mangroves can also survive in fresh water, but competition with true freshwater species limits mangrove’s growth in these areas (Poorter and Bongers 1993).

About 15 to 30 million ha of the earth are occupied by mangrove forests (Saenger et al. 1983, Lacerda et al. 1993, Mitsch and Gosselink 2000). Mangrove forests can be divided into two groups: those that came from the Old World and those that came from the New World (Mitsch and Grosselink 2000). The greatest number of mangrove species came from the Old World. They are concentrated in Asian countries such as Indonesia, Malaysia, Vietnam, and Thailand and in the Indo-West Pacific region, which includes Australia and East Africa. Only a small number of mangrove species are found in the New World, which includes the north and south coasts of America and the west coast of Africa (Taal 1994).

In Australia, mangrove forests are found along the coasts of all the mainland states, but they are concentrated mostly in the north (Saenger et al. 1977, Duke 1992). Mangroves in Australia have great flora diversity with a total of 47 taxa in 21 genera, about five times greater than most regions (Duke 1992). The richer flora area (about 30 species) extends from New Guinea to the north where flora is more diverse than in the Cape York Peninsula in the Queensland region (Saenger et al. 1977).

India's mangrove forests are estimated to cover about 356,000 ha with 58 different species. They are distributed along the eastern coasts to the western coasts and are concentrated in the Andaman and Nicobar Islands (Bay of Bengal). About 100,000 ha of the Andaman and Nicobar Islands are covered with mangroves. In the Gangetic delta (West Bengal), about 200,000 ha are occupied by mangroves. The eastern (Indo-Pacific) region has more flora diversity than the Western (Atlantic) region with major species being *Bruguiera*, *Ceriops*, *Lumnizera, Sonneratia* and *Xylocarpus* (Carrapa) (Blasco 1977).

The greatest number of mangrove species is found in the Indo-Malaysia and Papua New Guinea areas. Most of them are distributed along the west coast and in the Riau Islands south of Singapore. The distribution of mangrove forests in Indo-Malaysia varies considerably depending on the physiographic region. That is, whether the region is a large

estuary or small river and whether or not it has a protective coast. *Avicennia marina* and *Sonneratia alba* are the pioneer species growing on sediments and mudflats. However, as sediments and mudflats build up over time to a higher elevation, *Avicennia marina* and *Sonneratia alba* fail to compete with other species, mainly *Rhizophora apiculata*, and eventually secede back into the lower regions (Chapman 1976a).

Vietnam, the country of interest in this study, lies in the prosperous mangrove zone where mangrove forests are found growing extensively along the coastlines. However, they are restricted to only the southern part of the country. The currents in the Northern part of the sea (counterclockwise gyre) prevent mangrove propagules from Malaysia, the main distributor of mangrove propagules, from traveling past 13^{o}N (Morton and Blackmore 2001). The Can Gio district and the Mekong delta, parts of the Southeast Asian sub-region, are recognized as a biogeographical region with the most diverse mangrove species in the world. High flora and fauna diversity and varied fish and shellfish species have also been recorded in these regions (Tri et al. 2000). The predominant species in the Can Gio district and the Mekong delta are *Sonneratia, Avicennia, Rhizophora, Bruguiera* and *Ceriops* of which *Sonneratia and Avicennia* are always pioneer species with *Rhizophora, Bruguiera* and *Ceriops* occurring later (Ho 1963).

In Latin America, mangroves are present in all marine countries except for three southern nations of South America. About 4 to 6 million ha of Latin America are covered with mangrove forests. This amount is equivalent to the amount of mangrove forests in Southeast Asia and nearly twice the amount of mangrove forests in Africa. About 70% of mangrove forests in Latin America are concentrated in the Pacific and Caribbean coasts. Distribution of mangroves is limited in other regions because of cold water (Lacerda and Novelli 1999). Total mangrove area in North and Central America and in the Caribbean is about 2,206,046 ha with 63.6 % of this on the continent and 36.4 % on the island countries.

Most of the mangroves are concentrated in continental countries such as Mexico at 488,367 ha (Loza 1994), the United States (U.S.) at 280,594 ha (source: Continental Shelf Associates 1991), Panama at 170,827 ha (Osorio 1994) and Nicaragua at 155,000 ha (Garcia and Camacho 1994). In the islands, mangroves are concentrated in Cuba at 532,400 ha (Carrera and Santander 1994) and in the Bahamas at 141,957 ha (Bacon 1993).

In North America, *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), and *Laguncularia racemosa* (white mangrove), are widely distributed in Florida (U.S.), the Caribbean, Mexico, and Central America. Although *Rhizophora mangle* and *Avicennia germinans* can be found at 32^{o}N latitude (in Bermuda), they are restricted to lower latitudes on the mainland because of severe winter temperatures (Mendelssohn and McKee 2000). *Avicennia germinans* species are tolerant of low temperatures (West 1977) and can increase their distribution as far north as 30^{o}N latitude (east coast of Florida) (Savage 1972) and 29^{o} 18’ N (Gulf of Mexico coast in Louisiana and Texas) (Sherrod and McMillan 1985).

In the New World, four mangrove species are salt tolerant. *Rhizophora mangle, Avicennia germinans, Laguncularia racemosa,* and *Conocarpus erectus* are found in West Africa. Two species, *Rhizophora harrisonii* and *Rhizophora racemosa* are on the Pacific and Atlantic coasts of Central and South America, specifically on eastern Venezuela, the Guiana’s, and the Amazon mouth (Leechman 1918, Hou 1960, Pires 1964, West 1956).

2.1.3 Geomorphology

Mangroves respond well to various morphological processes. Climatic changes affect the geomorphologic processes, and these changes have a direct impact on mangrove ecology. Soil properties, including moisture content, texture, salinity, redox potential, and chemical composition, are functions of geomorphic processes (Thom 1982).

Soil or sediment is a substrate in the mangrove systems. The term “soil” is used to describe materials that show pedological structure, horizontal texture, and a relationship with

the parent material. While sediment consists of materials that can be produced in situ or come from outside of the mangrove systems, it does not have a relationship with the underlying parent material (Mendelssohn and McKee 2000).

Mangroves are best developed on tropical shorelines where there are active intertidal gradients bringing in a substantial amount of fine grain sediments which provides an optimal environment for mangrove development. These fine grain sediments are usually delivered by river flow from the inland to be deposited in the sea or they come from the adjacent eroding shorelines. However, mangroves also grow on substrates that are comprised of sands, volcanic lava, and where sand mixes with silt or organic matter. Carbonate material, underlain by calcareous skeletal material from reefs or by organic peat from mangrove root production, also provides a suitable environment for mangrove growth (Walsh 1974, Chapman 1976b, Mendelssohn and McKee 2000). Mangroves are also very versatile in that they can grow in soil with organic matter ranging from 10% to 90% of the total soil composition.

Mangrove habitats are often varied depending on various environmental conditions including the climate, the hydrology, the geo-physiology, the geomorphology and the petrology (Chapman 1976b). These conditions limit mangrove distribution, zonation, and succession (Thom 1982). Therefore, the historical and current effects of environmental processes need to be considered when studying mangrove habitats (Thom 1982).

The geology, physiology, and chemistry of the mangrove ecosystems are reflected by the physiographic, which mangroves can develop (Mendelssohn and McKee 2000, Mitsch and Gosselink 2000). Mangroves often occur in environmental settings that include a predictable period of landform and physical processes that are responsible for sediment transportation and deposition (Woodroffe 1992). Continuous landform and physical processes create several geomorphologic settings dominated by waves, tides, and rivers including: 1)

protected shallow bays, 2) protected estuaries, 3) lagoons, 4) the leeward sides of peninsulas and islands, 5) protected seaways, 6) behind spits and 7) behind off shore shell or shingle islands (Thom 1982). All of these geomorphologic settings indicate that mangroves need sufficient protection from waves to thrive. However, mangroves can also develop behind dunes at bare coasts and shallow barriers where there is no protection from waves (Chapman 1976b).

2.1.4 Hydrology

2.1.4.1 Hydrology and Mangrove Types

Mangrove development is a result of topography formation, in situ substrates, hydrology regimes and tidal action (Mitsch and Gosselink 2000). The dynamics of hydrology influence abiotic factors such as salinity, soil moisture, available oxygen, and available nutrients. It also affects biotic factors such as the dispersal of seeds and propagules (Mendelssohn and McKee 2000). According to Lugo and Snedaker (1974), mangrove forests can be classified into six types depending on the different physical hydrology conditions. The six mangrove forest types are: fringe mangroves, over wash mangroves, riverine mangroves, basin mangroves, dwarf mangroves, and hammock mangroves. Lugo et al. in their 1989 paper further simplified mangrove classification into four major types: 1) fringe mangroves, including over wash islands; 2) riverine mangroves; 3) basin mangroves, and 4) dwarf (or scrub) mangroves.

Fringe mangroves are grown along shorelines that have sufficient protection from wave action, such as in lagoons, some canals, and some rivers. Mangroves that are adjacent to the fringe mangrove area have higher than normal mean tides and exposure to daily tides. Low wave action allows fringe mangroves to develop dense prop roots. However, on occasion, fringe mangroves are also exposed to strong storms and winds because of their location along the shorelines. Fringe mangroves can also be found on narrow berms along the

coastline or in wide expanses along beaches with modest slopes where they may receive freshwater runoff and nutrients from rainfall, the ground water, and from the sea. The canopy height of fringe mangrove forests rarely exceeds 10 meters. Low primary production is especially evident in fringe mangroves that occur on over wash islands or spits where debris and litter are washed away daily by high tides (Mitsch and Gosselink 2000, Mendelssohn and McKee 2000).

Riverine mangrove forests are found in coastal rivers and creeks where they receive high freshwater input, sediment, and nutrients that are instrumental to their growth and productivity. Their prosperous trees produce canopies that are often more than 20 meters in diameter. Depending on the elevation and tidal regimes, the land in riverine mangrove forests can be dry for an extended amount of time, even though the water table is generally near the soil surface. Riverine mangroves export a great amount of organic matter to estuarine areas and the ocean because of the strong daily tidal effects. The salinity for riverine mangrove forests varies, but it is generally the lowest among all of the mangrove types. For example, frequent freshwater runoff during the wet season leads to a salinity level lower than 10 % (Mitsch and Gosselink 2000, Mendelssohn and McKee 2000).

Basin mangrove forests, the third type of mangrove forest described by Lugo et al. (1989), can be found inland, often behind fringe or riverine mangrove forests. The depressions or basins in the basin mangrove forests cause typical and extended flooding, which leads to insufficient soil drainage in this area. Extensive flooding and infrequent tidal flushing result in high salinities and low redox potential for this type of forest. A type of basin mangrove forest that deserves special interest is the hammock forest. Hammock forests occur inland and are isolated from typical basin mangroves, but they possess characteristics of both basin and shrub mangroves. Shrub mangroves are mangroves that grow in extremely insufficient environments and have low primary production. Hammock forests are located on

relatively raised platforms. The platforms are raised soil surfaces with less depression than typical basin mangrove forests' depressions because of peat build up accumulated from previous mangrove production (Mitsch and Gosselink 2000, Mendelssohn and McKee 2000)

Dwarf mangroves usually occur in areas with extreme environmental conditions such as sandy soil or limestone marl, poor nutrients, and low hydrology energy. Dwarf mangrove forests are scattered with no uniform growth or structure. Dwarf mangrove trees are small with heights less than 1.5 meters, and they are usually low in productivity compared to other mangrove forest types. Some dwarf forests are inundated by seawater during high tides or storm surges and are also flooded by the freshwater runoff during the rainy season (Mitsch and Gosselink 2000, Mendelssohn and McKee 2000).

2.1.4.2 Tidal Movement

Hydrological regime is a major factor in determining species distribution, productivity, and nutrient cycle in the mangrove ecosystems (Hughes et al. 1998). Hydrological regime refers to a combination of factors that includes the tidal currents, the tidal circulation, and the exchange of water. Tidal currents affect the geomorphology in which mangrove species can be established including the erosion and accretion of soil or the formation of mudflats. The tidal circulation in the mangrove system is a result of water movement characterized by the asymmetry between the ebb tide and the spring tides with the ebb tides always relatively short in duration with a stronger velocity than the spring tides (Wolanski 1992 and Kitheka 1997). During the ebb tides, a strong current flow can wash out sediment to the river mouth or to an estuary to support mangroves' zonation and establishment (Chapman 1976b, Wolanski 1992). The exchange of water between the mangrove ecosystem and the near shore zone, another hydrological regime, modifies nutrients and salinity concentrations. This is another important effect to mangrove properties. For example, lack of freshwater runoff during the dry season causes the system to have poor

water quality because of evapotranspiration and saltwater intrusion from inverse estuarine currents (Wolanski 1992).

Flooding frequency is one of the most important tidal phenomena that can affect mangrove growth. Long periods of no tidal action cause extremely high salinity levels in the soil surface. No tidal movement also prevents the distribution and establishment of viviparous seedlings (Chapman 1976b). Conversely, water inundation in mangrove soils leads to an anaerobic condition that affects root systems preventing the survival, growth, and expansion of mangrove trees. Although mangrove species are flood tolerant, and some species are viviparous, they are still susceptible to flooding damage during the seedling stage (McKee 1995b). High-energy wave action can prevent the deposition of fine sediments due to an increase in soil erosion and a decrease in soil accretion (Mendelssohn and McKee 2000). The deposition of fine sediments promotes plant growth as well as seedling and propagule establishment. Whereas high wave energy and tidal movements are examples of physical stresses that negatively affect mangrove development, tidal fluctuation supports the mangrove system by importing nutrients and oxygen, decreasing salt accumulation, decreasing accumulation of phototoxic compounds, and dispersing propagules (Mendelssohn and McKee 2000, Odum and Fanning 1973).

In tropical regions, during the monsoon period, river discharge depends on precipitation and evapotranspiration. Precipitation and evapotranspiration significantly affect the flow patterns and hence the water level of the mangrove system (Hughes et al. 1998). During the rainy season, high precipitation and large amounts of river discharge lead to a rise in water level and; therefore, flood a larger area than during the dry season (Thom et al. 1975).

Wind direction also has an influence on the water currents and the water distribution in the mangrove creek systems. The current velocity is partly responsible for the differences

in river water discharge into the tidal flats and the dense mangrove vegetation (Loon 2005). Current velocity is slower during high tide than during ebb tide. At high tide, water currents enter slowly into the creek system and the intertidal flat allowing suspended sediments to be suspended and water to settle in the bottom. However, during ebb tide, high current velocity brings resuspended sediment from the creek bed and transports the sediment seaward. The amount of suspended sediment during high tide is less than during ebb tide. Sedimentation on the intertidal flat has a tendency to return a larger amount of sediment out to the sea allowing the depth and narrowness of the tidal creeks to remain intact (Uncles et al. 1992). The tidal movement in the creeks and in the mangrove swamps also transports organic material and nutrients to the adjacent regions and seaward (Loon 2005).

2.1.4.3 Ground Water

The land in the mangrove systems is intersected by many creeks where the groundwater levels are usually very high. However, during high tide, groundwater does not contribute significantly to the hydrological regime due to the influx of water currents. During ebb tide, groundwater movement can have important effects on the mangrove hydrology during both the wet and dry seasons (Wolanski 1992). Groundwater is controlled by a group of tidal processes including precipitation, evapotranspiration, regional groundwater flow, and tidal regime variance (Loon 2005). The groundwater amplitude rapidly declines as it gets further away from the creek. However, at about 5 to 10 meters away from the creek, the water table movement remains constant. As groundwater gets further inland, its levels are controlled by rainfall and evapotranspiration. Groundwater level in the wet season varies considerably due to the amount rainfall. Groundwater levels in the dry season decrease gradually due to increases in evapotranspiration and a lack of water supply. High evapotranspiration and low water supply cause high salinity concentrations in groundwater and in some inland locations (Hughes et al. 1998).

Groundwater is an important factor that affects plants in the mangrove swamp. It determines the biochemistry surrounding the mangrove roots and the organisms that inhabit the mangrove swamp. It also has important effects on the chemistry of the creek water and is essential for plant respiration (Wolanski et al. 1999). The mixing of groundwater with surface water in the mud flats of mangrove swamps is an important process that provides a buffering mechanism for nutrient exchange between the coastal area and the mangrove forest. Groundwater movement also affects benthic algae photosynthesis and removes the anoxic conditions and the high phosphate concentrations near the bottom of the sediment (Mazda et al. 1990).

2.1.5 Morphology and Taxonomy

Mangroves can successfully grow in high salinity and anaerobic environments (Gill 1982). The mangrove environment can be extreme because of physicochemical parameter fluctuation (Saenger 1982). However, mangroves' morphological and physiological characteristics are modified to allow avoidance or tolerance of the toxic environment (Mendelssohn and McKee 2000). Some mangrove species have salt glands on their leaves, and their roots have aerial morphologies to help cope with salt and oxygen-free substrates. Not all mangrove species possess these special characteristics (Gill 1982). Some mangrove species such as Rhizophora *apiculata* and *Rhizophora mucronata* have propagules that can germinate while still attached to their parents. This is a strategy to help these species germinate under extreme conditions (Mendelssohn and McKee 2000).

In 1986, true mangrove species were classified by Tomlinson. True mangrove species are easily recognized in their habitat and they are never found in terrestrial communities. Their taxonomy is often at family or subfamily level. They are also divided by major and minor elements depending on their role in the forest structure and their ability to form homogeneous patterns. Major elements are species that dominate the ecosystem, and minor

elements are ecotone species with transitional and non-homogenous characteristics that connect the true mangrove to terrestrial habitats (Mendelssohn and McKee 2000).

Many mangrove species have special roots that are modified to reach oxygen when the soil is inundated. For example, *Avicennia* spp have roots that resemble bamboo shoots called pneumatophores. These roots are underground organs that rise above the soil surface to absorb oxygen. *Rhizophora* spp have roots with aerial morphologies that protrude near the trunk and project downward into the soil surface, feeding oxygen to the tree. Differences in mangrove species lie in their viviparous. Some mangroves such as *Rhizophora* spp. have seeds that develop into propagules on the parent tree. Once released from the parent tree, propagules' survival and development depend on factors such as water current, depth of inundation, water salinity, and competition with other mangrove species (Hogarth 1999).

2.1.6 Mangrove Development

Mangrove development, similar to the development of other plants that dominates the salt marshes, is dependent on sea level fluctuations. Both, the formation of wetland coasts and the distribution mangroves are a result of changes in the sea level during and since the Pleistocene period (Oliver 1982). Over the past 700,000 years, the sea level has changed dramatically due to nine glacial and ten interglacial periods (Shackleton and Opdyke 1973). About 18,000 years before presence (B.P.), sea level was about 100 m below its present level (Donn et al. 1962). However, the sea level has risen rapidly during the late Pleistocene and early Holocene periods, from about 17,000 to 7000 years B.P. As results of these changes, coastal wetlands were submerged and new wetlands were formed. Coastal wetlands developed between 8000 to 4000 years B.P., when the sea level was rising slowly (Aubrey and Emery 1993). During the middle to late Holocene period, the rate of sediment accretion was equal to or greater than the rise in sea level, allowing for widespread coastal wetland formation and extension. Currently, the coastal wetland areas in which mangroves develop

are composed of sediments from the Pleistocene period, which is covered by the sediments from the Holocene period. Sedimentation and less fluctuation in sea levels allow mangroves to maintain their intertidal position (Mendelssohn and McKee 2000).

2.1.7 Climate

Climate condition is one of the major environmental factors affecting mangrove distribution (MacNae 1968, Chapman 1976b). Most mangrove species cannot survive in extreme climate conditions such as in low temperatures and in areas with frequent frosts. Frequent and extreme frost limits mangrove distribution to the tropical and sub-tropical regions (Twilley 1998). Temperature is one single factor that related to mangrove distribution (Oliver 1982). In tropical regions, mangroves cannot survive average annual temperatures below 19^{o} C (Waisel 1972). Rapid fluctuations from -10^{o} C to $+10^{o}$ C, or short-term freezes, are sufficient to kill mangroves (West 1956). Most mangroves can survive monthly temperatures higher than 20^{o} C with variation in annual temperatures under 5^{o} C. Mangrove growth declines if the temperature progresses towards the colder limits. However, the effect of climate factors on mangrove growth and development varies among and within species (Mendelssohn and McKee 2000). For example, black mangroves on the east coast of Florida can stand several days at temperatures as low as 2^{o} C to 4^{o} C whereas red mangroves on the east coast of Florida can stand the same temperature for only 24 hours. Therefore, black mangroves on the east coast of Florida can extend further to the North than red mangroves (Mitsch and Gosselink 2000).

The growth and habitat of mangroves are controlled by the moisture regime in the mangrove forests which, in turn, is affected by rainfall, surface runoff, and tidal flooding (Oliver 1982). For example, high rainfall in Queen raises the humidity level providing an optimal environment for mangrove forests to develop (Macnae 1968). However, in the Red Sea and in some parts of Australia, the areas become arid during ebb tides limiting mangrove

growth and development (Chapman 1976b). Mangrove forests are enhanced in moist or wet climates where rainfall exceeds 2000 millimeters per year (Macnae 1968). In Costa Rica and Panama, where the average rainfall is high at about 2100 to 6400 millimeter per year, the canopy of the mangroves may reach 35 meters in height, and the aboveground biomass may weigh 280 metric ton ha^{-1} (Golley et al. 1969). High rainfall (500 to over 5000 millimeter per year) in the Caribbean islands has also enhanced the structure of the mangrove forests (Mendelssohn and McKee 2000). Mangroves are less prosperous on the Pacific Coast of Mexico due to drier and colder climates. Low precipitation (less than 500 mm per year) along the Gulf of California has contributed to lower biomass and less structured mangrove forests. The Can Gio mangrove forest, the focus area of this research, is characterized by high humidity with an average annual rainfall of about 1400 to 1600 millimeters and a yearly average temperature of 25^{o} C. In this region, the mangrove canopy is very dense with trees exceeding 25 meters in height and 25 to 40 cm in diameter (Tuan et al. 2002).

2.1.8 Salinity

Mangrove forests have a wide range of salinity (Davis 1940) and their growth is often limited by the stress from high salinity levels. Although mangrove soils are typically saline, they often vary depending on freshwater input, precipitation, evapotranspiration, and the tidal regime. At low elevations, the soils are usually flooded and can maintain saltwater with salinity levels from 33 ‰ to 38 ‰. Areas in high elevations experience infrequent flooding between ebb tides and spring tides and, when combined with freshwater runoff, the salinity may vary from 1 to 25 ‰. In areas with high evapotranspiration and normal tidal flooding, the salinity may increase to over 70 ‰ and the soils can develop hyper saline conditions (Mendelssohn and McKee 2000).

Salinity in mangrove systems changes from season to season and with different mangrove types. For example, the riverine mangrove system is often flushed with freshwater,

making the soil salinity less than that of seawater. In contrast, basin mangrove systems can have higher salinity levels than that of seawater because of evapotranspiration (Mitsch and Gosselink 2000). For instance, mangrove forests in North Queensland, Australia have a salinity ranging from 30 ‰ to 50 ‰, generally higher than that of the overlying water (Boto 1984).

In the coastal zone, the infestation of salt into the creek system is usually dependent on the stratification phenomenon. Salt infestation into the creek system is low during the rainy season because there is no strong mixing of freshwater and seawater. This is because a strong freshwater influx from the creek combined with ebb tide conditions allow freshwater which has a lower density, to dominate the top of the river water over seawater which has a higher density. This process is referred to as the stratification phenomenon (Uncles et al. 1992). Salt infestation is higher during the dry season. Lack of freshwater input and spring tides reduce the stratification of freshwater and seawater in the creek system. Strong tidal circulation leads to the mixing of freshwater and seawater and helps to push the newly mixed river water from the estuary into the creek system. Therefore, freshwater input is the main factor in determining salinity distribution of the mangrove creeks (Uncles et al. 1992).

Many mangrove species are either obligate halophytes or facultative halophytes and; therefore, can adapt to different salinity conditions. The botanical structure of these species copes with high salinity through the process of salt exclusion or salt restriction. However, salt tolerance is different from species to species (Chapman 1976b, Clough and Attiwill 1992). Some species can only tolerate salinity under 35 ‰, while others can survive hyper saline conditions. For example, *Rhizophora mangle* can grow in soil with salinity at 65 ‰ (Teas 1979) while *Avicennia marina* and *Lumnitzera racemora* can survive in soil with salinity as high as 90 ‰ (Macnae 1968). In general, mangrove species can tolerate high salinity for a

short period of time only, and the tolerance level is different for each species and at each location (Clough and Attiwill 1992).

2.1.9 Oxygen and Phytotoxins

Mangroves usually grow in waterlogged soil and must tolerate reduced conditions (Mitsch and Gosselink 2000). When a soil's rate of oxygen diffusion is low, the biological activity of microorganisms is also low (Clough and Attiwill 1992). Oxygen is depleted in waterlogged soil because the oxygen diffusion in water is slower by 10,000 times than that of air. Oxygen depletion requires soil microorganisms to use alternate oxidants such as nitrate (NO^{-3}), manganic manganese (Mn^{+4}), ferric iron (Fe^{+3}), and sulfate (SO_4^{-2}) as electron acceptors for energy leading to a low redox potential (Gambrell and Patrick 1978). Normal Eh values of waterlogged soil ranges from + 300 to - 250 mV, and its variance depends on the soil texture, oxidant availability, flooding duration and frequency, and organic matter content (Mendelssohn and Postek 1982, McKee, Mendelssohn and Hester 1988, Clough and Attiwill 1992, McKee 1993, Thibodeau and Nickelson 1986, Mitsch and Gosselink 2000, Mendelssohn and McKee 2000).

The redox potential in reduced soils influences soil biochemistry and varies depending on location. Wetland soils are even more reduced, and the lack of oxygen diffusion in wetland soils cause microbial populations to use alternate electron acceptors as primary electron acceptors (Gambrell 1994). In anaerobic soil, Eh can range from + 300 to -250 mV compared to aerobic soil (+ 400 mV to + 700 mV) (Delaune and Pezeshki 1991). When redox potential reaches + 400 mV to + 200 mV, oxygen (O_2), nitrate (NO_3^-), and manganese (Mn^{4+}) are reduced to water (H_2O), nitrogen (N_2) and manganous ions (Mn^{2+}), respectively. When a soil is in a complete reduced condition, redox potential can range from -200 mV to -100 mV and ferric iron (Fe^{3+}) will be reduced to ferrous iron (Fe^{2+}). When the soil is highly reduced, sulfate (SO_4^{2-}) is reduced to sulfide (S^{2-}). In very highly reduced

conditions, or when Eh is at the lowest levels, carbon dioxide (CO_2) is reduced to methane (CH_4) (Patrick and DeLaune 1977). Tomlinson (1986) has documented that complete lack oxygen occurs in soil layers deeper than 5 cm.

In wetland soil, oxygen may be enhanced by crab and worm holes (Clark and Hannon 1969) and by oxidized rhizospheres created by plant roots. Through these means, mangrove species can decrease the reduced condition in soils (Mendelssohn and McKee 2000). Increasing soil drainage is another method to increase oxygen diffusion into the soil and thereby decrease reduced conditions in mangrove wetlands (Mitsch and Gosselink 2000).

Most plants that grow in inundated environments can be damaged by the accumulation of soil phytotoxins (Mendelssohn and McKee 2000). Mangrove soil is often inundated with seawater and the soil pH is close to neutral. However, the soil can become extremely acidic, if it is drained and becomes oxidized due to sulfuric acid formation (Mitsch and Gosselink 2000). In marine environments, sulfate is the second most abundant anion in seawater and it can accumulate and be reduced under anaerobic conditions. The reducing process depends on the absence of oxygen in the soil and strongly reducing conditions (Postgate 1959) and the process can create toxic sulfide, which is one of the factors controlling mangrove species distribution.

2.1.10 Nutrients

Nutrients in mangrove forest soil are controlled by various biogeochemical processes including tidal regime, litter accumulation, and litter decomposition. Geographical location, elevation, soil properties, and microbial activities collectively affect the amount of nutrients in the mangrove soil (Boto and Wellington 1984, Lacerda et al. 1993). Nutrients are abundant further inland and in locations where freshwater input is high. Soil in high elevation usually contains more nutrients than soil in low elevation due to increased organic matter accumulation. Physical and chemical properties of soil, especially the redox potential, are

factors that also significantly affect nutrients on both the macro and micro levels (Clough and Attiwill 1992, Alongi 1997). For example, the water inundation that occurs in mangrove soils can lead to extreme redox potentials that lessen nutrient availability in soils. And finally, microbial activities generate humic and fluvic acid, and metal complexes which can increase nutrients in soils (Alongi 1997).

Nitrogen availability is limited in the mangrove ecosystem (Boto 1982, Mendelssohn and McKee 2000) due to high levels of sodium and the denitrification process. In wetland soils, ammonium is the main form of inorganic nitrogen. However, high levels of sodium in most mangrove soils displace ammonium, which is then washed away from the soil by heavy rain, water runoff, or tidal flushing (Clough and Attiwill 1992, Alongi 1997, Alongi et al. 1992). The remaining ammonium interacts with oxygen and is oxidized to nitrate (Ponnamperuma 1972). Through the denitrification process, nitrate is microbially transformed to N2O and N2, which are lost to the atmosphere. Through denitrification and leaching, nitrogen become limiting in the mangrove ecosystem. Organic phosphorus and dissolved inorganic phosphorus are low in the water currents of mangrove forests, and they often occur mainly in the form of HPO_4^{2-} at seawater pH (Alongi et al. 1992). Similar to nitrogen in the wetlands, dissolved phosphorus concentration is also affected by salinity concentration in that dissolved phosphorus decreases with increasing salinity (Robertson and Blaber 1992). In estuary regions, phosphorus concentration is dependent on the amount of rainfall. The lowest concentration is found in the dry season when primary production is optimal (Sarala Devi et al. 1983, Balakrishnan Nair et al. 1984 as cited in Alongi et al 1992).

Inorganic phosphorus in mangrove sediments is usually limited due to its absorption or strong binding to other elements such as calcium and iron (Boto and Wellington 1984). Inorganic phosphorous is especially limited for plants in sandy soil environments (Alongi 1997). Limited amounts of available phosphorus have been known to slow the growth of

mangrove forests (Broome et al. 1975, McKee and Feller 1994, Feller 1995). Phosphorus concentration varies by season, temperature, rainfall, oxygen availability, sediment type, and plant uptake (Boto 1982, 1984). Whereas the amount of ammonium is lower in reduced sediments, the amount of available phosphorus is often higher in reduced sediment (Mendelssohn 1979). As mentioned above, inorganic phosphorus in mangrove sediment is bounded by calcium, iron, and aluminum phosphates, and the inorganic phosphorous proportion increases with increasing in depth. Organic phosphorus concentration, conversely, is often higher near the soil surface (0-25cm) and affects the uptake of phosphorus by roots (Alongi et al. 1992).

In summary, the available nutrients in mangrove forests are affected by factors such as tidal regime, soil properties, microbial activity, salinity, and elevation. The tidal regime affects the distribution of mineral sediments and soil redox status, which controls the available inorganic forms of nutrients as well as nutrient formation and transformation (Mendelssohn and McKee 2000). Most nutrients in sediment are depleted by various processes and elements, but their levels can be maintained or increased with increases in tidal height, water inundation, interstitial salinity, redox potential, and pH (Alongi 1997). Organic matter and soil nutrients such as total and available nitrogen and phosphorous are relatively high landward but decrease as the soil progresses toward sea level (Tam and Wong 1997).

2.1.11 Community Structure

The term "structure" is used to describe mangrove forests' group characteristics such as species composition, biodiversity, tree height, stem diameter, basal area, tree density, age class distribution, and spatial distribution patterns (Smith 1992). Mangrove forests are easily recognized by their homogeneous species zonation characteristics (Snedaker 1982, Mendelssohn and McKee 2000). Their structure and species zonation are related to the hydrological regime. Each of the hydrological regime types can describe the characteristics of

one or more mangrove forest types. Different hydrological regimes result in more than 50 mangrove species around the world, but less than 10 species are found in New World, and only 3 dominant species are found in the Florida mangrove swamps. Red mangroves (*Rhizophora* spp.) are dominant in fringe mangrove forests, especially along the edges of the coastal lines, because of their dense prop roots. Black mangroves (*Avicennia* spp.) and white mangroves (*Laguncularia* spp.) frequently occur in riverine mangrove forests (Mitsch and Gosselink 2000). Other hydrological mangrove forest types, such as Basin mangrove forests, consist of all species with mixed structural patterns.

2.1.12 Zonation

Zonation refers to the natural succession phenomenon of mangroves in which pioneer species are established and develop in a new environment, followed by the other mangrove species. Environmental changes such as changes in elevation and varying of the tidal regime form new exposed mudflats allowing for the establishment and development of pioneer mangrove species (Thom et al. 1975). Strong zonation of mangrove species varies depending on local conditions, species composition, and recurring patterns. Each mangrove species forms a mono-specific band along the coastlines (Tomlinson 1986). The band's characteristics are a direct response to the individual species, variation in tidal inundation, salinity, freshwater input, and sediment composition (Semeniuk 1980, 1983). Different species or groups of species of mangroves can be found at different elevations and locations (Davis 1940). The interaction between the different species and individual trees or the competition between interspecific and intraspecific species plays an essential role in mangrove species zonation (Ellison et al. 2000).

The zonation ability of different mangrove species can be predicted by observing the environmental stress factors and the species competition (McKee 1995a, McKee 1995b, Ball 1980). Mangrove zonation further depends on the shape, size, and buoyancy of the

propagules (Rabinowitz 1978). For example, the propagules of *Avicennia germinans*, *Avicennia bicolor*, and *Lumnitzera racemosa* in Panama are carried further inland and establish themselves in higher elevations because of their high buoyancy and small size. In contrast, *Rhizophora mangle* and *Rhizophora harrisonii*'s propagules are larger and less buoyant, so they are found mainly in the lower intertidal zones (Chapman 1976b). However, in the Old World, *Rhizophora apiculata* are populated in the high intertidal zones, while *Avicennia* spp. and S*onneratia* spp. are found in the low intertidal zones.

Seed predation is another important factor determining mangrove zonation (Mendelssohn and McKee 2000). There are negative correlations between propagule predation rates and same species domination in some mangrove forests, and mangrove communities form where there is less floristic diversity (Lugo and Snedaker 1974).

In summary, mangrove zonation is determined by the climatic and tidal environment of a specific region. Land surface history, geomorphic and pedogenic processes have to be considered in studying mangrove zonation (Thom 1982). Mendelssohn and McKee (2000) suggest four basic processes to species zonation in mangrove ecosystems. The first process includes the dispersal and establishment of seeds or propagules. The next process consists of the attraction of seeds or propagules to predators. Seeds or propagules that are not consumed by predators have a greater chance to establish and develop. The third process takes into account the ability of species to tolerate different types of stress. High tolerance of stress increases the survival of a species and increases zonation. And finally, the last process focuses on the interspecies and intraspecies competition. Less competition will also increase mangrove zonation.

2.1.13 Primary Production

The mangrove wetland is an ecosystem with high primary productivity. However, accurate determinations of the standing biomass and net primary production of the mangrove

ecosystems is difficult to measure due to a wide range of hydrodynamic and biogeochemical conditions (Mendelssohn and McKee 2000, Mitsch and Gosselink 2000). However, many researchers have attempted to measure the standing biomass and net primary production of many mangrove forests in the world utilizing both direct and indirect methods. Mangrove production may be measured using four methods: measurement of litter fall, estimation of gas exchange, measurement of tree diameters, and the direct harvesting of standing trees with known age (Mendelssohn and McKee 2000).

Most data available on mangrove primary production are based on the litter fall rates, which vary from of dwarf forests at 2 metric tons $ha^{-1}yr^{-1}$ to that of riverine forests at 13 metric tons $ha^{-1}year^{-1}$. These data indicate that mangrove production decreases as they progress toward the subtropics from latitudes 0 to 20^{o}. Estimation of the net primary production from litter fall data in North American mangrove forests indicates that *Rhizophora mangle* is the highest net primary producer followed by *Avicennia germinans* and *Laguncularia racemosa* (Lugo et al. 1975). Using both the estimation of gas exchange and the measurement of litter fall methods to approximate primary production of riverine, basin, and scrub mangrove forests, previous study reported primary production ranging from 1,100 to 5,400 g m^{-2} $year^{-1}$ (1 g C = 2 g dry weight) for these forest types. Most primary production is higher in riverine mangrove forests than in scrub mangrove forests. From data collected in a Mexican mangrove forest, Day et al. (1987) found that primary production varies from 1,607 g m^{-2} $year^{-1}$ in fringe forests to 2,458 g m^{-2} $year^{-1}$ in riverine forests. Also in Mexico, Day et al. (1987) found a low net primary production in basin mangrove forests, ranging from 400 to 595 g m^{-2} $year^{-1}$. It was suggested that the productivity of riverine mangrove forests is influenced by nutrient and freshwater input, while the productivity of basin mangrove forests is influenced by the salinity and hydrological regime (Day et al. 1987).

The biomass of mangrove forests is often estimated by measuring directly from the stem diameter at diameter breast height (DBH) of 1.3 m (Clough and Attiwill 1992). Studies on old mangrove forests in Asia and in the Pacific, report above ground biomass ranging from 500 to 550 ton ha^{-1}. Above ground biomass may reach up to a maximum value of 700 ton ha^{-1} in undisturbed mangrove forests in the warm and humid tropics such as in the *Rhizophora* forest in north Australia. However, the ground biomass is less in areas with low temperature, arid climate, hyper saline soil and limited nutrients. Measurement of 10 year old standing *Rhizophora apiculata* on the west coast of the Malaysian peninsula showed that the mean annual above ground biomass reached 18 ton ha^{-1}. Study in Thailand, a man-made 6 to 14 years old *Rhizophora candelaria* has above ground biomass from 14 ton ha^{-1} to 33 ton ha^{-1}. In Vietnam, the above ground standing biomass of mangroves is higher than other areas. For example, in Thanh Phu, Ben Tre the above ground biomass of *Rhizophora apiculata* mangrove forests has been reported to be from 158 ton ha^{-1} to 415 ton ha^{-1} (Haanstra et al. 2002). Whereas in Tam Giang, Ca Mau the above ground biomass of *Rhizophora apiculata*s was measured to be significantly higher: from 218 ton ha^{-1} to 258 ton ha^{-1}. Free tidal movement in the region of Tam Giang, Ca Mau accounts for the high above ground biomass of *Rhizophora apiculata* (Haanstra et al. 2002).

2.2. Can Gio Biosphere Reserve

2.2.1 Topography

Mangrove forests in Can Gio have a concave shape with the lowest elevation being less than 1.5 m in the center of the forest. Elevation decreases gradually from the east to the south and the west. The highest elevation can be found in Giong Chua Hill located in compartment 14 at 10.1 m elevation (Tuan et al. 2002). The terrain of Can Gio can be divided into five categories based on mean sea levels. The first category consists of areas up to 0.2 meters in height. These areas are usually inundated with water and flood twice daily. The

second category consists of areas that are moderately inundated with water and flood once a day. These areas are from 0.2 m to 0.5 m in height. Areas that are 0.5 m - 1.0 m in height comprise the third category. Areas in the third category are rarely inundated with water and only flood once a month. Areas that are 1.0m- 1.5m in height belong to the fourth category and only flood yearly at high spring tides. And finally, category five consists of areas over 1.5m in height that flood infrequently, approximately once every few years (Nam 1994).

The topography of Can Gio is formed by alluvial from two main sources, the Soai Rap River and the flow from the Long Tau, Go Gia, and Thi Vai Rivers. The strong river flows of the Soai Rap River deposit a vast amount of alluvial in the estuary regions. Continuous deposition of alluvial builds up the morphology of the mangrove forest, moving it eastward away from the Soai Rap River. The flow from the Long Tau, Go Gia, and Thi Vai Rivers also deposit alluvial in the estuary. However, due to strong marine dynamics, the soil is eroded, especially in the Go Gia estuary, causing the morphology of the mangrove forest to move toward a northwest direction (Tuan et al. 2002).

2.2.2 Soil

Alluvial that was deposited in the swamp from the Saigon and Dong Nai Rivers form the soil of the mangrove forests in Can Gio. Soil development depends mainly on the high precipitation and density of the river systems. These complex river systems provide large alluvium deposition in the estuarine regions.

Four main soil types can be found in the Can Gio mangrove forests: 1) saline soil, 2) saline soil with low aluminum content, 3) saline soil with high aluminum content, and 4) soft sandy soil with mud deposits at the seashore (Tuan et al. 2002). According to Tu (1996), soil classification in the Can Gio mangrove forest is based on the three main salinity types: hypersaline-acidic soil, salinity-acidic soil, and saline soil. Hypersaline-acidic soil is soil with high total dissolved salts of up to 28 ‰ at the surface that can increase up to 38 to 45‰

in the layers below. Salinity-acidic soil is soil with considerable variation in salinity and acidity throughout the year and in different layers. Saline soil is soil that receives strong and direct effects from the sea. The salinity concentration of the saline soil depends on the influence of the tides. Saline soil is high in conductivity, total dissolved salts, and sodium exchange with a neutral pH at the surface layer and a more acidic pH in the deeper layers.

2.2.3 Climate

The climate of the Can Gio mangrove forest is characterized by tropical monsoons, which includes two seasons: the rainy season and the dry season. The rainy season is from May to October and the dry season is from November to April. The yearly average range of rainfall is from 1,300 to 1,400 mm. The highest rainfall occurs in September with rainfall from 300 mm to 400 mm. The amplitude of the daily average temperature varies from 5^{o} C to 7^{o} C. The monthly average temperatures are highest from March to May, and lowest from December to January, with the monthly average temperature ranging from 25.5 to 29.0^{o} C (Bich 1988). A yearly average temperature of 25.8^{o} C was measured at Do Hoa Gauging Station. The daily average solar radiation is always above 300 cal cm^{-2}. The maximum monthly average occurring in March at 14.2 K cal cm^{-2} and the minimum monthly average occurring in November at 10.0 K cal cm^{-2}. Radiation intensity does not vary significantly between the dry and rainy seasons (Tri et al. 2000, Tuan et al. 2002).

Humidity in Can Gio is usually higher than other areas in Ho Chi Minh City. During the wet season, humidity ranges from 79 % to 83 % with the most humid month being September. During the dry season, humidity ranges from 74 % to 77 % with the minimum humidity in April. The daily average evaporation is 4 mm with the highest occurring in April at approximately 8 mm day^{-1} and the lowest occurring in March at 3.5 to 6 mm day^{-1}. The monthly average evaporation is 120.4 mm with the highest monthly evaporation rate in June at 173.2 and the lowest in September at 83.4 mm (Tri et al. 2000, Tuan et al. 2002).

Two main wind directions can be found in Can Gio: southwest and northeast. The southwest direction occurs during the rainy season with the strongest velocity during July and August. The northeast direction occurs during the dry season with the strongest winds in February and March (Tuan et al. 2002).

2.2.4 The Destruction and Reforestation of the Can Gio Mangrove Forest

The total natural area of the Can Gio District covers an area of about 73,360 ha. During the two Indochina wars, most of the mangroves in Can Gio were destroyed (Hong 1977) and the species *Rhizophora apiculata, Rhizophora mucronata* disappeared. Some species remained in small groups. *Ceriops tagal* and *Eceocaria agallocha* regenerated naturally along the waterways, *Avicennia sp.* can be found in flooded areas, and *Phoenix paludosa* and *Acrostichum aureum* can be found on higher land.

In 1978, under support of the city government and the city forestry service, *Rhizophora apiculata* was planted in any uncovered lands as part of the reforestation process. The 22 years invested in the Can Gio mangrove reforestation has made it one of the largest reforestation areas in Vietnam, and it was recognized as an international biosphere reserve on January 21, 2000. Like other biosphere reserves in the world, the Can Gio Mangrove Biosphere Reserve serves three functions: 1) biodiversity restoration, 2) stimulation of environmentally responsible cultural and economic development; and 3) training, research, and education with regard to mangrove ecosystems.

The Can Gio Biosphere Reserve is divided into three zones: the core, the buffer, and the transition zones. Close relationships exist among the three zones. The core zone covers an area of 4,721 ha and was established with the long term purpose of landscape conservation and species biodiversity. This zone is strictly protected from human activities and is limited for research and monitoring purposes. In some cases and under close governmental supervision, local people are allowed to exploit natural resources through activities such as

fishing and harvesting to maintain their traditional ways of life. The second zone, the buffer zone, surrounds the core zone and covers an area of about 37,339 ha. Its purpose is to act as a buffer and to prevent any harmful activities impacting the core zone while creating large spaces for wildlife, providing a natural landscape, and serving as a cultural and ecological tourist destination. The last zone in the Can Gio Biosphere Reserve is called the transition zone. The transition zone covers an area of approximately 29,310 ha and is the outermost surrounding area and is important for maintaining socio-economic activities and promoting the development of the Can Gio district (Tuan et al. 2002).

2.2.5 The Flora

The Can Gio Mangrove Forest is located in the fourth zone of the Vietnam mangrove categorization system (Hong and San 1993). The prosperity of species in this location is similar to the richness of the mangrove species found in the Malaysian and Indonesian archipelagos. Using the list of 36 true mangrove species from Vietnam, Hong (1993) identified 33 species belonging to 19 genera and 15 families in Can Gio. However, Huynh (1997) recorded 42 species belonging to 36 genera and 24 families. In addition to the true mangroves and associated mangroves groups, there is also a list of immigrant species totaling up to 128 species belonging to 80 genera and 47 families (Huynh 1997). The Can Gio mangrove biodiversity and its individual characteristics are listed below in accordance with Hop (2001):

1. *Avicennia alba:* dominates and colonizes newly formed mudflats and also associates with *Sonneratia caseolaris and Avicennia officinalis.*

2. *Sonneratia alba*: high salinity tolerance; often distribute in coastal areas and newly formed alluvial flats in estuaries.

3. *Avicennia alba* & *Sonneratia alba* association: distribute along estuaries, riverbanks, and water inundated mudflats.

4. *Avicenniaceae* & *Rhizophora apiculata* association: develop prosperously on soil that is more stable.

5. *Rhizophora apiculata* association: covers large areas of stable land, it can be replaced gradually by planted associations. This is an important forest type that is dominant in total mangrove ecosystem areas.

6. *Rhizophora apiculata* & Shrub association: develops on higher land with small tree species, starting to be replaced by *Rhizophora apiculata*.

7. *Rhizophora mucronata* association: plants on higher mudflats, but not well adapted to the natural condition.

8. *Avicennia marina* association: distributes on compacted soil, higher tidal areas, and it has become accustomed to abandoned salt-ponds.

9. *Lumnitzera racemosa* association: distributes on higher ground, in stable clay that is rarely flooded by the tides. Also grows in abandoned salt-ponds.

10. *Phoenix paludosa* association: distributes on higher land with compact clay that rarely floods. It is often stands pure or is mixed with *Acrostichum, Pluchea indica, Thespesia populnea, and Hibicus tiliaceus.*

11. Cerios sp - Lumnizera racemora - Excoecaria agallocha association: distributes on compacted clay that rarely floods, and on higher land mixed with Acrostichum, Pluchea indica, Thespesia populnea.

12. *Arostichum aureum* association: wide distribution from saline to brackish water, on high land which floods only during spring tides.

13. *Sonneratia caseolaris* association: distributes on newly formed alluvial flats along brackish river banks, pure stands or mixed with *Avicennia alba, Avicennia officinalis* depending on the land elevation.

14. *Nypa fruiticans* association: distributes along low saline riverbanks, where the alluvial soil is developed. Pure stand or mixed with *Cryptocoryne ciliata, Acanthus ebracteatus, rushes, reeds* etc.

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CHAPTER 3

STUDY AREA DESCRIPTION AND EXPERIMENTAL DESIGN

3.1 Study Area Description

The MHO-8, a research and development project in the coastal zone of the Mekong Delta Vietnam is collaboration between Can Tho University of Vietnam and Wageningen Agriculture University of The Netherlands. This dissertation research was carried out in the Can Gio Biosphere Reserve (Figure 3.1) located in Can Gio District of Ho Chi Minh City in the southern part of Vietnam. Its latitude is 10°22'14''N – 10°40'09''S, and its longitude is 106°46'12''E – 107°00'59''E (Tuan et al. 2002).

Starting in 1978, mangrove forests in the Can Gio Biosphere Reserve, which were impacted by chemical warfare, were planted several times and resulted in different age classes of the forests. After 22 years of restoration and development, in January 21 2000, the mangrove forests were recognized as an International Biosphere Reserve. The total area of the Can Gio Mangrove Biosphere Reserve is 75,740 ha and can be divided into three zones: (1) the Core Zone is 4,721 ha and comprises high biodiversity mangrove ecosystems receiving full protection, (2) The Buffer Zone which is 37,339 ha and primarily functions to protect the core zone, and (3) the Transition Zone of 29,310 ha including coastal areas and seagrass beds, which can be used by local people to provide products and services (Tuan et al. 2002, Tri et al. 2000).

The topography of the Can Gio mangrove forests varies considerably with a minimum elevation range from 0 m - 1.5 m in northeastern region. The highest elevation is 10.1 m, occurring at Giong Chua "Hill" in Compartment 14 (Figure 3.1) (Tuan et al. 2002). The topography can be divided into five categories based on elevation relative to mean sea-level: (1) Elevation from 0.0 m - 0.2 m and flooded twice a day, (2) Elevation from 0.2 m - 0.5 m

and flooded once a day, (3) Elevation from 0.5 m - 1.0 m and flooded monthly, (4) Elevation from 1.0 m - 1.5 m and flooded only during high spring tides, and 5) Elevation over 1.5 m and seldom flooded (Nam et al. 1994).

Based on salinity, three main soil types can be recognized in the Can Gio district: (1) Hyper-saline acid soil with total dissolved salts of 28 ‰ at the surface and increasing to 38 - 45 ‰ in deeper soil layers, (2) Saline acidic soil with low salt concentration that varies considerably with depth and season, and (3) Saline soil with high conductivity, large total dissolved salts, high sodium exchange, and neutral pH at the soil surface and decreasing with depth (Tu 1996). Tuan et al. (2002) classified basically on aluminum, the soils in the Can Gio mangrove forest can be divided into four types: (1) Saline soil, (2) Saline soil with low aluminum content, (3) Saline soil with high aluminum content, and (4) Soft sandy soil with mud deposits at the coastline.

The climate of the Can Gio mangrove forest is of the tropical monsoon type with high humidity, high temperature, and a wet season from May to October and a dry season from November to April. The average annual precipitation ranges from 1,300 – 1,400 mm with the highest rainfall in September (300 – 400 mm). The annual average temperature is 25.8 ^{o}C and monthly average temperature is from 25.5 – 29.0 ^{o}C, with the highest temperatures occurring from March to May and the lowest from December to January. Solar radiation is always above 9 Kcal cm^{-2} month^{-1}, it is highest in March at 14.2 Kcal cm^{-2} month^{-1} and lowest in November at 10 Kcal cm^{-2} month^{-1} (Bich 1988, Tri et al. 2000, Tuan et al. 2000). During the wet season, humidity varies from 79 % - 83 % and is highest in September. During the dry season, humidity varies from 74 % - 77 % and is lowest in April (Tuan et al. 2002). Daily average evaporation is 4 mm, and is highest in April at around 8 mm day^{-1} and lowest in March at 3.5- 6 mm day^{-1}. The monthly average evaporation is 120.46 mm day^{-1} and is highest in June at 173.27 mm month^{-1} and lowest in September at 83.4 mm month^{-1}. During

the rainy season, the wind direction is southwesterly and is strongest during July and August. In the dry season, the wind direction is a north–northeasterly and is strongest in February and March (Tuan et al. 2002).

3.2 Study Site Selection

A preliminary survey was conducted of all the existing mangrove ecosystems in the Can Gio Biosphere Reserve. The mangrove ecosystems were evaluated and identified based upon their plant species, land elevation, and tidal regime. From this initial survey, two different regional mangrove ecosystems were chosen for the study: (1) A rarely flooded, high elevation mangrove system that is dominated by species such as the *Phoenix paludosa, Ceriops decandra, Acrostichum aureum, Rhizophora apiculata, Avicennia officinalis, Exceocaria algallocha*, *Hibiscus* sp and *Lumnitzera* sp. (2) A frequently flooded, low elevation mangrove ecosystem that is dominated by species such as *Rhizophora apiculata, Avicennia alba* and *Ceriops decandra*, but also containing *Avicennia officinalis* and *Acrostichum aureum*. Both sites are located in Compartment 17 (Figure 3.1), adjacent to the Dong Tranh River. The effect of hydrology on the structure and function of these two regional mangrove systems was selected for study. These two mangrove systems were selected for investigation because they are typical of high and low elevation mangrove forests in the Can Go Reserve. Therefore, the effects of differential hydrology on selected aspects of mangrove structure and function could be investigated.

3.3 Experiment Design

The low and high mangrove ecosystems are named Khe Vinh (KV) and Mui O (MO), respectively (Figure 3.2). Three replicate transects about 600 to 800 m long were set up perpendicular to the riverside at KV (Figure 3.3), and three replicate transects about 200 m long were delineated at MO (Figure 3.4). Depending on mangrove species composition, three zones were identified on each transect for both sites. At the Khe Vinh site, Zone 1

(Avicennia) was dominated by *Avicennia alba*, Zone 2 (Species transition) was a mixed zone of *Rhizophora apiculata*, *Avicennia alba*, *Ceriops decandra* and some minor species, and Zone 3 (Rhizophora) was dominated by *Rhizophora apiculata*. At the Mui O site, Zone 1 (Phoenix, Ceriops..,) was dominated by *Phoenix paludosa* and some minor species such as *Ceriops decandra*, *Acrostichum aureum, Exceocaria algallocha, Hibiscus tiliaceus* and *Lumnitzera* racemosa, Zone 2 (Species transition) was a mixed zone of *Rhizophora apiculata* and *Ceriops decandra*, and Zone 3 (Rhizophora) was dominated by *Rhizophora apiculata*. Within each zone on each transect, three replicate 20 m x 10 m plots were identified for sample collection.

A factorial design was used to statistically evaluate main effects and interactions. The main effects were "study site", comprising Khe Vinh and Mui O, "season", comprising dry season and wet season, and "zone", comprising zone 1, zone 2 and zone 3, as previously described. JMP statistical software was used to analyze the vegetation and environmental data. Significant differences among means were determined by the Tukey-Kramer post hoc test. All measured responses including, vegetation, soils, sedimentation, decomposition, and hydrology were analyzed with this statistical design.

Hydrologic variables such as ground water, groundwater electrical conductivity and flooding frequency were also collected. Litter fall, biomass, decomposition, sedimentation, species distribution and frequency, and soil monitoring of soil nutrients and soil composition were conducted as described in specific research chapters.

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Figure 3.1 A map of Vietnam showing the location of the Can Gio Mangrove Biosphere Reserve (Picture source: Management Department of Can Gio Mangrove Biosphere Reserve)

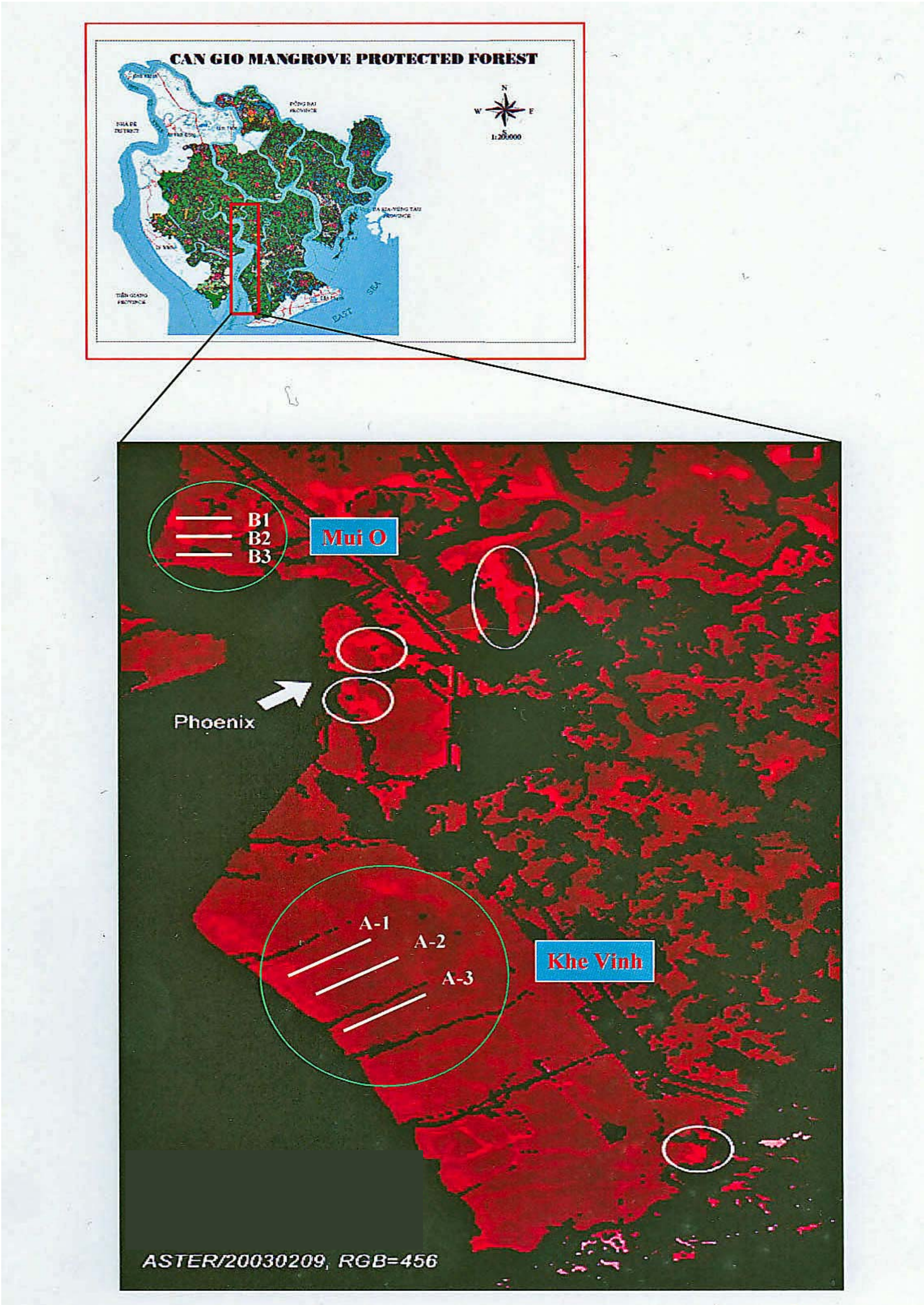

Figure 3.2 Location of the Khe Vinh (KV) and Mui O (MO) study sites in the Can Gio Mangrove Biosphere Reserve (Picture source from Management Department of Can Gio Mangrove Biosphere Reserve).

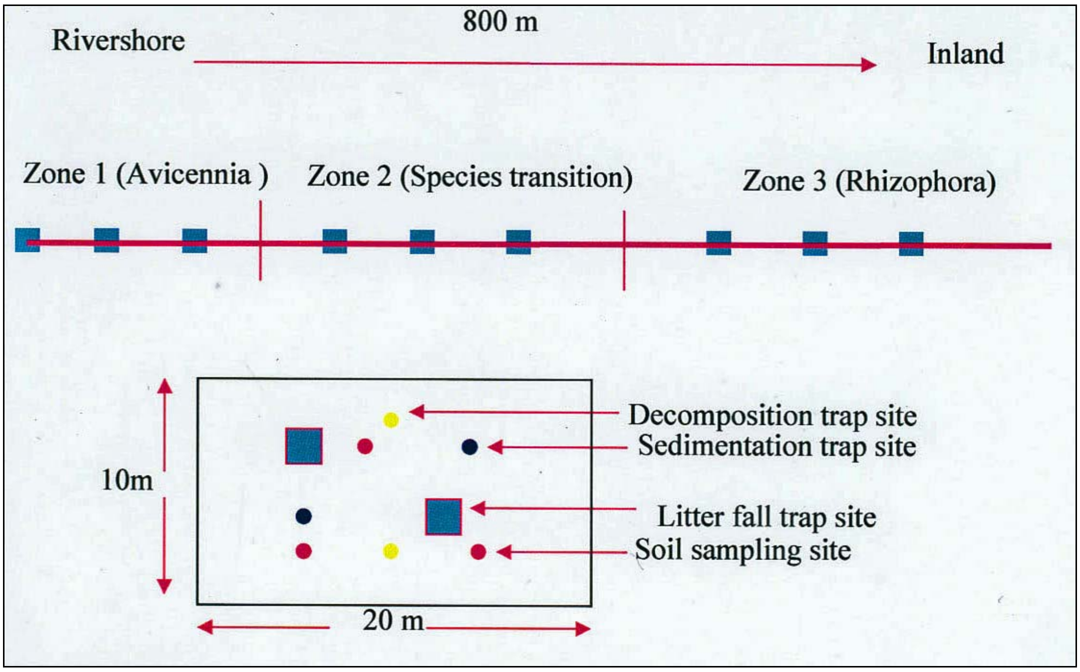

Figure 3.3 Transect design and sample-plots at the KV study site in the Can Gio Mangrove Biosphere Reserve. ■ is three replication sample plots in each zone. The rectangular (10 X 20 m) is described sample plot.

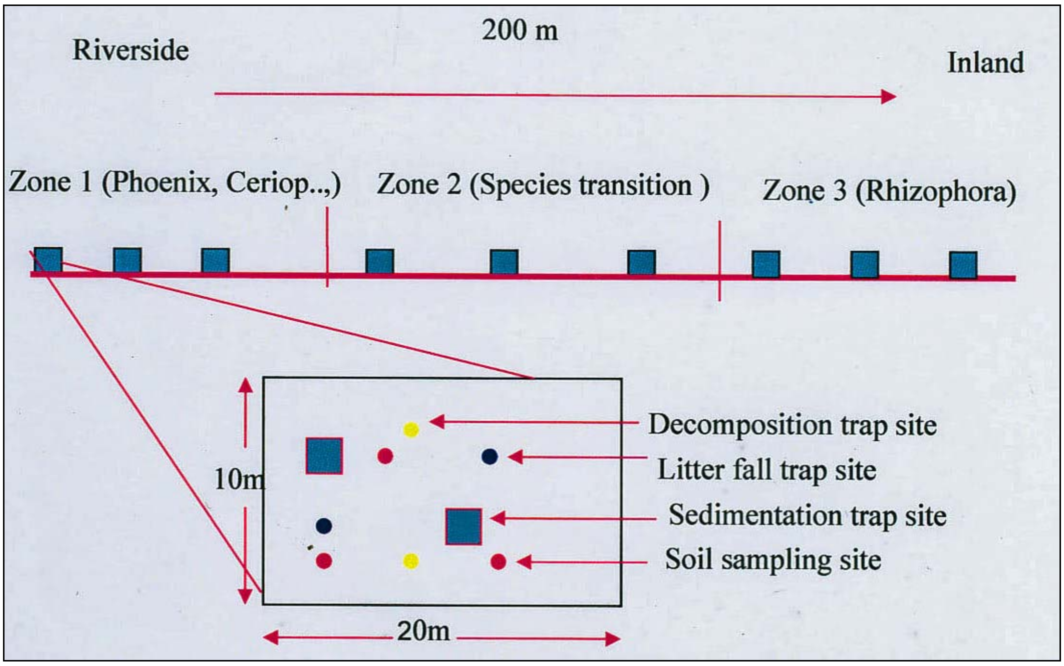

Figure 3.4 Transect design and sample-plot at the MO study site in the Can Gio Mangrove Biosphere Reserve. ■ is three replication sample plots in each zone. The rectangular (10 X 20 m) is described sample plot.

Tuan, L. D., T. T. Oanh, C. V. Thanh, and D. N. Qui, 2002: *Can Gio Mangrove Biosphere Reserve*. Agricultural Publishing House.

Tu, L. V., 1996: Agricultural Land of Ho Chi Minh City and Trend of Utilization. 58-61.

CHAPTER 4

THE HYDROLOGIC REGIME OF THE MANGROVE ECOSYSTEMS AT CAN GIO BIOSPHERE RESERVE

4.1 Introduction

The development and distribution of mangrove forests vary depending on both biotic and abiotic factors (Mendelssohn and McKee 2000). Differences in structure and function of mangroves are reflected in differences in their environmental setting, including their hydrological regime and soil characteristics. Local patterns of hydrology such as tidal wave effects, riverine influences, groundwater inputs, and surface drainage from uplands may affect the chemical and physical characteristics of the soil in mangrove habitats and the physiognomy of the mangrove forest (Lugo and Snedaker 1974). Hydrology plays a primary role in determining wetland structure and function (Nathan et al. 1999). The hydrological regime exerts a tremendous influence on the structure and function of wetlands and also affects abiotic factors such as salinity, soil moisture, soil oxygen, and nutrient availability. It also affects biotic factors such as the dispersal of seeds and propagules (Mendelssohn and McKee 2000). Water depth is commonly recognized as a primary physical factor that varies along elevation gradients in many wetland habitats (Howarth and Mendelssohn 1995). Studies of Kozlowski (1984), Mendelssohn and Burdrick (1988) and others have demonstrated that increased water depth depletes soil oxygen, affecting plant metabolism and growth through mechanisms such as reduced photosynthesis, altered nutrient uptake, and induction of hormonal imbalances. Flooding depth and redox status can control the distribution of mangroves. McKee (1995) demonstrated that the distribution of *Avicennia germimans* and *Rhizophora mangle* is controlled by water depth in the intertidal zone, which can be modified by aeration from above-ground roots (McKee 1993).

The stability of coastal environments allows for the development of a variety of plant communities depending on more local factors associated with hydrology (Twilley and Day 1999). Mangrove zonation occurs at several different spatial scales (Day et al. 1989), and the ecological classification of mangrove forests; such as fringe, basin, or dwarf; helps to describe the microtopographic effects of hydrology on the formation of forest types (Day et al. 1987). Depending on the tidal regime, Lugo and Snedaker (1974) have classified mangrove forests into five types: riverine, basin, fringe, overwash and dwarf. Mangrove development is also based on the influence of inputs from rivers, tides and other coastal processes. Thom (1982) identified five basic types, or classes, of environmental settings. Setting I consists of allochthonous coasts of low tidal range that tend to form deltas. Setting II consists of allochthonous coasts with terrigenous materials that are influenced by strong tidal currents resulting in shallow bays and mud flats. Setting III consists of coasts with minor river influence where autochthonous materials result in the formation of bays and lagoons dominated by higher wave energy. Setting IV consists coasts with combinations of features from both setting I and setting III, having high wave energy and river discharge. Setting V consists of drowned valley complexes.

Although water movement through the mangrove swamp is generally much smaller in magnitude than tidal currents, water movement is essential in determining soil biogeochemical processes and related structural and functional responses. It also has an important effect on the chemistry of adjacent tidal creek water (Wolanski et al. 1999). Ovalle et al. (1990) also showed that the mixing of surface water with ground water in mud flats in the front of the mangrove swamp is an important buffer-mechanism for nutrient exchange between the coast and adjacent mangrove forests. The momentum of the flowing groundwater mixes the bottom water with the overlaying water, resulting in the displacement of anoxic conditions and high phosphate concentrations. When the water leaves the swamp

by groundwater flow, the benthic algae photosynthesizing on the bottom sediment is entrenched in the sediment (Mazda et al. 1990). Groundwater flow is enhanced by the presence of decaying roots, crabs burrows, and other gaps which are important pathways for water, salt and nutrients. Groundwater flow prevents excessive accumulation of salt from evapotranspiration and can help transport nutrients in and out of the swamp (Wolanski et al. 1999).

Hydrological regime (i.e., water depth and flood duration and frequency) affects both the below-ground and above-ground water quality. During high tide, Eh, pH, and salinity levels are high, while PO_4^{-3} and NH_4^+ concentrations are low (Ovalle 1990, Bava and Seralathan 1999). The opposite is true at low tide. During ebb tide, salinity in creek water is low, possibly due to groundwater input to the creek. The out-welling water is enriched with PO_4^{-3} and NH_4^+ (Bava and Seralathan 1999). Salinity and dissolved inorganic nitrogen in water can have a close relationship as dissolved inorganic nitrogen decreases slightly with increasing salinity (Tanaka and Choo 2000).

Because the hydrology and related groundwater variables are important in controlling the structure and function of the mangrove forest, the objective of this chapter is to describe and quantify the hydrology of the Can Gio mangrove forest and how this hydrology affects selected water quality variables. The hydrological investigation addresses questions about the differences in tidal regime between the two study sites. This chapter also describes the effects of season and zone on hydrologic condition, which can influence species composition and performance along the flooding gradient.

4.2 Materials and Methods

The hydrological regime was quantified for the Khe Vinh (KV) and Mui O (MO) study sites, which are located in the 17th compartment of the Can Gio Biosphere Reserve. During initial surveys in early March 2004, the distance between the study sites and their

river mouth was measured by global positioning system (GPS) technology. The distance from KV to the Dong Tranh River mouth is approximately 3 kilometers (km), while the distance from MO to the Dong Tranh River mouth is 8 km. Both sites are affected by the tidal regime of the Dong Tranh River and the China Sea.

4.2.1 Elevation

Dense trees and muddy soil prevented free-movement for data collection. Therefore, a “Laser leveling” approach (UMAREX Softwaffen, GmbH & Co. KG company) was used to measure relative elevation of the soil surface along the transects (Loon 2005). The laser was installed and leveled, and the laser beam was projected on a specific tree (Figure 4.1). The height of the laser point above the soil surface was determined with a measuring tape (Figure 4.1-2a), and the distance from the shoreline to the tree was determined by the same method (Figure 4.1-D2). The laser level was then moved to the other side of the tree, and the laser projected backward to the same tree (Figure 4.1-2). Again the height of the laser point above the soil surface was measured (Figure 4.1-2b). The laser was turned forward again and projected on another tree (Figure 4.1-3). The height of the laser point above the ground surface (Figure 4.1-3a) and the distance to the shoreline (Figure 4.1-D3) were again measured. This procedure was repeated until the end of transect was reached. In this way, elevation was measured in sections of about 20 m between two successive mangrove trees. The different heights of the laser point were converted to height above the soil surface. In this way, the elevation of each section between two successive points along transect could be related to one another.

4.2.2 Hydrologic Regime

The hydrology of the three different vegetation zones (zone 1, zone 2 and zone 3) along each transect was measured and compared between the two study sites during both the dry and wet seasons. The hydrologic regime in the Can Gio mangrove forest was calculated

from tidal level data of the Vung Tau Hydrometerological Station. Tidal data from Vung Tau was applied to the study sites. First, the water level at the KV site was measured at two points, one along transect KV 1 and the other along transect KV 3. The points were named CG1 and CG2, respectively. Each measurement was replicated five times. The measurements were made at exactly 11:00 PM Dec 23, 10:00 AM Dec 24, 5:00 PM Dec 24, 1:00 PM Dec 25 and 8:00 AM Dec 26 in 2004. Second, these data were compared to predicted tidal levels and actual tidal levels at Vung Tau. The predicted level was named VT1 and actual tidal level was named VT2. The data collected at both Can Gio and Vung Tau were analyzed to determine the extent to which they differed. Flooded frequency was calculated for both the KV and MO sites by comparing the soil elevation data with the water level data. The flooding frequency was defined as the number of times the area flooded during the dry and wet seasons of 2005.

4.2.3 Electrical Conductivity (EC)

Electrical conductivity in the Dong Tranh River and the mangrove tidal creek was measured and compared at different points during the dry and the wet season. For the dry season, EC was measured at the beginning of the dry season from Dec 27 to Dec 29, in the middle of dry season from Jan 29 to Jan 31, and at the end of the dry season from Mar 10 to Mar 12. For the wet season, EC was only measured at the beginning of the wet season from May 4 to May 6. Also, differences in electrical conductivity between the river and in the tidal creek were determined. The electrical conductivity was measured by a diver instrument manufactured by Eijkelkamp Agrisearch Equipment Company, the Netherlands (Figure 4.2-A). The diver was suspended by a steel wire in a 4 meter long PVC tube with a 4.5 centimeter diameter (Figure 4.2-B). Holes were drilled along the PVC tube to allow water to flow in and out of the tube. One PVC tube was installed in the mangrove tidal creek and another PVC tube was installed in the river. EC was recorded every 20 minutes. However, because the

divers could not be left in salt water for a long period of time, EC data were only collected from Dec 2004 to May 2005.

4.2.4 Groundwater

Groundwater parameters that comprised EC and groundwater level were measured with peizometers, which are simple polymer tubes with holes that allow water to move in and out easily. There were three transects at each site, and the polymer tubes were installed along each transect. Electrical conductivity (EC) was determined with a conductivity meter, and ground water level was determined by measuring the water level in the peizometer at low tide during both the dry and wet seasons. Groundwater level allowed for determination of soil drainage.

The JMP statistical software (SAS/JMP6, Carey, North Carolina) was used to statistically analyze the data. Significant differences between means were determined by Tukeys HSD at 0.05 probability level.

4.3 Results and Discussion

4.3.1 General Description

Vietnam's coast is bounded by the South China Sea. The tidal regime is predominantly diurnal (Loon 2005); only the southwest coast and part of the middle of Vietnam have semi-diurnal tides. Can Gio, which is located in the southeastern coastal region of Vietnam, has semi-diurnal tides controlled by the China Sea (Tuan et al. 2002).

The Can Gio District has a complex river system (Figure 4.3). Freshwater, originating from the Saigon and Dong Nai Rivers, is discharged to the Can Gio mangrove forest and empties out via the Long Tau and Soai Rap Rivers by the main branches of Thi Vai and Go Gia Rivers. Thus, there is considerable mixing of saltwater and freshwater in the Dong Tranh estuary where this dissertation research took place. The river system covers an area of 32 %

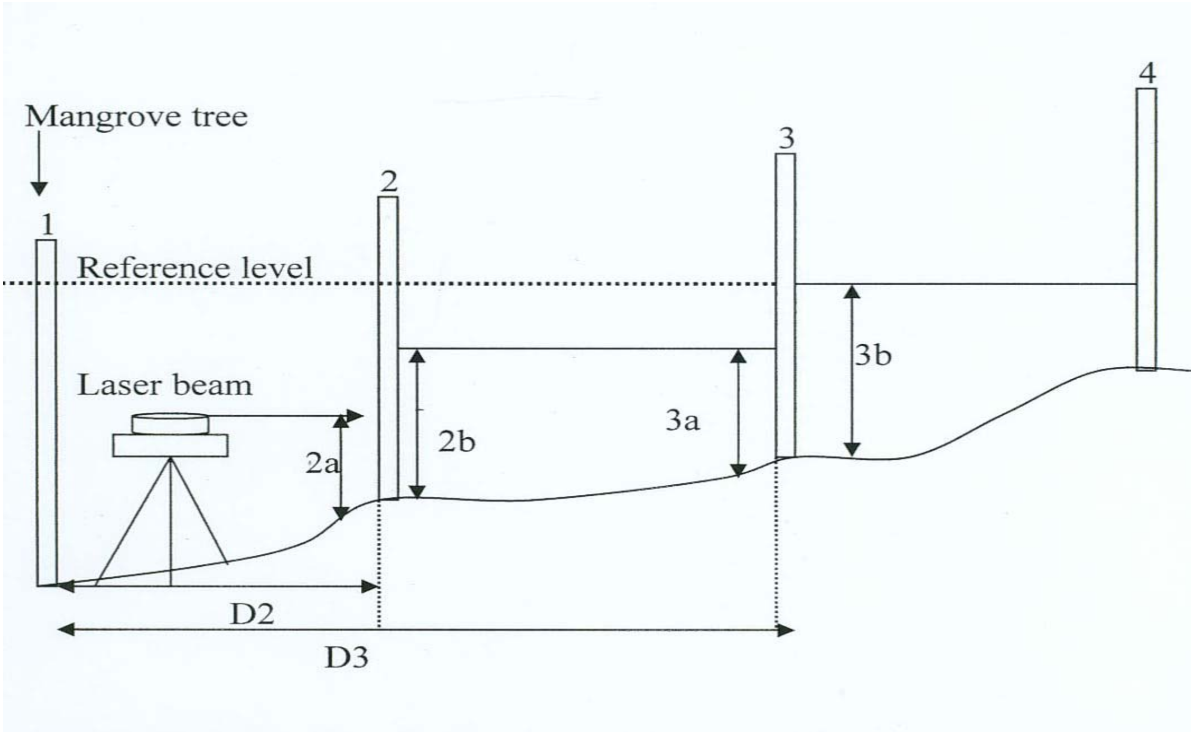

Figure 4.1 Laser leveling method D2 and D3 are the distances from the shoreline to the tree. 2a, 2b, 3a and 3b are the height of the laser point above the soil surface (modified from Loon 2005).

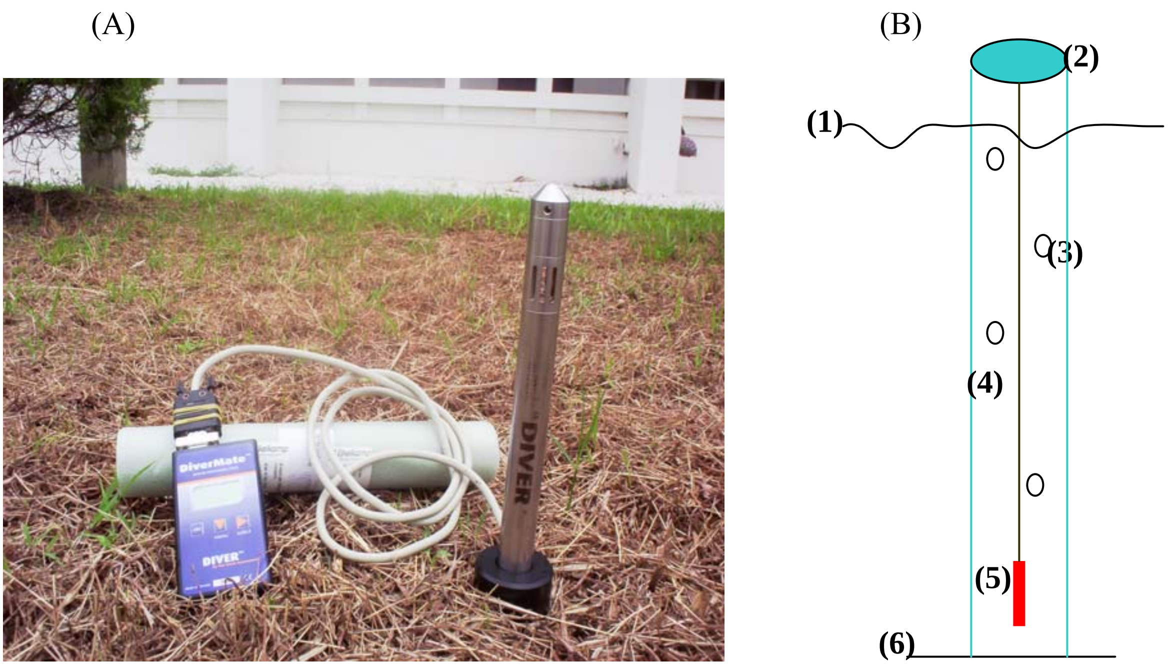

Figure 4.2 (A) Diver instrument for measuring water conductivity. (B) Diver in the water: (1) Water level, (2) PVC tube, (3) Hole, (4) Steel wire, (5) Diver and (6) Soil bottom.

of the total area of the Can Gio District and the majority of these rivers generally flow in a southeasterly direction (Tuan et al. 2002). These rivers affect local topography and the vegetation communities. Long Tau and Soai Rap are the two main terminal branches that affect the hydrologic regime of other subsidiary branches.

The Can Gio mangrove forest lies in a zone with a semi-diurnal tidal regime (i.e., two ebb and flood tides per day) except for some days during the month when one ebb and flood tide occur per day (Figure 4.3). Tidal amplitude ranges from about 2 m at mean tide to 4 m during spring tides. The two daily high and low tides differ in height. Maximum tidal amplitude, in the region of 4.0 - 4.2 m, is the highest observed in all of Vietnam. Tidal amplitude decreases with distance northward (i.e., inland). High tides reach their maximum peak between September and January at 3.6 - 4.1 m in the southern region and 2.8 - 3.3 m in the northern region of Can Gio. The maximum high tide occurs in October or November and the minimum in April or May. According to the monthly lunar calendar, from the 29th to the 3rd day of the month and from the 14th to the 18th day of month, the entire area of the Can Gio mangrove forest is flooded at high tide, this occurs twice a day. On the 8th and the 25th day of the month, low tide is at its minimum and the mangrove swamp is only flooded once per day (Tuan et al. 2002).

Initially, survey data generally indicated that the topography of the mangrove ecosystems was different between the two sites. KV occurred at a lower elevation and was wetter than MO. KV was frequently flooded, and the dominant plant species were *Avicennia alba, Rhizophora apiculata*, and *Ceriops decandra*. Because MO was rarely flooded, the soil was drier and compacted more than at KV. The dominant species were *Phoenix paludosa, Ceriops decandra*, *Acrostichum aureum, Excoecaria agallocha* and *Rhizophora apiculata.* Both the KV and the MO study sites are located in compartment 17 (Figure 4.4), but the MO site is further from the Dong Tranh River mouth than the KV site.

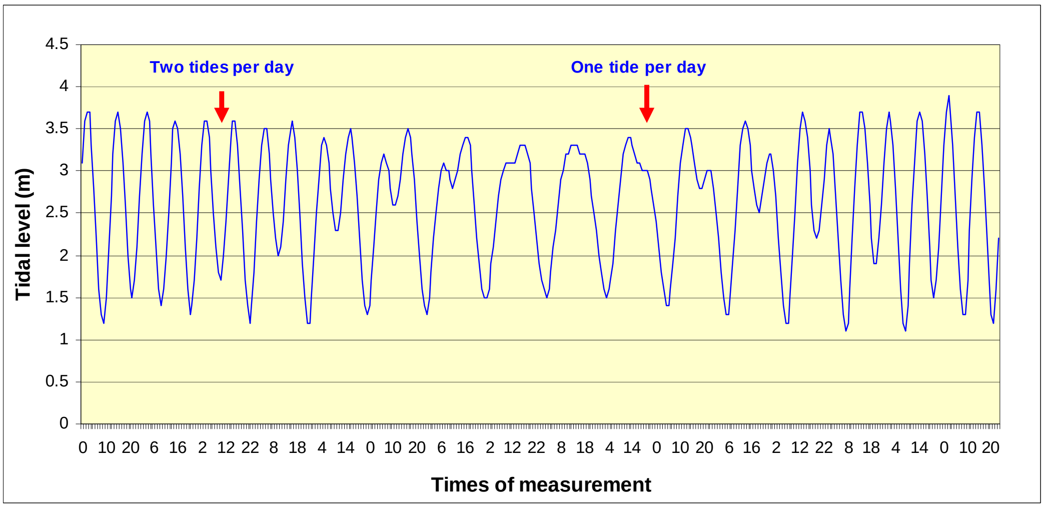

Figure 4.3 The daily tidal regime from March 22 to April 6 2005 in the Can Gio Mangrove Biosphere Reserve.

Figure 4.4 River systems of the Can Gio Mangrove Biosphere Reserve (Tuan et al. 2002). The KV and MO sites located in compartment 17 which along the Dong Tranh River.

The Can Gio Mangrove Biosphere Reserve is located on the southeastern coast of Vietnam. It is about 12 km from the Vung Tau meteorological station. The predicted tidal data at Vung Tau in 2005, the actual tidal data of Vung Tau, and the actual tidal measurements at Can Gio were compared. The statistical analysis showed that they were not significantly different (Figure 4.5).

4.3.2 Hydrologic Regime

Average high and low tides were significantly affected by season in 2005 (Table 4.5). Water levels at high tide and low tide in the dry season were significantly greater than in the wet season (Figure 4.6), while the tidal amplitude was not different between dry and wet seasons. Tidal levels were higher during the dry season compared to the wet season for two primary reasons. First, mean water levels in the China Sea are higher in the dry season than in the wet season (Tuan et al. 2002). Second, during the dry season the Tri An Hydroelectric Dam empties water into the Dong Tranh River estuary (Loon 2005). Thus, water levels at the study sites were higher in the dry season than in the wet season.

High and low tide levels significantly varied (Table 4.1) with the month of the year. The average monthly high tide level varied from 345.7 cm to 381.07 cm with the lowest levels occurring in June, July and August (Figure 4.7). These values, however, were not significantly different from May and September (Figure 4.7). The highest tide level occurred in December. This value was different from all months during 2005 except for January, February, October and November. The average monthly low tide was significantly different over the year (Table 4.1). The monthly low tides fell into three statistically different groups. Monthly low tides were lowest in June and July, which were significantly lower than the combined months of January, February, March, October, November and December (Figure 4.7). The intermediate group, which included April, May, August, and September, was not different from either the highest group or the lowest group (Figure 4.7). The monthly water

levels were high during the rainy season. This is because it was affected by the water levels of the China Sea (Tuan et al. 2002), the influx of the water from the Tri An Hydroelectric Dam (Loon 2005), and water originating upstream from the Saigon and Dong Nai Rivers (Tuan et al. 2002).

In contrast to the monthly and seasonal tidal regimes, the average daily tidal regime did not significantly differ through out the year (Table 4.1). The daily high tides and low tides ranged from 355.0 to 370.8 cm and 80.0 cm to 117.5 cm, respectively (Figure 4.8).

4.3.3 Electrical Conductivity of the Water Column

The electrical conductivity (EC) of the water column was significantly affected by the location and the season. However, EC was not significantly affected by the interaction season and zone (Table 4.2). The fluctuation in EC was similar for both the Dong Tranh River and the mangrove creek. EC increased to the highest levels at the end of the dry season. The EC values for the Dong Tranh River and the mangrove creek were significantly different from the EC values of other seasons (Figure 4.9). Generally, during the wet season, freshwater input from upstream rivers and channels dilutes the EC within mangrove systems (Lugo and Snedaker, 1974), thus resulting in an EC lower than in the dry season (Mitch and Gosselink, 2000, Mendelssohn and McKee 2000).Similar to the general trends in EC between the wet and the dry seasons, I found at my study site that the EC increased in the dry season. This increase may be due to (1) the effect of saline water from the China Sea, which penetrates further inland during the dry season [also found by Tanaka and Choo (2000)], (2) the lack of freshwater input, usually from rain during the rainy season, and (3) the higher evapo-transpiration during the dry season.

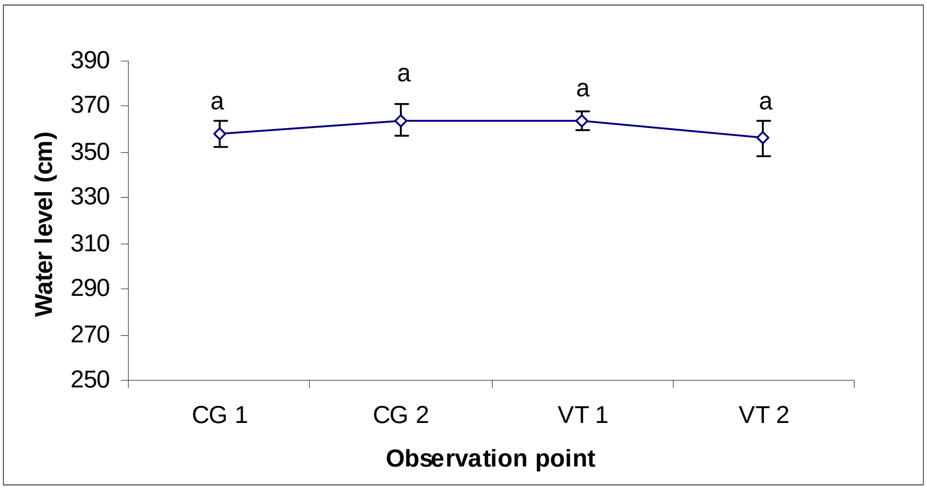

Figure 4.5 Comparison of highest water level (mean ± SE) between Can Gio and Vung Tau. CG1 and CG2 are water levels at transects KV1 and KV2, respectively, VT1 is the predicted water level and VT2 is actual water level at the Vung Tau meteorological station. Means with different letter are significantly different at $P \leq 0.05$.

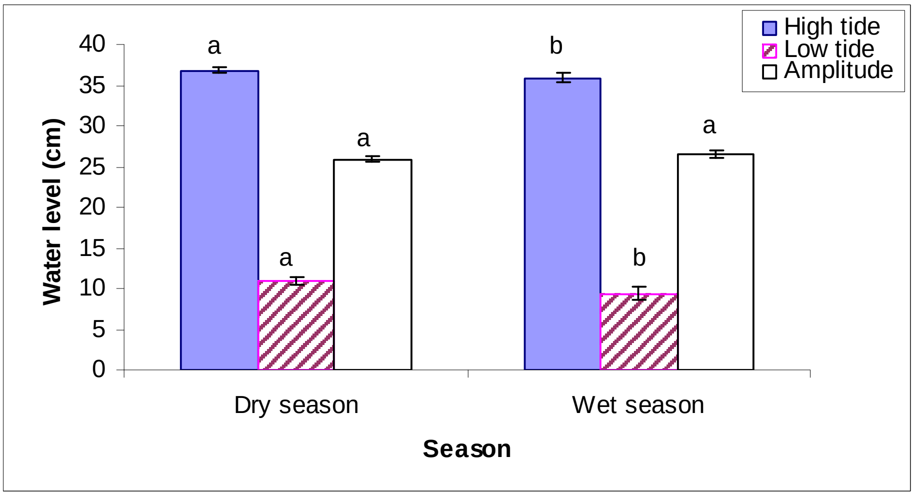

Figure 4.6 Water levels (mean ± SE) in the dry and wet seasons in 2005 at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters are significantly different at $P \leq 0.05$.

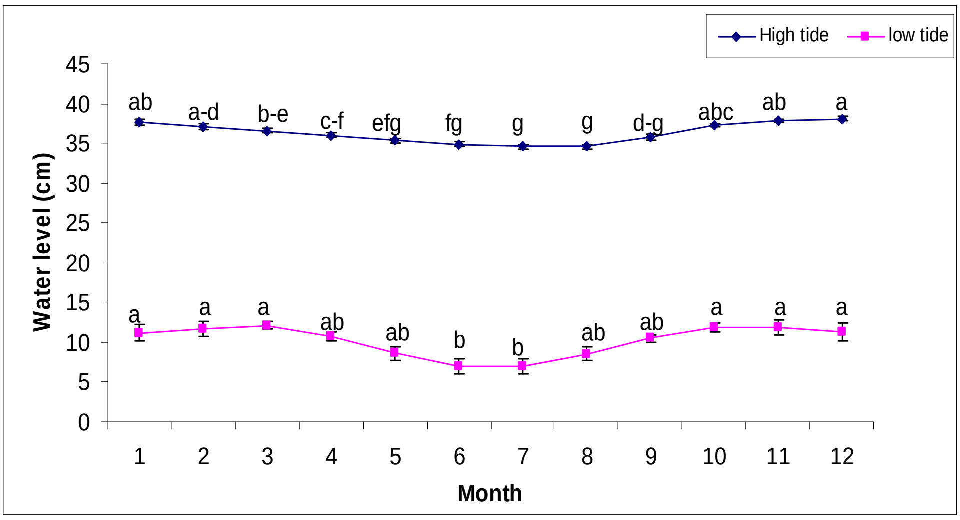

Figure 4.7 Monthly water levels (mean ± SE) at the study sites in the Can Gio Mangrove Biosphere Reserve in 2005. Means with different letters are significantly different at P ≤ 0.05.

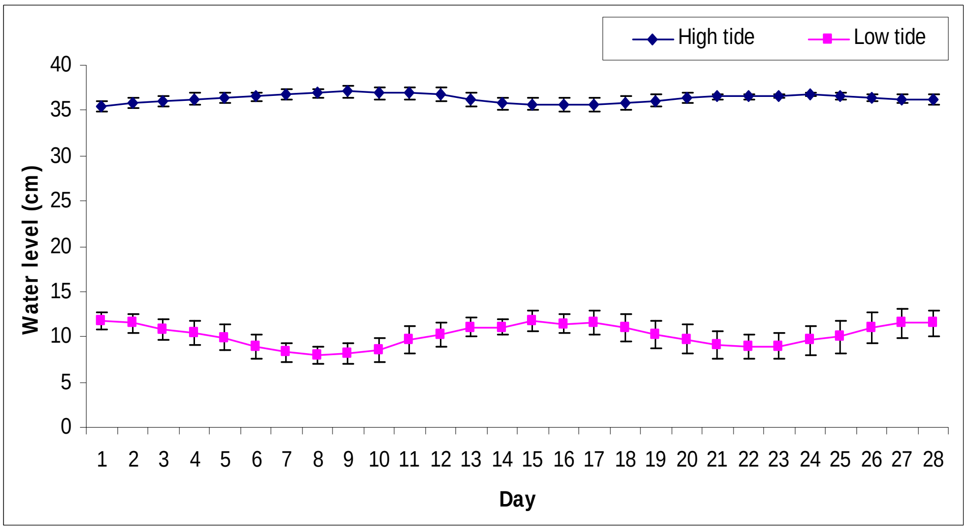

Figure 4.8 Daily tidal water levels (mean ± SE) at the study sites in the Can Gio Mangrove Biosphere Reserve in 2005. All the means were not significantly different at P ≤ 0.05.

However, EC in the Dong Tranh River was significantly higher than in the mangrove Creek (Figure 4.10) due to the tidal effect of the China Sea (Tuan et al. 2002). The high tide in the China Sea deposited a large amount of saline water into the Dong Tranh River causing the high EC level. The EC in the mangrove creek was lower because of the freshwater supply from water runoff into the creek that diluted the EC in the tidal creek water.

Table 4.1 F values and probability levels from analysis of variance of seasonal, monthly and daily water levels at the study sites in the Can Gio Mangrove Biosphere Reserve, (*) indicates statistical significance at alpha = 0.05.

		High tide		Low tide		Tidal amplitude	
Source	DF	F	P	F	P	F	P
Seasonal	1	21.67	<0.0001*	9.04	0.0028*	0.75	0.3870
Monthly	11	19.25	<0.0001*	5.47	<0.0001*	0.95	0.4966
Daily	27	0.59	0.9516	0.79	0.7668	0.99	0.4691

Table 4.2 F values and probability levels from analysis of variance of season, sampling location, and their interaction on the EC of the Dong Tranh River and mangrove tidal creek at the study sites in the Can Gio Mangrove Biosphere Reserve, (*) indicates statistical significance at alpha = 0.05.

Source	DF	F-ratio	Pro > F
Season (S)	3	153.04	<0.0001*
Sampling location (P)	1	30.07	<0.0001*
S x P	3	0.30	0.9516

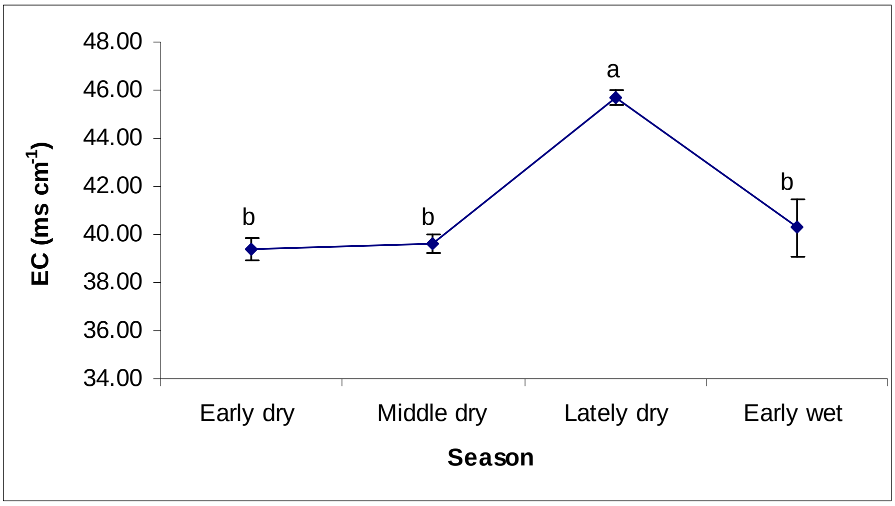

Figure 4.9 Comparison of electrical conductivity (EC) of the water column among seasons at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters are significantly different at P ≤ 0.05.

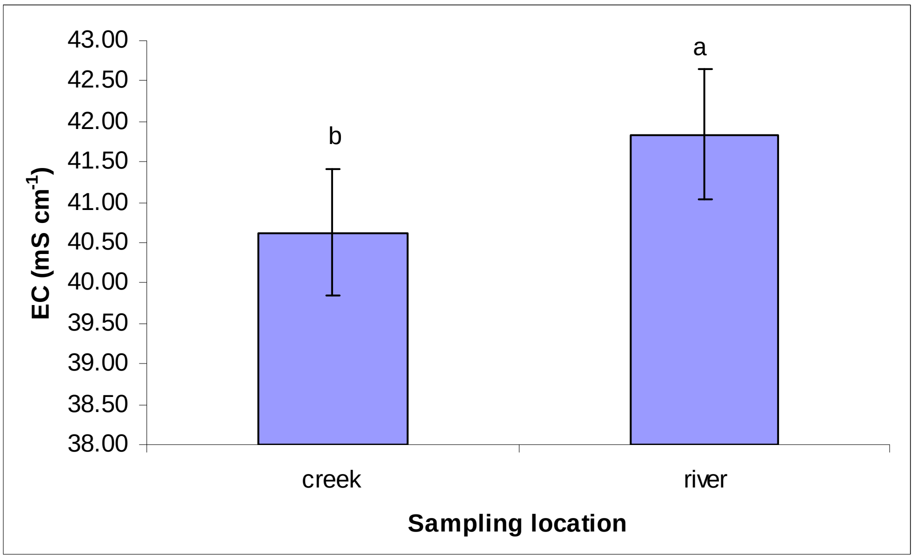

Figure 4.10 Comparison of electrical conductivity (EC) of water column between river and creek at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters are significant different at P ≤ 0.05.

4.3.4 Wetland Elevation

The elevation was found to be significantly affected by the site and the zone, as well as the combination of site and zone (Table 4.3). Elevations were the same at KV and MO except in zone 1, where the elevation at KV was lower than the elevation at MO (Figure 4.11).

Although the KV and the MO sites were located in the same compartment, they were significantly different in elevation because of the difference at zone 1. The difference of elevation may be explained due to the topography of Can Gio mangrove forest, which gradually decreases from the east to the south and from the east to the west (Tuan et al. 2002). Transects of the MO site were located close to the middle part of the Can Gio mangrove forest, where most elevations were found to be high. The direction of transects was from the east to the west, and the elevations of the three zones were the same. Transects of KV site were located at the end of the Southern part of the Can Gio mangrove forest. The direction of transects was from the east to the southwest where the elevations of zone 3 and zone 2 were not different from elevations of all the zones at the MO site. However, elevation of zone 1 at KV site was lowest compared to zone 2 and zone 3 of KV and all of the other zones of MO site.

4.3.5 Soil Drainage

Site, season and zone significantly affected soil drainage. Further, the interaction of site and zone was found to be highly significant; no other interactions were significant (Table 4.3). Soil drainage was significantly less in zone 1 at KV compared to the MO site (Figure 4.12) due to the effect of elevation, as also found by Mendelssohn and McKee (2000) and Mitsch and Gosselink (2000). Generally, soil that is often inundated due to low elevation has poor drainage, leading to differences in groundwater level (Day et al. 1987). In this study, soil drainage was significantly different in zone 1 because of the low elevation of zone 1 at

the KV site. Soil drainage was not different between zone 2 and zone 3 because of similar elevations at the zones at both sites. Contrary to this, the soil located adjacent to the river with steep slopes allows faster drainage. Similar results were found in this experiment. Zone 1 of the KV site had lower soil drainage because it had a low elevation and was also connected to the wide mudflat. In comparison to zone 1 at the MO site, the soil drainage is much greater because it had a high elevation and a steep slope. Hughes et al. (1998) also found that water table movement is negligible in soils located further inland. Correspondently, in this study, zone 2 and zone 3 were not different in soil drainage because they are located further inland.

The high water run-off during the wet season and the high evaporation during the dry season are the most important factors controlling the difference in ground water (Chapman 1976 and Loon 2005). In this study, soil drainage in the dry season was significantly greater than soil drainage in the wet season (Fig 4.13) due to less water input and higher evaporation, whereas in the wet season, more water run-off from higher elevations caused lower soil drainage.

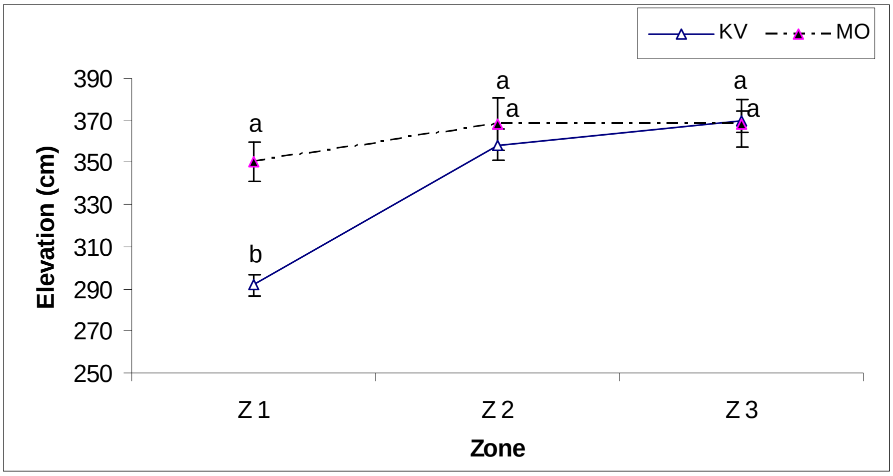

Figure 4.11 Effect of site and zone on elevation (mean ± SE) relative to mean sea level at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters are significantly different at $P \leq 0.05$.

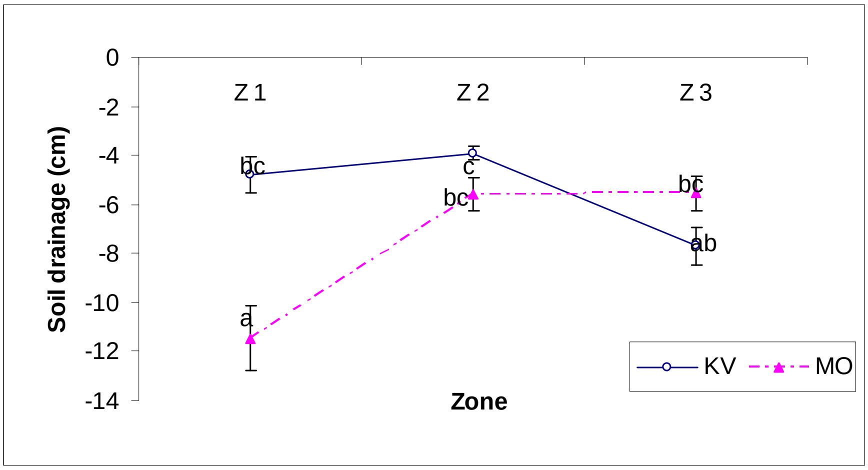

Figure: 4.12 Interaction of site and zone on soil drainage (mean ± SE) relative to the soil surface at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters are significantly different at $P \leq 0.05$.

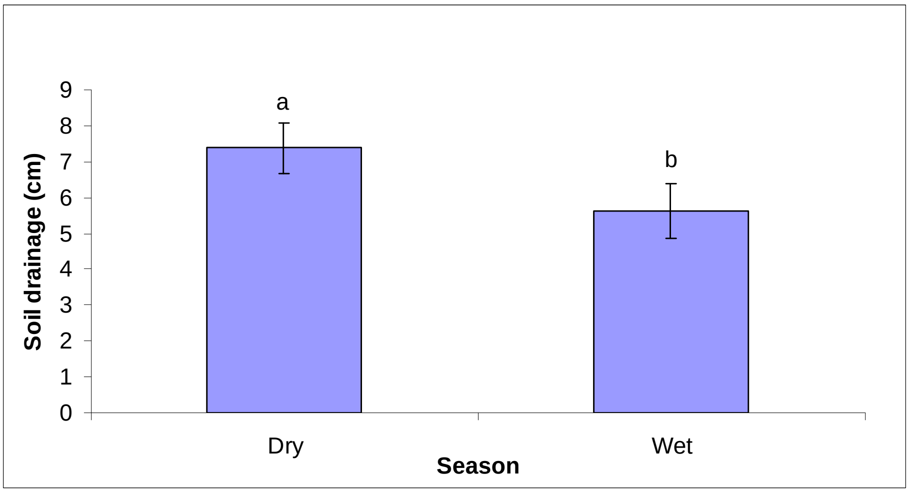

Figure: 4.13 Effect of season on soil drainage (mean ± SE) relative to the soil surface at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with letters are significantly different at $P \leq 0.05$.

4.3.6 Electrical Conductivity (EC) of the Groundwater

All treatment main effects and their interactions, except for the interaction of season and zone and the interaction of site and season and zone, had significant effects on groundwater EC (Table 4.3). Overall, groundwater EC was significantly greater in the dry season compared to the wet season at 47.49 mS cm^{-1} ± 0.58 and 3.50 mS cm^{-1} ± 0.27, respectively. Also, in the dry season, the groundwater EC was significantly higher at the KV site than MO site, but during the wet season, groundwater was equal at the two sites (Figure 4.14). EC of groundwater is affected by the weather (Wolanski 1992 and Loon 2005). In both KV and MO sites, the EC of groundwater was diluted due to freshwater run-off and the precipitation during the dry season.

In contrast, EC of groundwater was more concentrated during the dry season than the wet season because of the high temperature and the high evapotranspiration.

In addition, tidal regime also affects the EC of groundwater (Mitch and Gosselink 2000, Mendelssohn and McKee 2000). Analysis of the results of the study indicated that the EC at the KV site was only higher than the EC at the MO site in the dry season due to lower elevation and more seawater penetration at the KV site during the dry season.

Groundwater EC at the two study sites also differed depending on zone. Groundwater EC in zone 2 and zone 3 was significantly higher at the KV site than the MO site (Figure 4.15). In zone 1, groundwater EC did not significantly differ between the study sites (Figure 4.15). Ovalle et al. (1990) and Tanaka and Choo (2000) found that saltwater from the tidal creek affects the soil and in turn the EC of ground water. My field investigation showed that groundwater EC was high in zone 2 and zone 3 of the KV site due to the continuous supply of saltwater from a small creek nearby. Groundwater EC was low in zone 2 and 3 of the MO site because there were no creeks available to supply the saltwater.

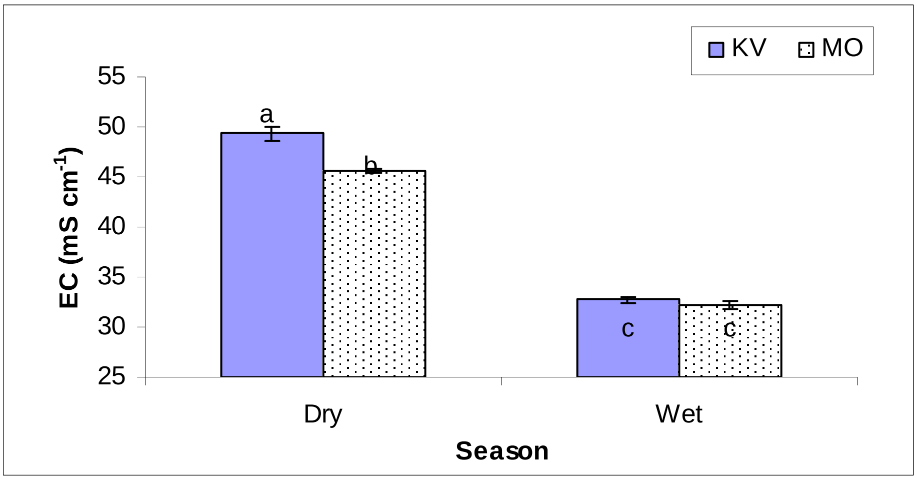

Figure 4.14 Interaction of site and season on groundwater EC (mean ± SE) at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters are significantly different at P ≤ 0.05.

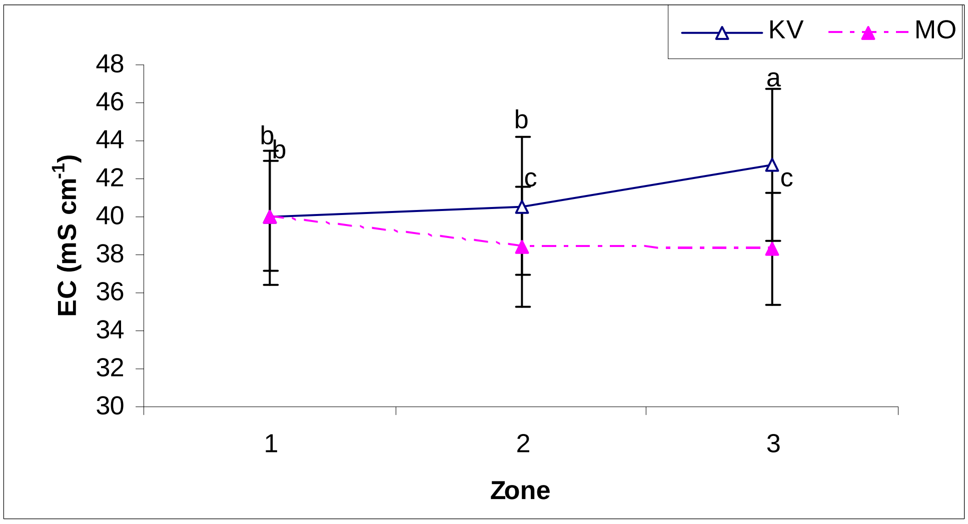

Figure 4.15 Interaction of site and zone on ground water EC (mean ± SE) at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters are significantly different at P ≤ 0.05.

4.3.7 Flooding Frequency

Flooding frequency was significantly affected by site, season, zone and the interaction of site and zone (Table 4.3). Flooding frequency in the dry season was significantly greater than flooding frequency in the wet season (Figure 4.16) because of the water discharged upstream from the Saigon and Dong Nai Rivers (Tuan et al. 2002), an effect that was also found by Thom et al. (1975) and Hughes et al. (1998) in similar sites. During the wet season, the Tri An Hydroelectric Dam stores upstream water, and during the dry season it empties the water into the Can Gio mangrove system causing higher flooding frequency during the dry season (Loon 2005). During the wet season, the freshwater was provided by the high rainfall, but during the dry season, the freshwater was not enough for Tri An Hydroelectric Dam to operate the dynamos to make the power. Therefore the Tri An Hydroelectric Dam has to store water in the wet season and empty during the dry season.

Site differences were dependent on zone. In zone 1, the flooding frequency at the KV site was approximately twice that of the MO site (Fig 4.17). In contrast, in zone 2 and 3, the flooding frequency did not significantly differ between the two study sites. At either study site, flooding frequency was significantly greater in zone 1 than in zones 2 and 3. As previously mentioned, zone 2 and zone 3 did not differ significantly (Fig 4.1.7). Local topography can greatly affect flooding frequency (Howard and Mendelssohn 1995). In this study, zone 1 of the KV site had significantly higher flooding frequency due to lower elevation compared to zone 1 of the MO site. Zone 2 and zone 3 at both KV and MO sites had similar flooding frequency due to similar elevations.

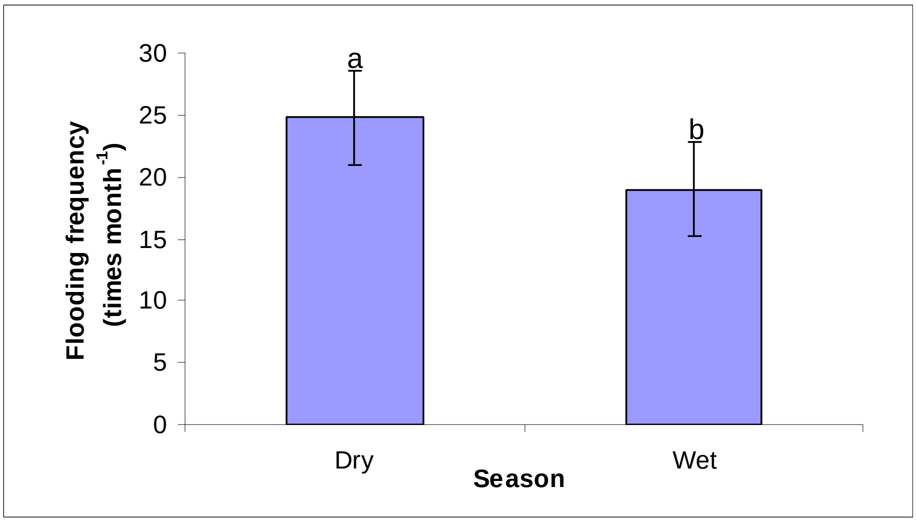

Figure 4.16 Effect of season on flooding frequency (mean ± SE) in 2005 at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters are significantly different at P ≤ 0.05.

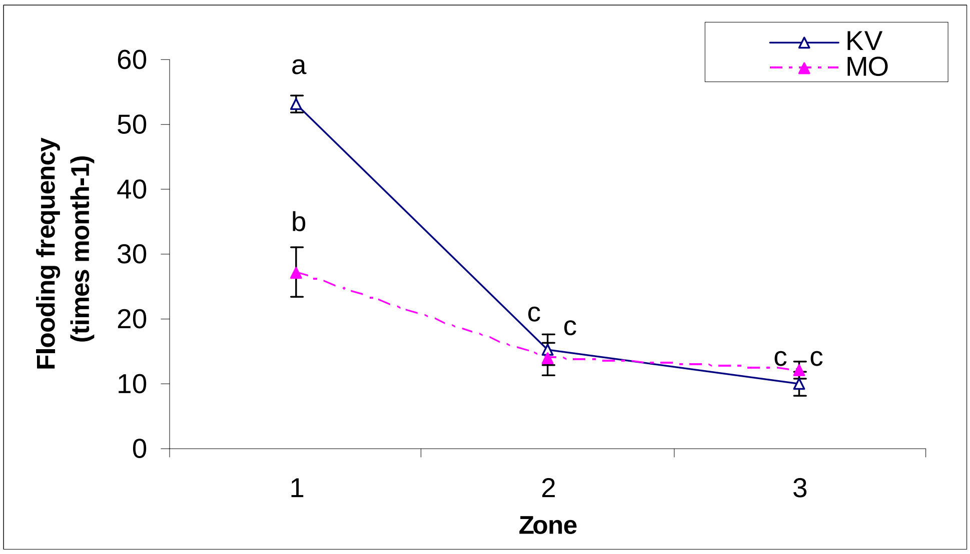

Figure 4.17 Interaction of site and zone on flooding frequency (mean ± SE) at the study sites in the Can Gio Mangrove Biosphere Reserve. Mean with different letters are significantly different at P ≤ 0.05.

Table 4.3 F values and probability levels from analysis of variance of elevation, electrical conductivity (EC) of the ground water, soil drainage and flooding frequency at the study sites of the Can Gio Mangrove Biosphere Reserve, (*) indicates statistical significance at alpha = 0.05. Elevation was analyzed for the site, zone and site by zone interactions.

		Elevation		Ground water EC		Soil drainage		Flooded frequency	
Source	DF	F-ratio	Prob > F	F-ratio	Prob > F	F-ratio	Prob > F	F-ratio	Prob > F
Site (Si)	1	14.33	0.0026*	62.73	<0.0001*	8.64	0.0072*	17.29	0.0004*
Season (Se)	1	--	--	2971.63	<0.0001*	6.17	0.0204*	10.68	0.0033*
Si x Se	1	--	--	33.61	<0.0001*	0.01	0.9358	0.16	0.6890
Zone (Z)	2	11.56	0.0016*	5.06	0.0147*	7.72	0.0026*	104.29	<0 .0001*
Si x Z	2	10.34	0.0025*	22.44	<0.0001*	13.10	<0.0001*	26.25	<0.0001*
Se x Z	2	--	--	1.90	0.1719	0.34	0.7135	0.004	0.9965
Si x Se x Z	2	--	--	1.76	0.1941	0.36	0.6985	0.076	0.9270

4.4 Conclusions

The results of this study showed that the water levels measured at Can Gio were not different from the water levels measured at the Vung Tau Hydrometerological Station. Similar to the tidal regimes of Vung Tau, the tidal regimes at Can Gio study sites were mainly affected by the tidal regimes of the South China Sea and the tidal regimes of the Dong Tranh River.

The tidal levels were different during the year. The highest tidal level occurred from November to January and the lowest tidal level occurred from June to July (Figure 4.7). Monthly tidal levels showed that there were two high tides during a month (Figure 4.8). The first occurred around the middle of the month and the second occurred around the end of the month. The water level during the dry season was higher than in the wet season due to the influx of water from the Tri An Hydroelectric Dam.

The EC of water was highest at the end of the dry season, while EC of water in the wet season, the beginning of the dry season, and the middle of dry season were found to be similar and lower than the EC of water at the end of the dry season. The EC in the Dong Tranh River was higher than the EC in the mangrove creek due to the creek receiving water runoff from areas higher in elevation.

The difference in elevation between the KV site and the MO site was mainly due to zone 1 at the KV site, which was significantly lower compared to all other zones. The differential elevation had effects on flooding frequency, soil biogeochemistry, and the structure and function of the mangrove forest. Soil drainage was affected by the elevation of the site and the flooding frequency. In this study, soil drainage was lowest in zone 2 at the KV site and highest in zone 1 at the MO site.

The EC of ground water at the KV site was higher than at the MO site. The EC of the ground water in the wet season was lower than in the dry season. The EC of the ground water

was found to be highest in zone 3 at the KV site and lowest in zone 2 and zone 3 at the MO site.

The flooding frequency was also affected by elevation and season. Flooding frequency changed the soil biogeochemistry and, possibly, the function of the mangrove forest. The KV site had a higher flooding frequency than the MO site. The higher flooding frequency at the KV site was due to the fact that zone 1 of the KV site had the lowest elevation. Also, flooding is more prevalent during the dry season than in the wet season due to water released from the Tri An Hydroelectric Dam, which increases water level downstream.

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CHAPTER 5

EFFECT OF HYDROLOGY ON THE SOIL PROPERTIES OF CAN GIO MANGROVE FORESTS

5.1 Introduction

One of the typical features of mangrove soils is recurrent flooding frequency, which is the time when the soil is covered with excess water and the plants have to adapt to the anaerobic conditions. Excess water in soil is a major factor that causes changes in soil biogeochemistry because of the low redox potential. Excess water exerts its influence on the plant physiological functions and the oxygen depletion so severely that it prevents normal root respiration. In the absence of oxygen, microbial processes occur that can generate plant toxins, such as hydrogen sulfide (Delaune and Pezeshki 1991).

Excess water in mangrove soils often limits gaseous oxygen from diffusing into the sediment. The result is that the available dissolved oxygen is rapidly used as a terminal electron acceptor. Once oxygen is consumed, other oxidized substances, which also act as terminal electron acceptors, are microbially reduced during anaerobic respiration (Gambrell 1994). The range of redox potential (Eh) in soils varies considerably from upland soils to wetland soils. However, for inundated soils, Eh can be as low as -250 mV to -300 mV (Delaune and Pezeshki 1991). When the soil is in a weakly reduced condition, the Eh decreases from +400 mV to +200 mV, and some of the elements such as oxygen, nitrogen and manganese are reduced. When the soil is moderately reduced, the Eh decreases below -100 mV to + 100 mV and iron is also reduced. When the soil is in a strongly reduced condition (< -150 mV), sulfate and carbon dioxide are reduced (Patrick and DeLaune 1977).

Mangrove soils are often acidic, and in highly reduced conditions the Eh can range from -100 to - 400 mV (Mitsch and Gosselink 2000). When the soil lacks oxygen, nitrate is the first component in the soil to be utilized as a terminal electron acceptor by facultative and

obligate anaerobes. Therefore, nitrates are typically limited in wetland soil (Turner and Patrick 1968, Delaune and Pezeshki 1991).

In wetland soils, Eh is low due to water inundation. The low Eh alters the soil biochemistry by depleting some necessary nutrients (Patrick and DeLaune 1977), producing toxins (Ponnamperruma 1972; DeLaune et al. 1983), and reducing the decomposition of organic substrates (Ponnamperuma 1972). Oxygen deficiency affects root elongation, decreases flood tolerance, and causes root metabolism to switch to anaerobic fermentation (Hochachka and Somero 1973). Oxygen deficiency also affects the surviving anaerobic roots (DeLaune et al 1984; Burdick and Mendelssohn 1987), the survival and competitive ability of wetland plants (DeLaune et al. 1983), and limits active uptake of essential elements such as nitrogen and phosphorous (Delaune and Pezeshki 1991).

Depending on the soil oxygen status, Eh plays an important role in changing the soil pH. Generally, pH in wetland soils ranges from 6.5 to 7.5 (Gambrell 1994), except in soils that are already acidic or alkaline (Patrick and Mikkelsen 1971, Ponnamperuma 1972).

Mangrove soils are typically saline (Mendelssohn and McKee 2000) and provide a wide range of salinity necessary for mangrove species to compete with other salt tolerant species (Davis 1940). In mangrove soils, salinity is usually highly concentrated and is less variable in interstitial soil water than in surface water and extends further inland than normal high tides (Mitsch and Gosselink 2000).

The salinity in soil water varies depending on factors such as the flooding frequency, precipitation, presence of tidal creeks, drainage gradient, water table depth, and freshwater inflow (Mitsch and Gosselink 2000; Mendelssohn and McKee 2000). The salinity varies from season to season and for different types of mangrove forests. Mangrove distribution along intertidal coastlines often experience stress from the saline environment, which affects mangrove productivity and species distribution (Mitsch and Gosselink 2000).

Hydrologic fluctuations and substrate quality enhance the growth and survival of mangroves (Doyle 2003). Rivers are important sources of nutrients to coastal systems containing mangroves, especially in the supply of nitrogen and phosphorus. Soil organic matter, nitrogen, phosphorus, and potassium are correlated to flooding frequency and tidal amplitude. The concentrations of soil organic matter, total nitrogen, extractable nitrogen, phosphorus, and potassium were found to be high in landward sites and decreased gradually along tidal gradients, whereas pH and salinity increase with distance from landward to seaward sites (Tam and Wong 1997).

The characteristics of the soil are some of the most important environmental factors controlling the structure and function of the mangrove forests. In particular, soil nutrient status has the most direct control on mangrove ecosystems (Boto and Wellington 1984). Generally, nutrients, such as nitrogen, limit growth, and in some cases, phosphorus is also growth limiting. For example, nutrient enrichment had resulted in a significant enhancement of growth in *Rhizophora mangle* and *Avicennia marina* (Boto 1992). Mangrove distribution is dependent on species-response to reduced conditions, conditions that affect the mangrove soil biochemistry, and in turn, affect mangrove zonation and flood tolerance (McKee 1993).

The distribution and development of mangrove forests are an important reflection of the hydrologic regime. However, the relationship between the hydrological regime, soil characteristics and mangrove forest development in the Can Gio mangrove forests, as well as other mangrove forests across Vietnam, has received little attention. Therefore, this research chapter investigates the relationship between soil properties and hydrology. Also, the effect of hydrology on soil biogeochemistry and on the structure and function of the mangrove ecosystem of the Can Gio Biosphere Reserve located in the Can Gio District of Vietnam are described.

5.2 Materials and Methods

Soil physical and chemical characteristics were measured at three zones along three replicate transects at both Khe Vinh and Mui O sites (Figures 3.2, 3.3 and 3.4). The zones were differentiated based on the elevation and vegetation. Tree species and species distribution were determined on each zone of each transect. Soil sampling was done in the topsoil at 0 – 10 cm and the subsoil at 30 – 40 cm, for a total of nine sampling sites at KV and nine sampling sites at MO. The sampling for most parameters was carried out in March 2004 during the dry season and repeated in September, 2004 during the wet season.

For bulk density and soil moisture, soil samples with a volume of 100 cm^3 were collected in a corer (Blake and Hartge 1986). Samples were oven dried to a constant weight at 105°C and the soil moisture was calculated by comparing the soil weight before and after drying. Soil bulk density was calculated as the oven dry weight per unit volume of soil (g cm^{-3}).

Soil samples for organic matter (OM), pH, electrical conductivity (EC), cation exchangeable capacity (CEC) and soil nutrient concentration were collected with a 10-cm diameter auger. Redox potential (Eh) was measured directly in the field with a portable Eh meter (WTW- Multiline F/set-3). The samples were then transported inside an insulated cooler to the laboratory of Soil Science and Land Management Department, Can Tho University for analysis.

Particle size was analyzed by the pipette method (Day 1965 and Green 1981) and soil OM was analyzed by the Walkey - Black method (Nelson and Sommers 1996). For sediments pH and EC, a 1:2.5 soil solution was filtered and the filtered solution was measured with a pH/mV/temp meter (WTW- Multiline F/set-3). CEC was determined after extracting the soil sample with 0.1M $BaCl_2$ and titrating with a 0.01M NaOH solution (Sumner and Miller, 1996). Total nitrogen (N) was analyzed by the Kjeldahl method (Bremner 1996) and NH_4-N

by the indophenol method (Mulvaney 1966). Total phosphorus (P) was determined colorimetrically after the conversion of organic phosphorus to an inorganic form by digesting the soil with concentrated H_2SO_4. The available phosphorus (P_2O_5) was measured by the Bray method (Kuo 1996).

A factorial design was used to statistically analyze main effects and interactions of the difference of soil properties between the KV site and MO sites, between dry and wet seasons, among zones (zone 1, zone 2 and zone 3), and between topsoil and subsoil, as previously described in Chapter 3. JMP statistical software was used to analyze soil data. Significant differences among means were determined by the Tukey – Kramer post – hoc test.

5.3 Results and Discussions.

5.3.1 Soil Texture

The soil texture at both KV and MO was dominated by clay and silt, which together comprised more than 95 % of the soil by weight. Only the subsoil at the two more landward zones, zone 2 and zone 3, along the MO transect had a sand composition of greater than 10%, but even at these sites, sand comprised only 12 - 16 % of the soil by weight (Table 5.1).

On average, clay comprised about 55 – 60 %, and silt about 35 – 40 % of the topsoil by weight at both KV and MO (Table 5.1). The proportion of clay was also significantly higher than that of silt in the subsoil at the most seaward zone (Zone 1) at KV and MO. The two more landward zones (Zone 2 and Zone 3) of the MO transects had roughly equal proportions of silt and clay, and the two more landward zones of the KV transects had somewhat higher proportions of silt than clay (Table 5.1).

Even though soil texture was not consistently affected by the hydrological regime, the clay component was significantly correlated ($r = 0.5112$, $P = 0.0012$) with the flooding frequency (Figure 5.1).

Lugo and Snedaker (1974) recognized the Can Gio mangrove forests as a type of riverine mangrove. The soils of the Can Gio mangrove forest were deposited by the original alluvium from Sai Gon and Dong Nai Rivers (Tuan et al. 2002) which consisted mostly of silt and clay (Dang and Ho 1993). As a result, the soils in the study sites were 95 % dominated by silt and clay. Even though the KV site and the MO site are located along the banks of the Dong Tranh River, KV is located closer to the River's mouth, and thus receives more fine sediment than MO. The fine sediments flow in from the Sai Gon and Dong Nai Rivers and get deposited at the river mouth

Zone 1, a riverside zone, received more clay than Zone 2 and Zone 3, landward zones, due to its low elevation and high flooding frequency. In this study, the flooding frequency was found to be positively correlated with the clay percentage (Figure 5.1). Patterson and Mendelssohn (1991) also explained that the heavier particles settle out of suspension first during the short flooding period while the finer particles need a longer flooding period to settle out of suspension and accumulate on the soil.

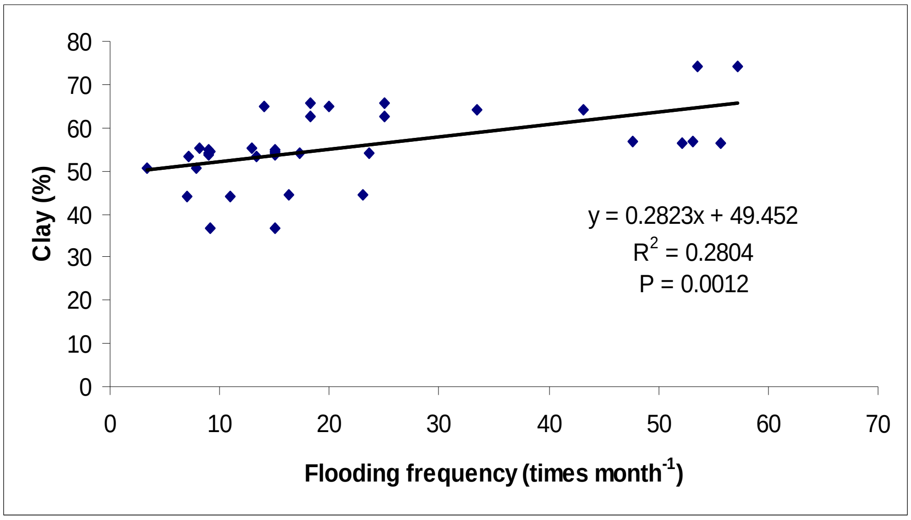

Figure 5.1 The relationship between flooding frequency and clay percentage during the dry and wet season across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

Table 5.1 Comparison of soil texture at the study sites in the Can Gio Mangrove Biosphere Reserve, (*) indicates a significant effect at alpha = 0.05, ns indicates a non-significant effect. The means ± standard errors with different letter are significantly different at P ≤ 0.05.

SOURCE	SAND (%)	SILT (%)	CLAY (%)
SITES	*	*	ns
- KV	2.37 ± 0.63 b	44.53 ± 3.01 a	53.08 ± 4.67 a
- MO	7.34 ± 1.41 a	35 05 ± 1.05 b	57.54 ± 3.15 a
ZONES	*	ns	*
1	2.22 ± 0.37 b	35.35 ± 1.99 a	62.41 ± 1.91 a
2	5.06 ± 1.63 a	42.10 ± 3.45 a	52.75 ± 3.64 ab
3	7.28 ± 1.80 a	41.92 ± 3.33 a	50.79 ± 3.77 b
DEPTHS	*	*	*
- Topsoil	2.95 ± 0.46 b	36.39 ± 2.14 b	60.65 ± 2.17 a
- Subsoil	6.76 ± 1.57 a	43.19 ± 2.61 a	49.98 ± 2.90 b
SITE*ZONE	*	ns	ns
KV-1	1.30 ± 0.20 c	38.30 ± 3.65 a	60.66 ± 3.67 a
KV-2	1.35 ± 0.50 c	47.40 ± 5.91 a	51.24 ± 6.25 a
KV-3	4.48 ± 1.58 bc	48.15 ± 5.61 a	47.36 ± 6.33 a
MO-1	3.15 ± 0.49 c	32.67 ± 1.10 a	64.61 ± 1.15 a
MO-2	8.76 ± 2.46 ab	36.80 ± 2.50 a	54.26 ± 4.29 a
MO-3	10.09 ± 2.94 a	35.68 ± 1.39 a	54.22 ± 4.23 a
SITE*DEPTH	*	ns	ns
KV-Topsoil	2.00 ± 0.80 b	39.87 ± 4.03 ab	58.12 ± 4.27 ab
KV-subsoil	2.75 ± 1.01 b	49.18 ± 4.10 a	48.05 ± 4.66 b
MO-Topsoil	3.90 ± 0.22 b	32.90 ± 0.45 b	63.18 ± 0.38 a
MO-subsoil	10.77 ± 2.34 a	37.20 ± 1.82 b	51.91 ± 3.61 ab
ZONE*DEPTH	*	ns	*
Z 1-Topsoil	2.58 ± 0.65 c	35.50 ± 1.44 a	61.91 ± 1.14 a
Z 1-Subsoil	1.87 ± 0.39 c	35.21 ± 3.91 a	62.91 ± 3.82 a
Z 2-Topsoil	2.58 ± 0.81 c	36.42 ± 4.92 a	61.00 ± 4.73 ab
Z 2- Subsoil	7.54 ± 2.94 ab	47.78 ± 3.90 a	44.50 ± 2.98 bc
Z 3- Topsoil	3.70 ± 0.99 bc	37.25 ± 4.50 a	59.05 ± 4.85 abc
			(table con’d)

Z 3- Subsoil	10.87 ± 2.85 a	46.58 ± 4.47 a	42.53 ± 3.45 c
SITE*ZONE*DEPTH	*	ns	ns
KV-Z 1-Topsoil	1.26 ± 0.39 b	36.95 ± 2.89 a	61.78 ± 2.51 a
KV-Z 1-Subsoil	1.34 ± 0.21 b	39.12 ± 7.55 a	59.53 ± 7.74 a
KV-Z 2-Topsoil	0.89 ± 0.46 b	40.94 ± 9.97 a	58.16 ± 10.17 a
KV-Z 2-Subsoil	1.81 ± 0.91 b	53.86 ± 5.78 a	44.32 ± 6.64 a
KV-Z 3-Topsoil	3.84 ± 2.20 b	41.73 ± 9.02 a	54.42 ± 9.80 a
KV-Z 3-Subsoil	5.11 ± 2.68 b	54.57 ± 5.93 a	40.31 ± 7.38 a
MO-Z 1-Topsoil	3.90 ± 0.45 b	34.05 ± 0.06 a	62.03 ± 0.52 a
MO-Z 1-Subsoil	2.41 ± 0.68 b	31.33 ± 2.05 a	66.28 ± 1.37 a
MO-Z 2-Topsoil	4.27 ± 0.46 b	31.90 ± 1.14 a	63.83 ± 0.67 a
MO-Z 2-Subsoil	13.26 ± 3.13 a	41.70 ± 2.44 a	44.69 ± 0.40 a
MO-Z 3-Topsoil	3.55 ± 0.24 b	32.77 ± 0.00 a	63.68 ± 0.24 a
MO-Z 3-Subsoil	16.64 ± 0.65 a	38.60 ± 1.10 a	44.76 ± 0.44 a

5.3.2 Soil Moisture

Soil moisture was highly affected by the main-effects of zone, site, and season but minimally affected by depth (Table 5.2). However, the four-way interaction among zone, site, season, and depth was significant (Table 5.2). Hence, the effect of zone on soil moisture was dependent on site, season and depth.

At KV, all zones had statistically equal soil moistures during the dry season. However, during the wet season at KV, soil moisture significantly decreased from zone 1 to zone 3 (Table 5.3). At the MO study site, in contrast, soil moisture increased from zone 1 to zone 3 in both wet and dry seasons (Table 5.3). No significant differences in soil moisture occurred between topsoil and subsoil except at the MO site in zone 1 during the wet season (significant site x season x zone x depth interaction, Tables 5.2 and 5.3) Overall, soil moisture was significantly higher in the wet season than in the dry season (Table 5.3).

Soil moisture had a low, but significant, negative correlation with soil drainage ($r = -0.4030$, $P = 0.0134$) during the dry season at the MO site (Figure 5.2), while it had a highly

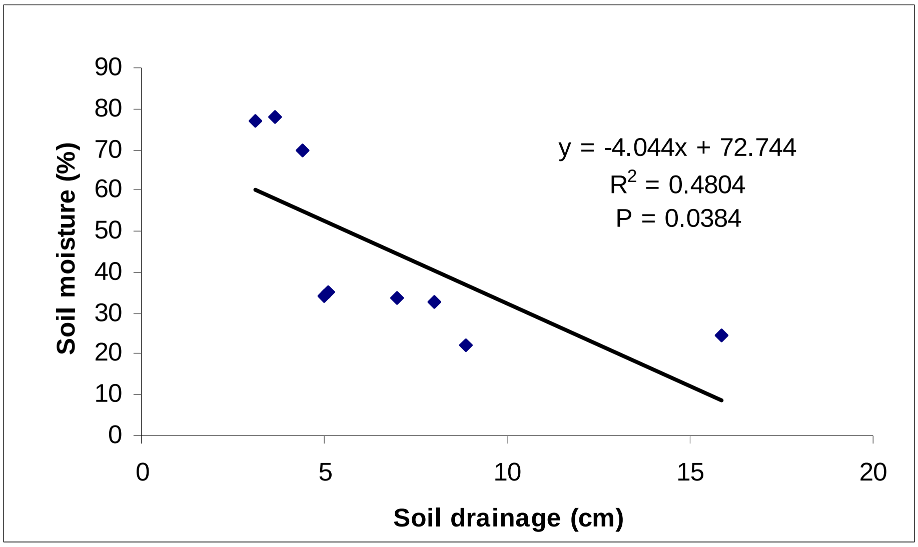

Figure 5.2 The relationship between soil moisture and soil drainage during the dry season across all zones at the MO site in the Can Gio Mangrove Biosphere Reserve.

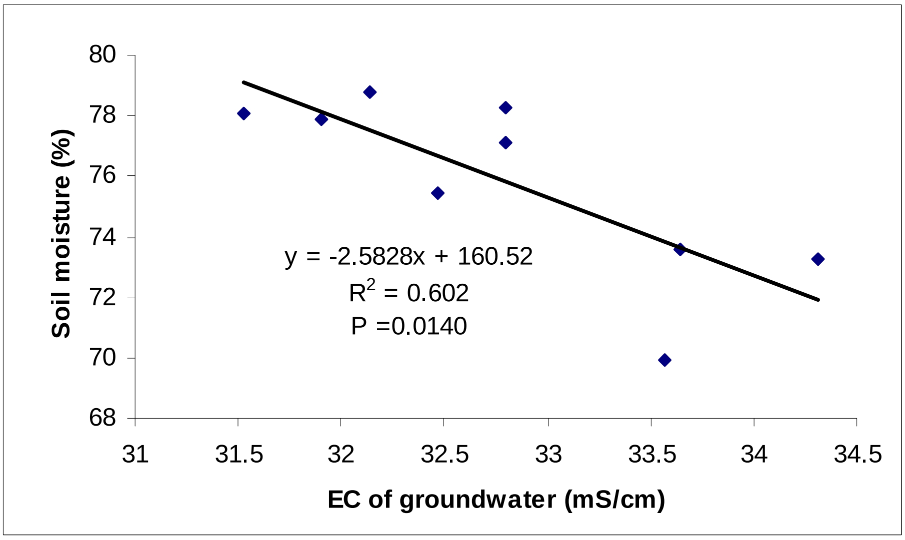

Figure 5.3 The relationship between soil moisture and EC of the groundwater during the wet season across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

significant negative correlation with the EC of ground water ($r = -0.9470$, $P < 0.0001$) during the wet season at the KV site (Figure 5.3).

Generally, soil moisture in the wet season was higher than in the dry season because of the increase in precipitation during the wet season. Additionally, soil moisture is lower in the dry season because of an increase in evaporation. Moreover, the landward zones such as zone 3 at KV (KV-Z3) or the riverside zones such as zone 1 at MO (MO-Z1) occurred at high elevation, with low flooding frequency, and high soil drainage, resulting in lower soil moisture than other zones.

5.3.3 Soil Bulk Density

Soil bulk density was significantly affected by two, three-way interactions: site x season x depth and site x zone x depth (Table 5.2). The four-way interaction between site, season, zone and depth was not significant (Table 5.2).

The interactive effect of site, season and depth on soil bulk density was similar for the KV and MO sites (Table 3.2). In the wet season, the topsoil had significantly higher bulk density than the subsoil, but only at the MO site (Table 3.3). Also, the bulk density of the subsoil was significantly greater in the dry season compared to the wet season, but again only at the MO study site (Table 3.3).

The interactive effect of site, zone and depth on soil bulk density did not differ between the topsoil and the subsoil except zone 1 of the MO site (Table 5.3). At KV, soil bulk density was greatest in zone 3, but only for the subsoil, while at MO, bulk density was greatest in zone 1 (for both topsoil and subsoil) (Table 3.3).

Soil bulk density was negatively correlated ($r = -0.8497$, $P < 0.0001$) with soil moisture (Figure 5.4) and organic matter (OM) but in the topsoil only ($r = - 0.6660$, $P = 0.0026$) (Figure 5.5). No significant relationship was found between soil bulk density and tidal regime.

Mitsch and Gosselink (2000) suggested that soil bulk density decreases as the water holding capacity of the soil and the organic matter in the soil increase. Similar results were found in this study. The interaction of site and zone and depth (Table 5.3) demonstrated that zones with low elevation had low soil bulk density. For example, the bulk density of the topsoil and subsoil in zone 1 at KV, a zone with a low elevation, had a low bulk density. This is because zones with low elevation have high flooding frequencies and therefore are inundated with water, which decreases the rate of decomposition of organic matter. Consequently, inundation of water and low decomposition lead to low soil bulk density.

The high negative correlation between water content, i.e., soil moisture, and soil bulk density (Figure 5.4) indicate that decreases in moisture lead to increases in soil bulk density. Soil bulk density was also found to have a relationship with the organic matter in the topsoil (Figure 5.5). Correspondingly, zone 1 at MO, a zone with higher elevation, faster water drainage, and lower organic matter had a higher soil bulk density which also agrees with data presented by Mitsch and Gosselink (2000), and Gambrell and Patrick (1978).

5.3.4 Soil pH

Soil pH was significantly affected by two three-way interactions: site x season x depth and site x zone x depth (Table 5.2). The four-way interaction among zone, site, season, and depth had no effect on soil pH (Table 5.2).

The effect of season and depth on soil pH was different for each site (Table 5.3). At the KV site, soil pH was significantly less in the dry season compared to the wet season for both topsoil and subsoil. At the MO site, soil pH also significantly increased from the dry to the wet season, but only in the topsoil (Table 5.3).

Soil pH was dependent on the interactive effects of site, zone and depth (Table 5.3). At KV, pH was lower in zone 3 than zone 1, but only in the subsoil. At MO, pH did not differ by zone at either depth (Table 5.3).

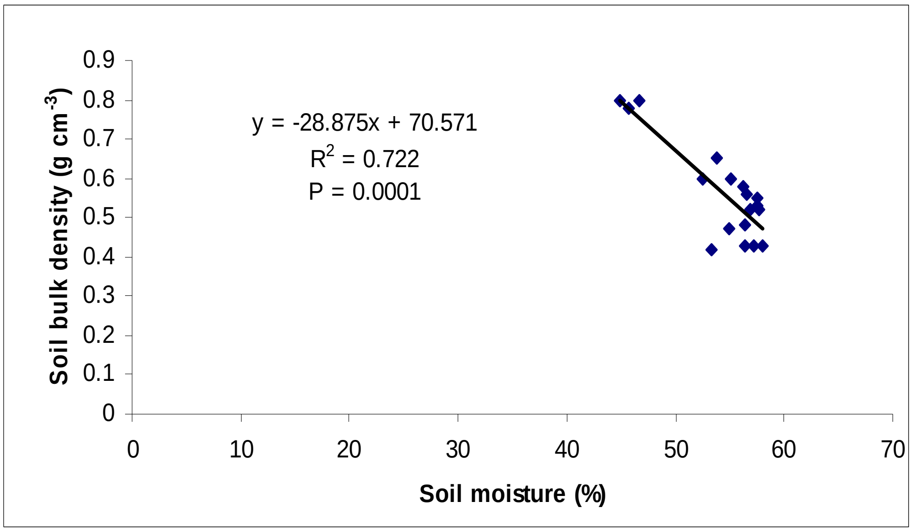

Figure 5.4 The relationship between soil moisture and soil bulk density across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

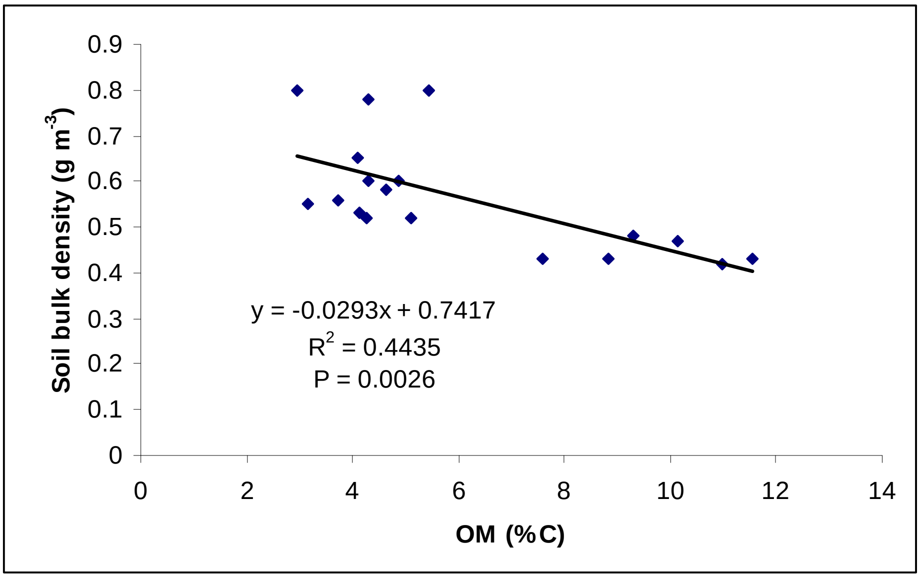

Figure 5.5 The relationship between OM and soil bulk density across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

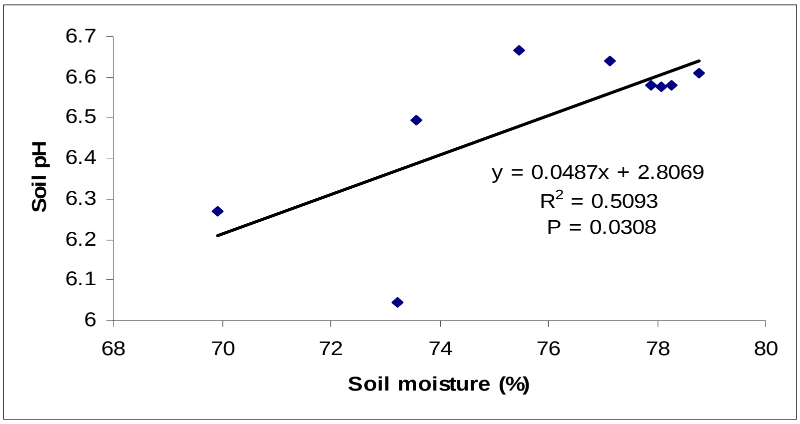

Figure 5.6 The relationship between soil pH and soil moisture during the wet seasons across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

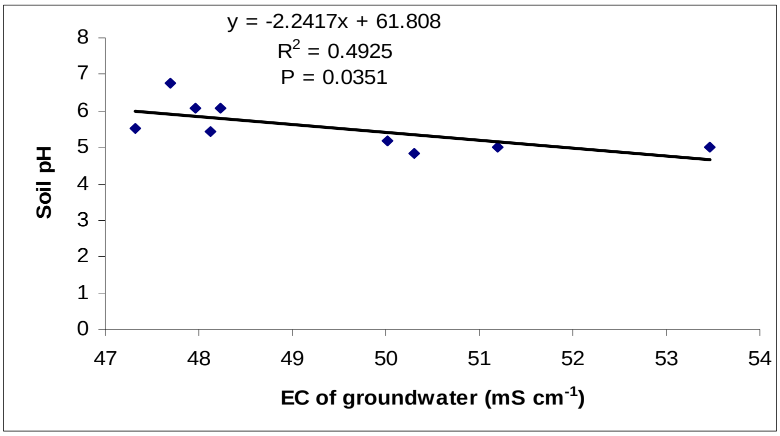

Figure 5.7 The relationship between soil pH and EC of the groundwater during the dry season across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

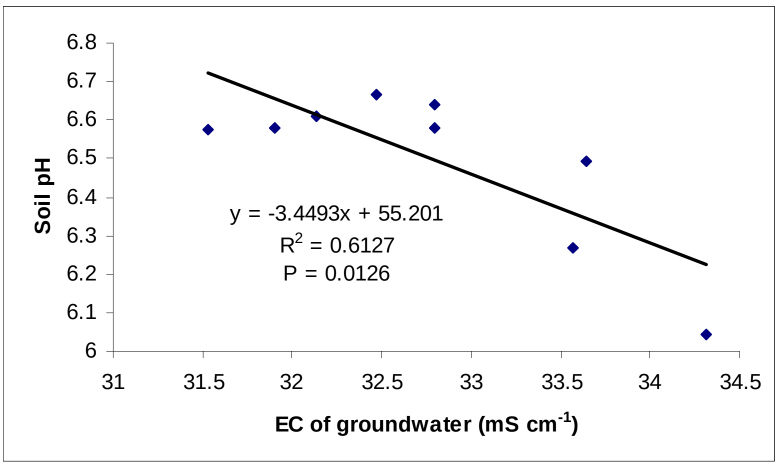

Figure 5.8 The relationship between soil pH and EC of the groundwater during the wet season across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

Season was a major factor affecting soil pH, albeit influenced by soil depth and site. During the dry season, the soil is desiccated and receives more oxygen leading to high oxidation and hence, low pH. During the wet season, pH is diluted by precipitation and water runoff leading to a higher pH. Zone had a relatively small effect on soil pH. However, at the KV site, zone 3 had a lower soil pH than zone 1, but only in the subsoil. Soil pH was positively correlated ($r = 0.7144$, $P = 0.0003$) with soil moisture during the wet season (Figure 5.6) and negatively correlated with the EC of groundwater during the dry season ($r = -0.7017$, $P < 0.0351$) and the wet season ($r = -0.7827$, $P = 0.0126$) at the KV site (Figures 5.7 and 5.8).

Landward soils with high elevation are drier and more acidic than riverside soils (Tam and Wong, 1997). Others have suggested that most wetland soils have circum-neutral pHs (6.5 to 7.5) (Gambrell 1994, Mitsch and Gosselink 2000). In general, areas with low elevation, high flooding frequency, and anaerobic conditions (Patrick and Mikkelsen 1971, Ponnamperuma 1972) have near-neutral pH, but some areas with specific soil types have non-neutral pHs (Patrick and Mikkelsen 1971, Ponnamperuma 1972). It was found in this study that most of the soils at the Can Gio mangrove forests were circum-neutral to slightly acidic, depending on soil moisture (Figure 5.6) and groundwater EC (Figure 5.7 and 5.8)

5.3.5 Soil Redox

Soil redox (Eh) was highly affected by three, two-way interactions: site x zone, site x depth, and season x depth (Table 5.2). Three-way and four-way interactions were not significant (Table 5.2).

The effect of zone on Eh was dependent on site (Table 5.2). At KV, Eh was significantly lower in zones 1 and 2 than in zone 3. In contrast, at MO Eh was lower in zones 2 and 3 compared to zone 1 (Table 5.3).

The effect of site on Eh was dependent on depth (Table 5.2). Eh of the MO site was significantly higher than at the KV site, but the difference was only significant for the topsoil (Table 5.3). Also, the Eh of the topsoil was significantly greater than that of the subsoil at both sites (Table 5.3).

Eh was higher in the dry season compared to the wet season, but only for the topsoil (significant interaction between season and depth, Table 5.2 and 5.3). Similar to the interactive effect between site and depth, Eh in the dry season was higher than in the wet season, but only in the topsoil (Table 5.3).

Soil redox had a positive correlation with soil drainage ($r = 0.6429$, $P = 0.0001$) (Figure 5.9) and a negative correlation with soil moisture during the wet season only ($r = -0.8459$, $P < 0.0001$) (Figure 5.10).

Mangrove soils are often reduced with Eh ranging from –100 to –400 mV (Mitsch and Gosselink 2000). Depending on the water inundation status, Eh at the study sites ranged from 311 mV to –120 mV. Most of the Eh values during the dry season at the higher elevation zones were greater in the topsoil compared to most Eh values in the subsoil during the wet season at low elevation (i.e. zone 1 of the KV site). The differences in Eh may be explained by the difference in water inundation, which is related to elevation and flooding frequency.

The biogeochemical processes in mangrove soils are also affected by elevation and flooding frequency, which regulate the delivery of oxygen into the soils. High elevation and low flooding frequency in zone 1 at the MO site and in zone 3 at the KV site allowed greater levels of oxygen to penetrate into the soil thus increasing the Eh. In contrast, low Eh was found in zone 1 at the KV site. Low elevation and high flooding frequency in this zone prohibited oxygen from penetrating into the soil which decreased the Eh.

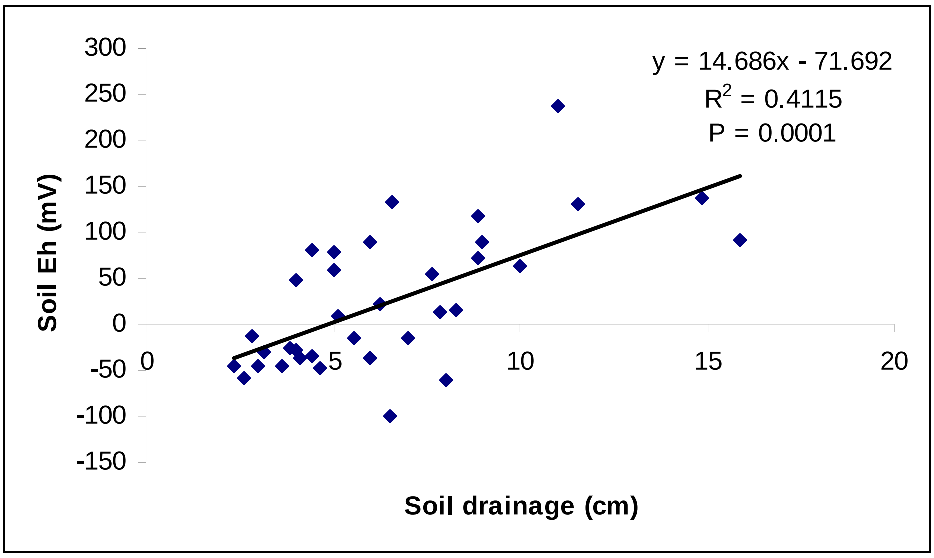

Figure 5.9 The relationship between soil Eh and soil drainage during the dry and wet seasons across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

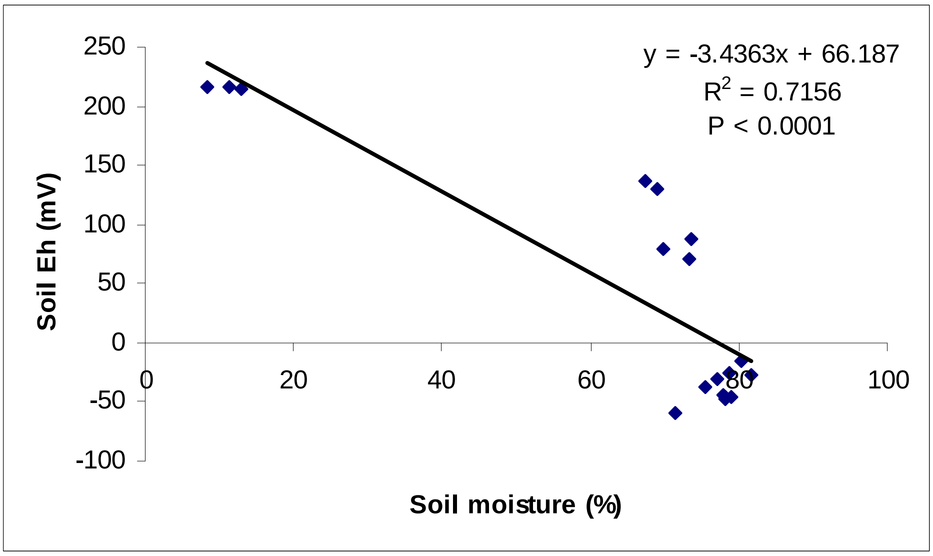

Figure 5.10 The relationship between soil Eh and soil moisture during the wet season across all zones at the KV and MO sites in Can Gio Mangrove Biosphere Reserve.

The Eh of the subsoil was lower than the Eh of the top soil during both dry and wet seasons due to greater soil moisture in the subsoil. The difference in Eh between season and depth may be explained by the difference in the soils' oxygen status.

Overall, Eh was positively correlated with soil drainage (Figure 5.9) due to oxygen availability while it was negatively correlated with soil moisture (Figure 5.10) due to oxygen deficiency as suggested by McKee (1993).

5.3.6 Soil Electrical Conductivity

Soil electrical conductivity (EC) was highly affected by season and zone, minimally affected by depth, and not affected at all by site. All treatments and their interactions had effects on the soil EC, except for the interactions of site and season, site and zone, site and season and zone, site and depth, and zone and depth (Table 5.2).

Generally, EC for all treatments were higher in the dry season than in the wet season. The EC levels in zone 1, 2 and 3 in the dry season at both sites were not significantly different, except for the treatment of MO – Dry – Z1, which had significantly lower EC than other treatments. Similarly, there was no difference in EC among the treatments of the wet season at KV site, but at the MO site the EC of MO – Wet – Z2 was significantly higher than MO – Wet – Z1 (Table 5.3).

The EC of KV – Subsoil was significantly higher than the EC of all other treatments. Furthermore, there was no significant difference among these treatments (Table 5.3). Interaction by zone and depth indicated that EC of the topsoil and EC of the subsoil of all three zones were not different except for at Z2 - Subsoil, where the EC was significantly higher and at Zone 1 - Topsoil, where the EC was significantly lower compared to all other interaction treatments (Table 5.3). Soil EC was negatively correlated with EC of groundwater during the wet season at the KV site ($r = -0.7695$, $P = 0.0153$) (Figure 5.11) and to EC of groundwater during the dry season at the MO site ($r = -0.6711$, $P = 0.0478$) (Figure 5.12).

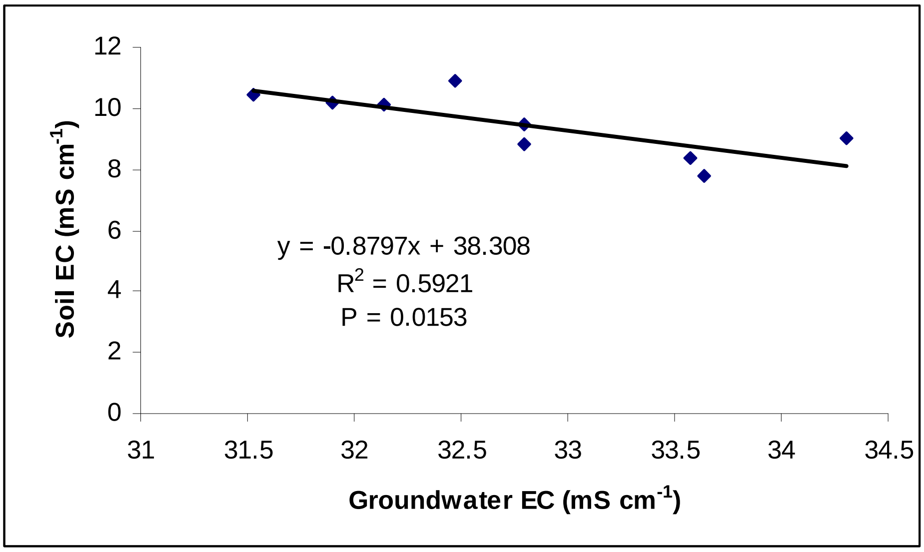

Figure 5.11 The relationship between soil EC and groundwater EC during the wet season across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

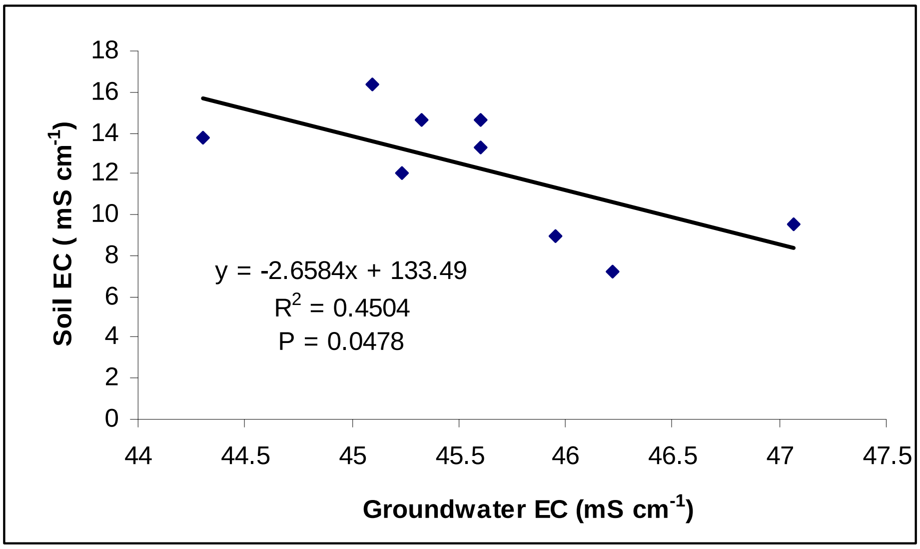

Figure 5.12 The relationship between soil EC and groundwater EC during the dry season across all zones at the MO site in the Can Gio Mangrove Biosphere Reserve.

Generally, the fluctuation of EC in soil is an intertwining function of elevation and the duration of tides, the intensity of rainfall, the groundwater EC, and the freshwater that enter the mangrove swamp via the rivers, creeks and runoff (Mitsch and Gosselink 2000).

EC was lower in the wet season than in the dry season due to the diluting of EC by precipitation and water runoff during the wet season. Contrary to this, in the dry season, EC was more concentrated because of the high evaporation. The analysis of the interaction of site and depth indicated that the EC of the KV – Subsoil was higher than the others (Table 5.3). The high EC in the KV-Subsoil can be explained by its lower elevation and higher seawater inundation than other areas. In addition, only the soil EC of the treatment of Z2 – Subsoil was found to be higher than Z2- Topsoil demonstrating that soil EC had a relationship with the EC of groundwater. Zone 2 had a medium elevation and low soil drainage in the subsoil which allowed for salt to penetrate and remain in the soil (Tam and Wong 1997). However, soil EC has a negative relationship with groundwater EC at the KV site during the wet season (Figure 5.11), but at the MO site, the negative correlation occurred during the dry season (Figure 5.12).

5.3.7 Cation Exchange Capacity

The cation exchangeable capacity (CEC) was not affected by site and zone, but it was highly affected by season and depth. Except for the interactions of site and season, site and zone, zone and depth, site and season and depth, and also site and zone and depth, soil CEC was not affected by any other interactions (Table 5.2).

The statistical analysis of interaction by site and season and depth indicated that the CEC of all treatments were not different except for MO – Wet – Topsoil which was significantly higher compared to all of the others, and KV – Wet – Top which was higher than KV – Dry – Subsoil and both the topsoil and the subsoil of MO – Dry (Table 5.3). Interaction of site and zone and depth showed that CEC was not different among the treatments at KV site. Correspondingly, CEC at MO site was not different among treatments except for MO – Z3 – Topsoil, which had significantly higher CEC than other treatments, but its CEC was not different from the CEC of MO – Z2 – Topsoil. When comparing CEC

between the two sites, KV and MO, it was found that CEC were not different in most zones and depths except for at MO-Z2-Topsoil where the CEC was significantly higher than the CEC at KV-Z2-Topsoil and at MO-Z3 where the CEC was significantly higher than KV-Z3 in both the topsoil and the subsoil (Table 5.3).

Soil CEC was positively correlated with EC of groundwater ($r = -0.7418$, $P = 0.0221$) during the dry season at the KV site (Figure 5.13), but it was negatively correlated with the soil moisture during the wet season at the KV site ($r = 0.7441$, $P = 0.0221$). Soil CEC was negatively correlated with the soil moisture during the wet season at the MO site ($r = 0.999$, $P < 0.0001$) (Figures 5.14 and 5.15).

In this study, CEC did not vary considerably among treatments. CEC varied from 15.13 ± 1.02 for the treatment of KV - Dry - Z2 - Subsoil to 32.65 ± 0.43 for the treatment of MO - Wet - Z3 – Topsoil. Highly concentrated CEC were found in the top soil of high elevation zones such as zone 1, zone 2, and zone 3 at the MO site and zone 2 and zone 3 at the KV site. The higher CEC in these instances may be explained through the relationship with flooding frequency (Figure 5.13) and with EC of groundwater (Figure 5.14). Higher CEC is dependent upon low flooding frequency. Low flooding frequency coupled with less tidal flushing allowed for more OM to be stored in the soil which led to a higher CEC in the soil.

Figure 5.13 shows that the CEC had a positive relationship with the EC of the groundwater. As with CEC, EC of groundwater was also affected by the flooding frequency. High flooding frequency increased the EC of the groundwater and at the same time, increased the CEC in the soil. CEC also had a strong correlation with soil moisture (Figures 5.14 and 5.15) during the wet season, when higher soil moisture leads to an increase in CEC.

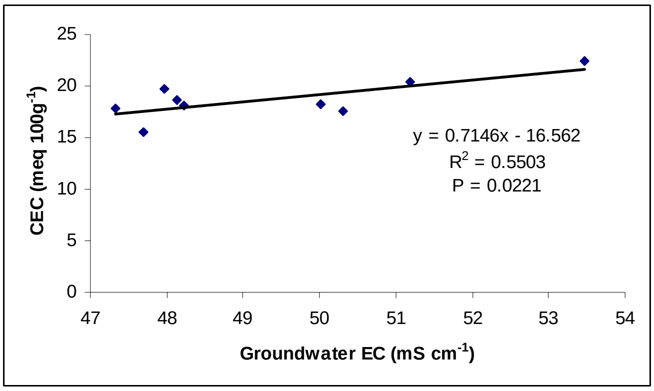

Figure 5.13 The relationship between soil CEC and groundwater EC during the dry season across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

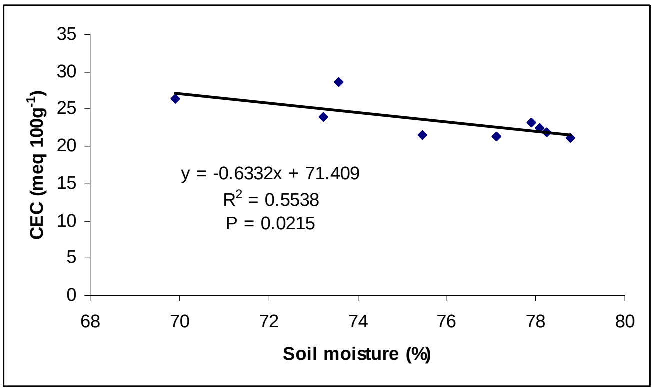

Figure 5.14 The relationship between CEC and soil moisture during the wet season across all zones at the KV site in Can Gio Mangrove Biosphere Reserve.

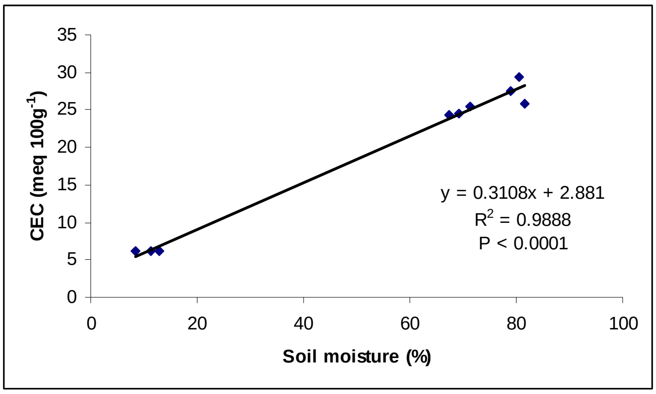

Figure 5.15 The relationship between CEC and soil moisture during the wet season across all zones at the MO site in Can Gio Mangrove Biosphere Reserve.

Table 5.2 F values and probability levels from analysis of variance of bulk density, pH, Eh, EC and CEC at the study sites in the Can Gio Mangrove Biosphere Reserve, (*) indicates statistical significance at alpha = 0.05.

		Bulk density		Soil moisture		pH		Eh		EC		CEC	
Source	DF	F-ratio	Prob >F	F-ratio	Prob >F	F-ratio	Prob >F	F-ratio	Prob >F	F-ratio	Prob >F	F-ratio	Prob >F
Site (Si)	1	0.41	0.5230	31.3499	0.0001*	4.93	0.0311*	4.93	0.0311*	1.89	0.1749	1.96	0.1673
Season (Se)	1	5.31	0.0255*	4584.5900	<0.0001*	67.43	<0.0001*	4.92	0.0313*	60.20	<0.0001*	93.56	<0.0001*
Si x Se	1	12.52	0.0009*	16.1233	0.0002*	0.47	0.4958	0.44	0.0566	8.07	0.0066*	7.40	0.0090*
Zone (Zo)	2	92.20	<0.0001*	16.5898	<0.0001*	5.46	0.0073*	14.13	<0.0001*	15.96	<0.0001*	1.80	0.1755
Si x Zo	2	171.85	<0.0001*	54.1934	<0.0001*	3.14	0.0521	33.87	<0.0001*	33.04	<0.0001*	4.17	0.0213*
Se x Zo	2	6.08	0.0044*	0.3454	0.7097	2.13	0.1288	0.11	0.8874	2.58	0.0858	2.74	0.0742
Si x Se x Zo	2	1.78	0.1804	3.9003	0.0269*	0.18	0.8340	22.23	0.1181	4.56	0.0153*	1.18	0.3138
Depth (De)	1	0.35	0.5580	4.5836	0.0374*	1.57	0.2155	105.39	<0.0001*	9.84	0.0029*	35.77	<0.0001*
Si x De	1	14.91	0.0003*	12.6704	0.0008*	0.74	0.3920	30.82	<0.0001*	7.04	0.0108*	3.08	0.0855
Se x De	1	4.83	0.0328*	0.3025	0.5848	0.01	0.9896	12.05	0.0011*	0.66	0.4183	1.32	0.2556

(table con'd)

Si x Se x De	1	5.57	0.0224*	1.0909	0.3015	4.58	0.0373*	0.24	0.6207	0.01	0.9388	7.71	0.0078*
Zo x De	2	12.85	<0.0001*	6.8631	0.0024*	0.59	0.5582	1.31	0.2779	3.67	0.0327*	3.71	0.0316*
Si x Zo x De	2	9.60	0.0003*	2.4235	0.0994*	3.65	0.0334*	3.07	0.0554	1.77	0.1805	7.35	0.0016*
Se x Zo x De	2	0.16	0.8523	0.5264	0.5941	0.62	0.5380	0.16	0.8499	0.15	0.8594	1.12	0.3341
Si x Se x Zo x De	2	1.22	0.3038	4.7136	0.0135*	0.12	0.1310	0.08	0.9184	0.08	0.9210	2.70	0.0767

Table 5.3 Mean comparison of bulk density, soil moisture, pH, Eh, EC and CEC between sites, seasons, zones, depths and their interactions at the study sites in the Can Gio Biosphere Reserve. The means ± standard errors with different letter are significantly different at P ≤ 0.05

Source	**Bulk density** (g/cm3)	**Soil moisture** (%)	**pH**	**Eh** (mV)	**EC** (mS/cm)	**CEC** (meq/100g)
Site (Si)						
KV	0.57 ± 0.01 a	56.10 ± 3.36 a	6.02 ± 0.12 a	10.33 ± 12.33 b	11.27 ± 0.39 a	21.06 ± 0.72 a
MO	0.56 ± 0.03 a	52.63 ± 3.90 b	5.79 ± 0.10 b	37.20 ± 22.37 a	11.75 ± 0.53 a	22.00 ± 1.04 a
Season (Se)						
Dry season	0.58 ± 0.02 a	33.40 ± 0.86 b	5.47 ± 0.11 a	37.19 ± 20.42 a	12.84 ± 0.45 a	18.27 ± 0.69 a
Wet season	0.55 ± 0.02 b	75.33 ± 0.93 a	6.34 ± 0.04 b	10.34 ± 15.34 b	10.18 ± 0.36 b	24.79 ± 0.71 b

(table con'd)

Si * Se						
KV - Dry	0.59 ± 0.01 ab	36.38 ± 0.47 b	5.55 ± 0.18 b	19.70 ± 18.84 ab	13.09 ± 0.40 a	18.72 ± 0.88 c
KV - Wet	0.57 ± 0.01 a	75.82 ± 0.79 a	6.50 ± 0.06 a	0.95 ± 16.16 b	9.46 ± 0.27 c	23.40 ± 0.82 b
MO - Dry	0.56 ± 0.05 a	30.42 ± 1.33 c	5.39 ± 0.15 b	54.67 ± 36.42 a	12.59 ± 0.82 a	17.83 ± 1.10 c
MO - Wet	0.53 ± 0.04 b	74.84 ± 1.71 a	6.19 ± 0.02 a	19.73 ± 26.42 ab	10.90 ± 0.63 b	26.18 ± 1.10 a
Zone (Zo)						
Zone 1	0.66 ± 0.03 a	51.85 ± 4.68 b	6.09 ± 0.10 a	59.11 ± 25.94 a	10.24 ± 0.58 b	21.23 ± 0.86 a
Zone 2	0.52 ± 0.01 b	55.76 ± 4.40 a	5.95 ± 0.15 ab	-18.73 ± 16.17 b	12.57 ± 0.46 a	20.94 ± 1.10 a
Zone 3	0.51 ± 0.02 b	55.49 ± 4.40 a	5.67 ± 0.14 b	30.91 ± 21.06 a	11.72 ± 0.56 a	22.42 ± 1.30 a
Si * Zo						
KV - Z1	0.53 ± 0.01 c	57.90 ± 6.10 a	6.24 ± 0.17 a	-22.42 ± 41.52 c	11.96 ± 0.79 abc	20.50 ± 0.82 ab
KV - Z2	0.55 ± 0.01 c	56.60 ± 6.21 ab	6.22 ± 0.20 ab	-13.73 ± 28.31 c	11.51 ± 0.54 bc	19.43 ± 0.94 ab
KV - Z3	0.61 ± 0.02 b	53.80 ± 5.61 b	5.61 ± 0.23 c	67.13 ± 17.46 b	10.36 ± 0.62 c	23.25 ± 1.62 a
MO - Z1	0.79 ± 0.04 a	45.80 ± 6.90 c	5.95 ± 0.12 abc	140.64 ± 35.21 a	8.51 ± 0.49 d	21.97 ± 1.51 ab
MO - Z2	0.46 ± 0.02 d	54.93 ± 6.50 ab	5.69 ± 0.21 bc	-23.72 ± 27.40 c	13.64 ± 0.62 a	22.45 ± 1.95 b
MO - Z3	0.43 ± 0.01 d	57.17 ± 7.00 a	5.73 ± 0.20 abc	-5.31 ± 38.65 c	13.08 ± 0.78 ab	21.59 ± 2.07 ab
Se * Zo						
Dry - Z1	0.70 ± 0.05 a	30.52 ± 2.24 d	5.78 ± 0.17 bc	74.74 ± 41.52 a	11.50 ± 0.98 bc	19.02 ± 1.21 b

(table con’d)

Dry - Z2	0.50 ± 0.02 c	35.00 ± 0.72 c	5.53 ± 0.20 cd	-3.32 ± 28.31 bc	13.46 ± 0.61 a	17.51 ± 1.23 b
Dry - Z3	0.53 ± 0.03 c	34.70 ± 0.61 c	5.09 ± 0.23 d	40.14 ± 34.32 ab	13.55 ± 0.60 a	18.29 ± 1.26 b
Wet - Z1	0.63 ± 0.04 b	73.17 ± 1.95 b	0.12 ± 0.12 a	43.48 ± 32.34 ab	9.97 ± 0.38 d	23.45 ± 0.84 a
Wet - Z2	0.51 ± 0.02 c	76.53 ± 1.39 a	6.37 ± 0.21 a	-34.13 ± 15.80 c	11.69 ± 0.60 b	24.37 ± 1.19 a
Wet - Z3	0.52 ± 0.03 c	76.28 ± 1.38 ab	6.25 ± 0.20 ab	21.67 ± 25.71 abc	9.89 ± 0.60 cd	26.55 ± 1.52 a
Si * Se * Zo						
KV - Dry - Z1	0.54 ± 0.01 cde	37.72 ± 0.59 d	5.90 ± 0.25 abc	0.96 ± 32.94 bc	14.44 ± 0.48 a	18.52 ± 1.07 de
KV - Dry - Z2	0.54 ± 0.02 cde	36.07 ± 0.53 d	5.80 ± 0.33 a-d	3.60 ± 31.93 bc	12.50 ± 0.88 ab	17.48 ± 1.26 de
KV - Dry - Z3	0.61 ± 0.03 cd	35.35 ± 1.03 d	4.95 ± 0.22 d	54.55 ± 33.93 abc	12.32 ± 0.30 abc	20.15 ± 2.13 cde
KV - Wet - Z1	0.53 ± 0.02 def	78.08 ± 0.73 a	6.58 ± 0.13 a	-45.79 ± 17.43 c	9.48 ± 0.26 cde	22.49 ± 0.51 a-d
KV - Wet - Z2	0.57 ± 0.01 de	77.13 ± 0.85 ab	6.64 ± 0.17 a	-31.07 ± 18.71 c	10.51 ± 0.35 b-e	21.37 ± 0.87 b-e
KV - Wet - Z3	0.62 ± 0.03 d	72.25 ± 1.09 bc	6.27 ± 0.10 ab	79.72 ± 11.26 ab	8.40 ± 0.29 e	26.35 ± 1.78 ab
MO - Dry - Z1	0.86 ± 0.03 a	23.33 ± 1.01 e	5.66 ± 0.18 bcd	148.52 ± 65.74 a	8.56 ± 0.77 de	19.52 ± 2.27 cde
MO - Dry - Z2	0.46 ± 0.03 efg	33.93 ± 1.24 d	5.27 ± 0.34 cd	-10.25 ± 49.87 bc	14.42 ± 0.71 a	17.53 ± 2.26 de
MO - Dry - Z3	0.45 ± 0.03 fg	34.03 ± 0.65 d	5.23 ± 0.26 cd	25.75 ± 62.84 bc	14.78 ± 0.95 a	16.43 ± 1.05 e
MO - Wet - Z1	0.72 ± 0.06 b	68.27 ± 2.56 c	6.23 ± 0.02 ab	132.75 ± 33.32 b	8.47 ± 0.69 cde	24.42 ± 1.57 abc
MO - Wet - Z2	0.45 ± 0.02 efg	75.93 ± 2.77 ab	6.10 ± 0.05 abc	-37.18 ± 27.29 c	12.78 ± 0.96 ab	27.38 ± 1.37 a
MO - Wet - Z3	0.41 ± 0.01 g	80.32 ± 0.83 a	6.23 ± 0.02 ab	-36.38 ± 37.86 c	11.38 ± 0.9 bcd	26.57 ± 2.66 ab

(table con’d)

Depth (De)						
Subsoil	0.57 ± 0.02 a	55.03 ± 3.60 a	5.97 ± 0.13 a	-38.35 ± 12.78 b	12.05 ± 0.42 a	19.52 ± 0.70 a
Topsoil	0.56 ± 0.03 a	53.70 ± 3.71 b	5.84 ± 0.10 a	85.88 ± 16.70 a	10.97 ± 0.49 b	23.55 ± 0.94 b
Si * De						
KV - Subsoil	0.54 ± 0.01 a	55.66 ± 4.71 a	6.04 ± 0.22 a	-18.19 ± 14.51 c	11.36 ± 0.50 b	19.64 ± 0.92 b
KV - Topsoil	0.59 ± 0.01 b	56.54 ± 4.94 a	6.00 ± 0.12 a	38.85 ± 17.89 b	11.19 ± 0.60 b	22.48 ± 1.01 a
MO - Subsoil	0.58 ± 0.05 b	54.40 ± 5.57 a	5.90 ± 0.13 a	-58.50 ± 20.36 c	12.73 ± 0.66 a	19.40 ± 1.08 b
MO - Topsoil	0.54 ± 0.03 ab	50.87 ± 5.60 b	5.67 ± 0.16 a	132.91 ± 23.84 a	10 76 ± 0.78 b	24.61 ± 1.59 a
Se * De						
Dry - Subsoil	0.56 ± 0.04 a	34.24 ± 1.08 b	5.53 ± 0.20 b	-45.93 ± 18.35 c	13.23 ± 0.53 a	16.64 ± 0.89 c
Dry Topsoil	0.59 ± 0.03 ab	32.57 ± 1.34 b	5.40 ± 0.13 b	120.31 ± 23.83 a	12.44 ± 0.74 a	19.90 ± 0.96 b
Wet - Subsoil	0.56 ± 0.04 b	75.82 ± 1.10 a	6.41 ± 0.68 a	-30.77 ± 18.15 c	10.86 ± 0.54 b	22.39 ± 0.51 b
Wet - Topsoil	0.54 ± 0.02 ab	74.83 ± 1.52 a	6.27 ± 0.05 a	51.45 ± 21.01 b	9.51 ± 0.43 c	27.20 ± 1.09 a
Si * Se * De						
KV - Dry – Subsoil	0.58 ± 0.02 a	36.43 ± 0.86 b	5.45 ± 0.34 c	-26.81 ± 20.27 d	13.02 ± 0.46 a	16.74 ± 0.96 d
KV - Dry - Topsoil	0.54 ± 0.01 ab	36.33 ± 0.50 b	5.64 ± 0.13 bc	66.21 ± 23.60 bc	13.36 ± 0.69 a	20.69 ± 1.19 bcd
KV - Wet - Subsoil	0.60 ± 0.02 a	74.88 ± 1.11 a	6.63 ± 0.07 a	-9.58 ± 21.59 cd	9.70 ± 0.41 bc	22.53 ± 0.78 bc
KV - Wet - Topsoil	0.55 ± 0.02 ab	76.75 ± 1.10 a	6.36 ± 0.08 a	11.48 ± 24.82 cd	9.23 ± 0.34 c	24.28 ± 1.45 b

(table con’d)

MO - Dry - Subsoil	0.60 ± 0.06 a	32.03 ± 1.73 c	5.61 ± 0.21 bc	-65.06 ± 30.47 d	13.45 ± 0.99 a	16.54 ± 1.55 d
MO - Dry - Topsoil	0.58 ± 0.08 a	28.82 ± 1.98 c	5.16 ± 0.20 c	174.40 ± 33.55 a	11.72 ± 1.31 ab	19.11 ± 1.52 cd
MO - Wet - Subsoil	0.49 ± 0.03 b	76.75 ± 1.93 a	6.19 ± 0.03 ab	-51.96 ± 28.67 d	12.02 ± 0.85 a	22.25 ± 0.71 bc
MO - Wet Topsoil	0.57 ± 0.07 a	72.92 ± 2.79 a	6.19 ± 0.02 ab	91.42 ± 29.32 b	9.79 ± 0.80 ab	30.11 ± 0.89 a
Zo * De						
Z1 - Subsoil	0.63 ± 0.03 b	53.72 ± 6.65 a	6.22 ± 0.18 a	9.84 ± 21.48 cd	10.83 ± 0.62 bc	19.71 ± 1.04 bc
Z1 - Topsoil	0.70 ± 0.06 a	49.98 ± 6.83 b	5.97 ± 0.12 ab	108.38 ± 43.72 a	9,64 ± 0.98 c	22.76 ± 1.25 ab
Z2 - Subsoil	0.52 ± 0.02 cd	56.76 ± 6.23 a	6.04 ± 0.23 ab	-82.72 ± 10.36 e	13.65 ± 0.57 a	19.72 ± 1.43 bc
Z2 - Topsoil	0.49 ± 0.02 d	54.76 ± 6.50 a	5.86 ± 0.21 ab	45.28 ± 15.56 bc	11.50 ± 0.59 b	22.16 ± 1.66 bc
Z3 - Subsoil	0.55 ± 0.03 c	54.61 ± 6.32 a	5.66 ± 0.23 b	-42.17 ± 24.49 de	11.66 ± 0.79 b	19.12 ± 1.24 c
Z3 - Topsoil	0.50 ± 0.03 cd	56.37 ± 6.39 a	5.68 ± 019 ab	103.99 ± 16.85 ab	11.78 ± 0.84 b	25.72 ± 1.87 a
Si * Zo * De						
KV - Z1 - Subsoil	0.55 ± 0.00 de	57.75 ± 8.38 a	6.52 ± 0.25 a	-20.25 ± 23.78 cde	11.72 ± 1.15 bc	21.31 ± 1.34 abc
KV - Z1 - Topsoil	0.51 ± 0.01 d-g	58.05 ± 9.67 a	5.96 ± 0.17 ab	-24.59 ± 32.25 cde	12.20 ± 1.19 bc	19.69 ± 1.66 bc
KV - Z2 - Subsoil	0.57 ± 0.02 cd	56.70 ± 8.96 ab	6.19 ± 0.36 ab	-63.01 ± 11.92 de	12.09 ± 0.52 bc	17.46 ± 1.91 c
KV - Z2 - Topsoil	0.53 ± 0.02 def	56.49 ± 9.45 ab	6.25 ± 0.21 ab	35.55 ± 19.39 bcd	10.92 ± 0.94 bc	21.39 ± 1.16 abc
KV - Z3 - Subsoil	0.65 ± 0.03 bc	52.53 ± 8.54 bc	5.43 ± 0.42 b	28.68 ± 24.48 bcd	10.26 ± 0.79 bc	20.13 ± 1.84 bc
KV - Z3 - Topsoil	0.58 ± 0.02 cd	55.07 ± 8.05 ab	5.80 ± 0.20 ab	105.59 ± 12.29 b	10.46 ± 1.04 bc	26.37 ± 2.35 a

(table con'd)

MO - Z1 - Subsoil	0.71 ± 0.05 b	49.69 ± 10.85 c	5.91 ± 0.19 ab	39.94 ± 32.20 bc	9.93 ± 0.28 cd	18.10 ± 1.41 c
MO - Z1 - Topsoil	0.88 ± 0.02 a	41.91 ± 9.26 d	5.98 ± 0.16 ab	241.34 ± 17.25 a	7.09 ± 0.43 d	25.83 ± 1.84 a
MO - Z2 - Subsoil	0.47 ± 0.02 e-h	56.82 ± 9.52 ab	5.90 ± 0.28 ab	-102.43 ± 13.20 e	15.21 ± 0.41 a	21.98 ± 3.33 abc
MO - Z2 - Topsoil	0.44 ± 0.02 gh	53.03 ± 9.68 abc	5.48 ± 0.29 b	55.00 ± 25.52 bc	12.08 ± 0.73 bc	22.93 ± 1.45 abc
MO - Z3 - Subsoil	0.45 ± 0.01 fgh	56.68 ± 10.05 ab	5.89 ± 0.20 ab	-113.02 ± 5.57 e	13.07 ± 1.16 ab	18.11 ± 1.51 c
MO - Z3 - Topsoil	0.41 ± 0.01 h	57.66 ± 10.68 ab	5.57 ± 0.34 b	102.40 ± 33.13 b	13.10 ± 1.16 ab	25.08 ± 3.42 ab
Se * Zo * De						
Dry - Z1 - Subsoil	0.68 ± 0.06 a	32.22 ± 3.05 cd	5.87 ± 0.27 abc	1.98 ± 39.58 bcd	12.01 ± 1.04 a-d	21.31 ± 1.33 cd
Dry - Z1 - Topsoil	0.71 ± 0.09 a	28.83 ± 3.42 d	5.69 ± 0.16 abc	147.50 ± 62.45 a	10.99 ± 1.76 b-e	19.96 ± 1.81 bcd
Dry - Z2 - Subsoil	0.53 ± 0.02 ab	36.59 ± 0.39 c	5.71 ± 0.40 abc	-83.44 ± 18.20 d	14.47 ± 0.71 a	17.47 ± 2.17 cd
Dry - Z2 - Topsoil	0.47 ± 0.03 c	33.40 ± 1.06 cd	5.36 ± 0.28 bc	76.80 ± 25.03 ab	12.45 ± 0.86 a-d	21.39 ± 1.37 cd
Dry - Z3 - Subsoil	0.56 ± 0.04 ab	33.90 ± 0.67 cd	5.03 ± 0.28 c	-56.34 ± 27.80 d	13.22 ± 0.83 ab	20.13 ± 1.10 d
Dry - Z3 - Topsoil	0.49 ± 0.04 ab	35.48 ± 0.98 c	5.15 ± 0.20 c	136.64 ± 26.20 a	13.88 ± 0.93 a	26.37 ± 1.74 bcd
Wet - Z1 - Subsoil	0.58 ± 0.01 b	75.21 ± 0.61 ab	6.56 ± 0.14 a	17.71 ± 20.96 bcd	9.65 ± 0.26 ed	18.10 ± 0.62 bc
Wet - Z1 - Topsoil	0.67 ± 0.08 a	71.13 ± 3.83 b	6.24 ± 0.30 ab	69.25 ± 62.42 abc	8.30 ± 0.62 e	25.83 ± 1.46 b
Wet - Z2 - Subsoil	0.52 ± 0.04 ab	76.93 ± 2.81 a	6.38 ± 0.13 a	-82.01 ± 11.85 d	12.83 ± 0.79 abc	21.98 ± 1.23 bc
Wet - Z2 - Topsoil	0.50 ± 0.03 ab	76.12 ± 0.76 ab	6.37 ± 0.11 a	13.76 ± 6.39 bcd	10.55 ± 0.67 b-e	22.93 ± 1.76 ab
Wet - Z3 - Subsoil	0.54 ± 0.05 ab	75.31 ± 1.95 ab	6.29 ± 0.05 a	-28.00 ± 42.24 cd	10.11 ± 1.04 cde	18.11 ± 0.87 bc

(table con'd)

Wet - Z3 - Topsoil	0.50 ± 0.06 ab	77.25 ± 2.05 a	6.21 ± 0.09 ab	71.34 ± 11.69 abc	9.67 ± 0.71 de	25.08 ± 1.78 a
Si * Se * Zo * De	**Ns**	**(*)**	**ns**	**Ns**	**ns**	**Ns**
KV - Dry - Z1 - Subsoil	0.55 ± 0.01 b-g	39.01 ± 0.01 d	5.67 ± 0.04 a-d	-17.54 ± 47.91 d-i	14.10 ± 0.87 abc	19.13 ± 1.82 d-g
KV - Dry - Z1 - Topsoil	0.53 ± 0.00 b-h	36.43 ± 0.30 d	5.62 ± 0.20 a-e	19.46 ± 52.80 c-i	14.77 ± 0.55 ab	17.90 ± 1.44 efg
KV - Dry - Z2 - Subsoil	0.56 ± 0.03 b-f	36.77 ± 0.69 d	5.71 ± 0.67 a-e	-55.63 ± 24.90 e-i	13.09 ± 0.56 a-d	15.13 ± 1.02 g
KV - Dry - Z2 - Topsoil	0.52 ± 0.03 b-h	35.37 ± 0.64 d	5.88 ± 0.31 a-e	62.84 ± 31.13 b-g	11.91 ± 1.79 a-e	19.83 ± 1.18 c-g
KV - Dry - Z3 - Subsoil	0.64 ± 0.05 b	33.52 ± 0.87 de	4.48 ± 0.16 e	-7.26 ± 36.94 d-i	11.85 ± 0.46 a-e	15.79 ± 1.53 efg
KV - Dry - Z3 - Topsoil	0.57 ± 0.01 b-e	37.18 ± 1.10 d	5.42 ± 0.16 b-e	116.36 ± 23.88 a-d	12.79 ± 0.11 a-d	24.33 ± 1.67 a-f
KV - Wet - Z1 - Subsoil	0.55 ± 0.01 b-f	76.48 ± 0.34 ab	6.68 ± 0.04 a	-22.96 ± 22.93 d-i	9.34 ± 0.38 def	23.49 ± 0.35 b-g
KV - Wet - Z1 - Topsoil	0.50 ± 0.03 c-h	79.67 ± 0.13 ab	6.29 ± 0.04 abc	-68.63 ± 21.72 f-i	9.62 ± 0.42 c-f	21.48 ± 0.40 b-g
KV - Wet - Z2 - Subsoil	0.59 ± 0.02 bcd	76.63 ± 1.83 ab	6.66 ± 0.00 ab	-70.39 ± 6.06 f-i	11.08 ± 0.11 b-f	19.79 ± 0.92 c-g
KV - Wet - Z2 - Topsoil	0.55 ± 0.01 b-g	77.62 ± 0.08 ab	6.62 ± 0.03 ab	8.26 ± 12.91 c-i	9.93 ± 0.52 b-f	22.94 ± 0.66 b-g
KV - Wet - Z3 - Subsoil	0.65 ± 0.05 b	71.54 ± 1.69 b	6.37 ± 0.06 ab	64.62 ± 18.40 b-g	8.67 ± 0.58 def	24.29 ± 0.69 a-f
KV - Wet - Z3 - Topsoil	0.60 ± 0.03 bcd	72.95 ± 1.60 b	6.17 ± 0.15 a-d	94.81 ± 8.26 b-e	8.13 ± 0.11 ef	28.41 ± 3.34 abc
MO - Dry - Z1 - Subsoil	0.81 ± 0.04 a	25.43 ± 0.53 d	5.56 ± 0.26 a-e	21.50 ± 71.80 c-i	9.91 ± 0.52 c-f	15.30 ± 1.33 g
MO - Dry - Z1 - Topsoil	0.91 ± 0.02 a	21.22 ± 0.64 d	5.76 ± 0.30 a-e	275.54 ± 17.82 a	7.21 ± 0.93 f	23.83 ± 2.33 a-g
MO - Dry - Z2 - Subsoil	0.50 ± 0.03 c-h	36.41 ± 0.50 d	5.70 ± 0.60 a-e	-111.25 ± 16.23 hi	15.85 ± 0.59 a	19.07 ± 4.33 d-g
MO - Dry - Z2 - Topsoil	0.43 ± 0.04 fgh	31.44 ± 1.15 d	4.48 ± 0.15 de	90.75 ± 44.38 b-f	12.99 ± 0.46 a-d	16.00 ± 2.08 efg

(table con'd)

MO - Dry - Z3 - Subsoil	0.48 ± 0.01 c-h	34.28 ± 1.15 d	5.57 ± 0.32 a-e	-105.42 ± 9.61 hi	14.59 ± 1.16 ab	15.37 ± 1.91 fg
MO - Dry - Z3 - Topsoil	0.41 ± 0.02 gh	33.79 ± 0.83 d	4.88 ± 0.35 cde	156.91 ± 9.50 abc	14.97 ± 1.76 ab	17.50 ± 0.87 efg
MO - Wet - Z1 - Subsoil	0.60 ± 0.02 bc	73.94 ± 0.32 ab	6.26 ± 0.00 a	58.37 ± 4.26 b-g	9.95 ± 0.33 c-f	21.00 ± 0.52 b-g
MO - Wet - Z1 - Topsoil	0.85 ± 0.00 a	62.59 ± 0.69 c	6.19 ± 0.04 abc	207.13 ± 0.51ab	6.98 ± 0.18 f	27.83 ± 0.66 a-d
MO - Wet - Z2 - Subsoil	0.44 ± 0.02 e-h	77.23 ± 6.00 ab	6.09 ± 0.10 ab	-93.63 ± 23.02 ghi	14.57 ± 0.27 ab	24.90 ± 0.46 a-e
MO - Wet - Z2 - Topsoil	0.46 ± 0.04 d-h	74.62 ± 0.81 ab	6.11 ± 0.04 ab	19.25 ± 2.74 c-i	11.16 ± 1.27 b-f	29.85 ± 1.76 ab
MO- Wet - Z3 - Subsoil	0.42 ± 0.01 fgh	79.09 ± 1.36 ab	6.20 ± 0.01 a-d	-120.63 ± 2.24 i	11.54 ± 1.74 a-f	20.85 ± 0.54 c-g
MO - Wet - Z3 - Topsoil	0.40 ± 0.01 h	81.54 ± 0.23 a	6.25 ± 0.04 a-d	47.87 ± 8.01 b-h	11.22 ± 0.29 b-f	32.65 ± 0.43 a

5.3.8 Organic Matter (OM)

The two two-way interactions of site and zone as well as season and zone, and the three-way interaction of site x season x depth affected the soil OM. Soil OM was not affected by the four-way interaction (Table 5.4).

The effect of zone on OM was dependent on site. At the KV site, OM was similar among the three zones. At the MO site, OM in zone 1 was significantly lower than in zone 2 and zone 3 (Table 5.5). Overall, OM in zones 1, 2, and 3 of the MO site was significant greater than OM in zones 1, 2, and 3 of the KV site (Table 5.5).

Similarly, the effect of zone on OM was dependent on season. During both the dry and the wet seasons, OM in zone 1 was significantly lower than in zone 2 and zone 3 (Table 5.5). A difference in OM was found between the dry and the wet season, but only in zone 2 (Table 5.5).

Soil OM was also dependent on the interaction of site, season, and depth. At the KV site, no difference in soil OM was detected between the topsoil and the subsoil during both the dry and wet seasons (Table 5.5). However, at the MO site, OM in the topsoil was less than in the subsoil, but only in the wet season (Table 5.5). Overall, OM was higher at the MO site than the KV site for both the dry and wet seasons (Table 5.5).

Soil OM had significant negative correlation with flooding frequency ($r = -0.6741$, $P = 0.0464$) but only during the wet season at the MO site (Figure 5.16). It also had a significant negative correlation with groundwater EC during the dry season ($r = -0.7930$, $P = 0.0108$) and the wet season ($r = 0.6772$, $P = 0.0451$) (Figures 5.17 and 5.18) at the MO site.

Mangrove forests in general are the primary producers in the estuaries. They contribute large amounts of organic matter in the form of autochthonous litter fall and act as a trap for allochthonous organic matter (Cloutier et al. 2005). The accumulation of organic matter in mangrove soils is affected by the hydrological regime (Tam and Wong 1997).

Analysis in this study indicates that OM at the MO site was higher than at the KV site due to the MO site's higher elevation and lower flooding frequency. The reduced flushing of litter by daily tides at the MO site allows for more OM to remain in the soil, while frequent flushing of litter fall by daily tides contributes to the lack of OM in the soil at the KV site.

The botanical origin of the organic material and the degree to which it decomposes are important to OM accumulation (Clymo 1983). The accumulation and decomposition of OM in wetlands are a function of the anaerobic conditions created by standing water and poor soil drainage (Mitsch and Gosselink 2000). Standing water and poor drainage support soil reduction which leads to low decomposition of OM in the soil. In this study, zone 1 of the KV site had higher flooding frequency and soil reduction than other zones due to its low elevation. In contrast, zone 3 had a lower flooding frequency and less soil reduction because it was at a higher elevation. Tam and Wong (1997) found that low OM occurs in zones with high flooding frequency or high daily tidal flushing (Figure 5.16). Accordingly, lower OM was found in zone 1 than in zones 2 and 3 because of the formers high flooding frequency. Overall, it was found that OM was highest during the wet season at the MO site. However, in this study, low OM was found in zones with high groundwater EC during both the dry and the wet seasons at the MO site (Figure 5.17 and 5.18).

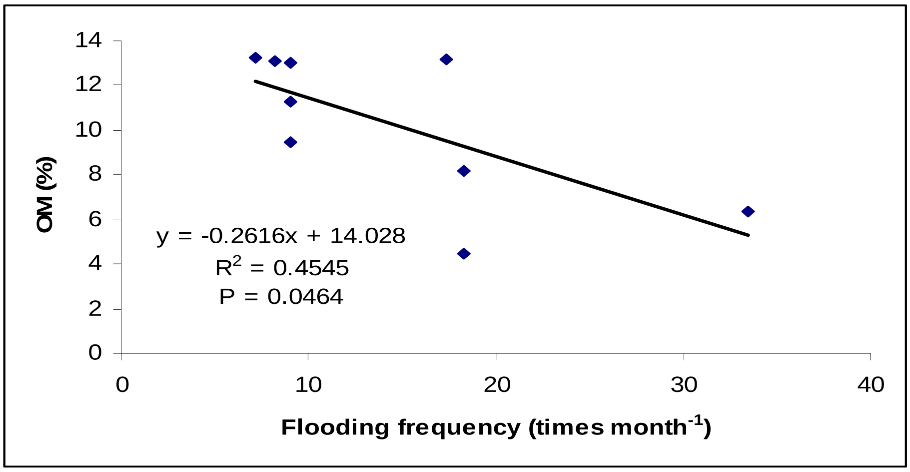

Figure 5.16 The relationship between OM and flooding frequency during the wet season across all zones at the MO sites in the Can Gio Mangrove Biosphere Reserve.

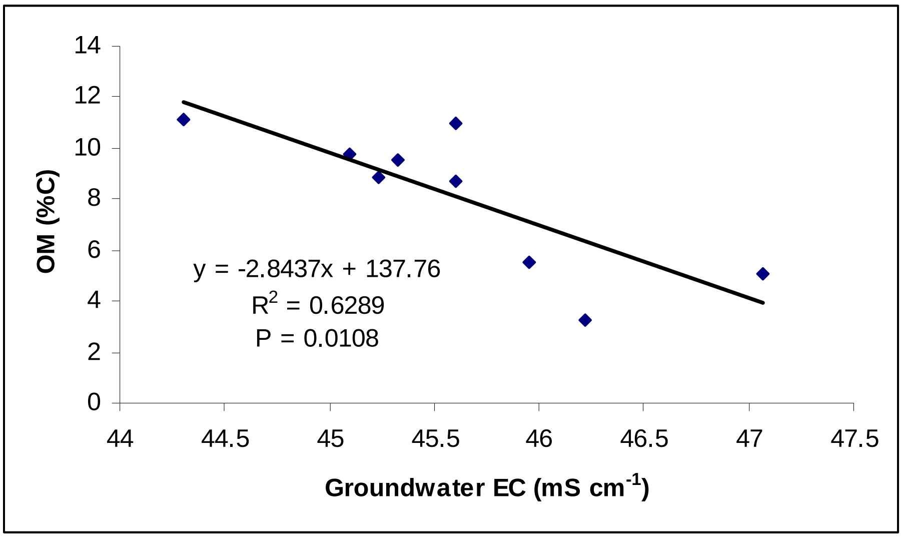

Figure 5.17 The relationship between OM and groundwater EC during the dry season across all zones at the MO sites in the Can Gio Biosphere Reserve.

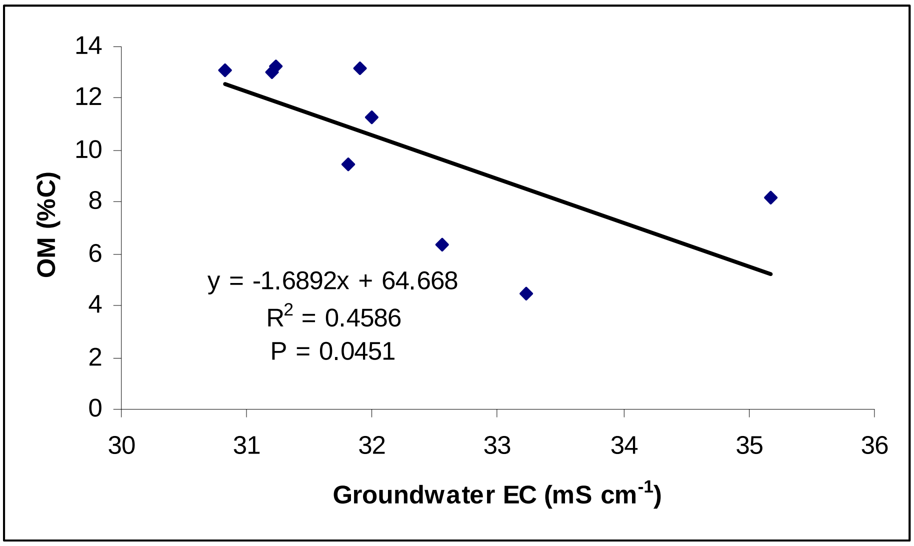

Figure 5.18 The relationship between OM and groundwater EC during the wet season across all zones at the MO site in the Can Gio Mangrove Biosphere Reserve.

5.3.9 Total Soil Nitrogen (Total N)

Total soil N was significantly affected by two three-way interactions: site x season x zone and site x season x depth. However, the effect of these interactions on total N was minimal (Table 5.4). The four-way interaction was not significant (Table 5.4).

The effect of zone on total N was dependent on season and site. At the KV site, total N did not differ by zone for either season (Table 5.5). However, at the MO site, total N in zone 2 was significantly higher than in zones 1 and 3, but only during the wet season. Total N in zone 2 at the MO site was also greater in the wet season than in the dry season (Table 5.5). Generally, MO site had a significantly higher total N than the KV site, but only during the wet season (Table 5.5).

The effect of season on total N was dependent on site and depth. At the KV site, no difference in total N was found between the topsoil and the subsoil or between dry and wet seasons (Table 5.5). At the MO site, in contrast, total N was significantly higher in the topsoil than the subsoil but only in the wet season (Table 5.5). Total N was generally higher at the MO site than at the KV site except in the subsoil during the dry season (Table 5.5).

Total N had a negative relationship with flooding frequency ($r = -0.5464$, $P = 0.0005$) (Figure 5.19).

Mangrove forests are typically nutrient-limited, especially in nitrogen (Boto, 1992). A very small portion of total N exists in inorganic form (Tam and Wong 1997). In this study, total N was generally not different between seasons and depths or among zones. Total N was higher at the MO site due to the site's higher elevation.

Total N is determined by the amount of litter fall and the rate of litter decomposition. The amount of litter fall and the rate of litter decomposition are affected by flooding frequency and the intensity of tidal flushing, which in turn affect total N in soil. In other

words, total N is lessened through the daily tidal flushing of organic matter that derives from autochthonous litter fall (Tam and Wong 1997).

The quantity and quality of litter decomposition on the soil surface of areas with lower elevation are strongly affected by tidal activity (Twilley 1985, Twilley et al. 1986). In fact, this research demonstrates that total N was also affected by flooding frequency (Figure 5.19)

5.3.10 Soil NH_4^+-N

Season had a significant main effect on soil NH_4^+-N (Table 5.4). In contrast, the main effects of site, zone and depth significantly interacted to affect soil ammonium (Table 5.4).

NH_4^+-N in the wet season was significantly greater than in the dry season (Table 5.5). The effect of zone on NH_4^+-N was dependent on site and depth. NH_4^+-N in the topsoil was not significantly different from that in the subsoil among zones for both the KV and MO sites except in zone 3 of the MO site, where the topsoil had twice the ammonium level than the subsoil (Table 5.5).

Flooding frequency, a component of the hydrological regime, had a negative relationship with NH_4^+-N. However, this negative relationship only occurred in the subsoil ($r = -0.4327$, $P = 0.0075$) (Figure 5.20).

NH_4^+-N in the wet season was higher than in the dry season, possibly due to soil acquiring NH_4^+-N from the water runoff. The soil receives more oxygen during the dry season, which can lead to a lower NH_4^+-N. Because of abundant water, most soils in the KV and MO sites have low levels of NH_4^+-N. This finding may be explained by the nitrification and denitrification processes that dominate the wetland soil. Similar to the findings for total N, the analysis in this study indicated that soil with high flooding frequency had low NH_4^+-N (Figure 5.20).

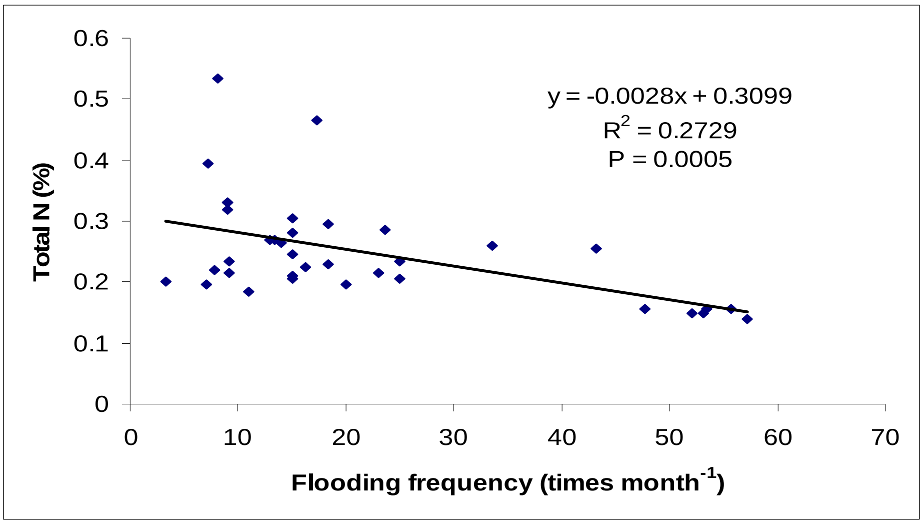

Figure 5.19 The relationship between total N and flooding frequency during the dry and wet seasons across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

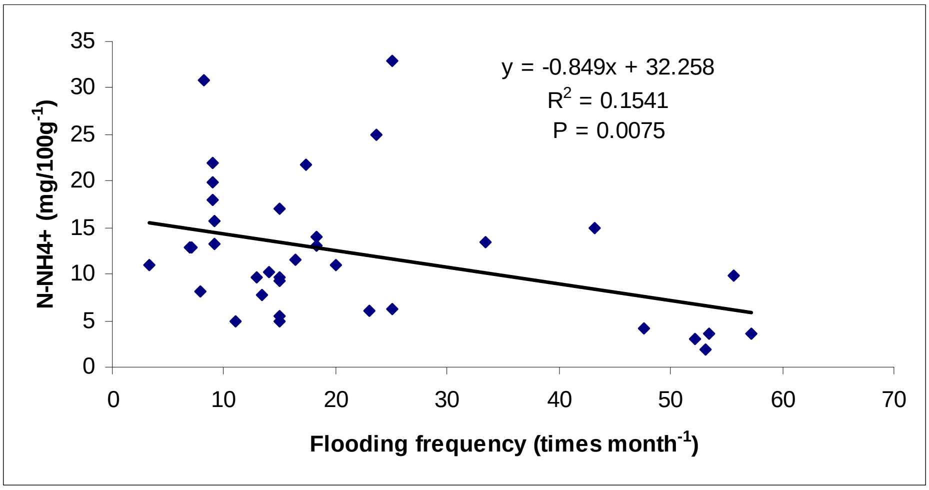

Figure 5.20 The relationship between $NH4^{+}$-N in the subsoil and flooding frequency during the dry and wet seasons across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

5.3.11 Total Phosphate and Available Phosphate (P)

Total P was not significantly affected by any main effect or any interactive effect (Table 5.4). However, available P was significantly affected by the main effect of season and by the interaction of site and zone (Table 5.4). The three-way and four-way interactions had no effect on available P (Table 5.4).

Available P in the wet season was significantly greater than in the dry season (Table 5.5). The effect of zone on available P was dependent on site. At the KV site, available P significantly increased from zone 1 to zones 2 and 3. At the MO site, available P was statistically equal among all zones. Available P was significantly greater at the KV site than the MO site, but only for zones 2 and 3 (Table 5.5).

There were no significant correlations between the hydrological regime and total P. However, available P was negatively correlated with flooding frequency ($r = -0.8408$, $P < 0.0001$) during the wet and dry seasons at the KV site (Figure 5. 21) and positively correlated with the soil moisture ($r = 0.3869$, $P = 0.0180$) (Figure 5.22).

Mangrove soils contain a high proportion of organic P due to their high organic matter content (Boto 1984). Although organic matter varies among site, season, zone and depth, no difference in total P was found in this study. However, available P was different, because it was higher during the wet season than the dry season. This occurrence may be due to changes in the availability of phosphorus. When the soil becomes anaerobic, ferric (Fe^{3+}) iron which binds lightly with P is reduced to a ferrous iron (Fe^{2+}), which is more soluble and can be more readily exchanged with the soil solution (Gambrell and Patrick 1978, Mitsch and Gosselink 2000). In general, pore-water P concentrations can be strongly regulated by ions and by the redox condition of the sediments (Sherman et al. 1998). In this study, the KV site had a higher flooding frequency and greater soil reduction than the MO site; therefore, phosphorus could be released easily into the pore-water.

However, I also found a negative correlation between available P and flooding frequency (Figure 5.21). This correlation may be due to the common relationship between flooding frequency and OM. Higher flooding frequency leads to lower OM, which could then reduced the mineralization of available P. Available P was also negatively correlated with soil moisture (Figure 5.21). Soil with high moisture becomes reduced, lowering the OM decomposition rate which could then lead to low available P (Figure 5.22).

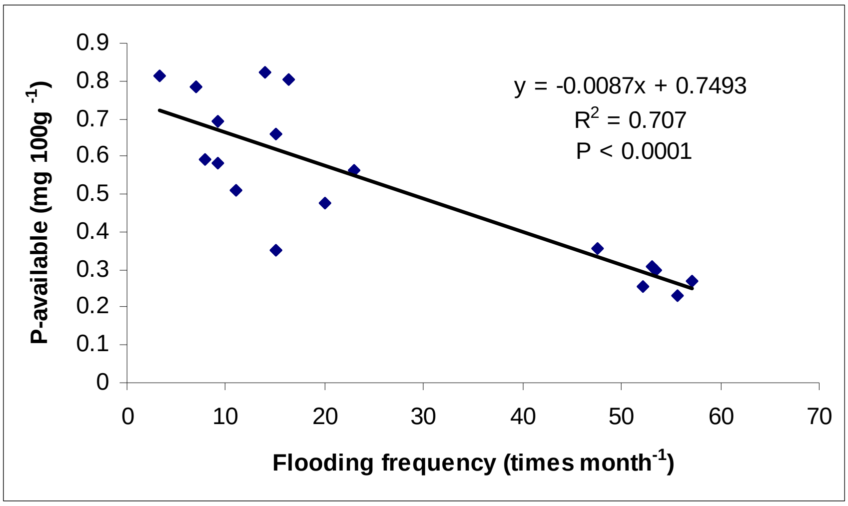

Figure 5.21 The relationship between available P and flooding frequency during the dry and wet seasons across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

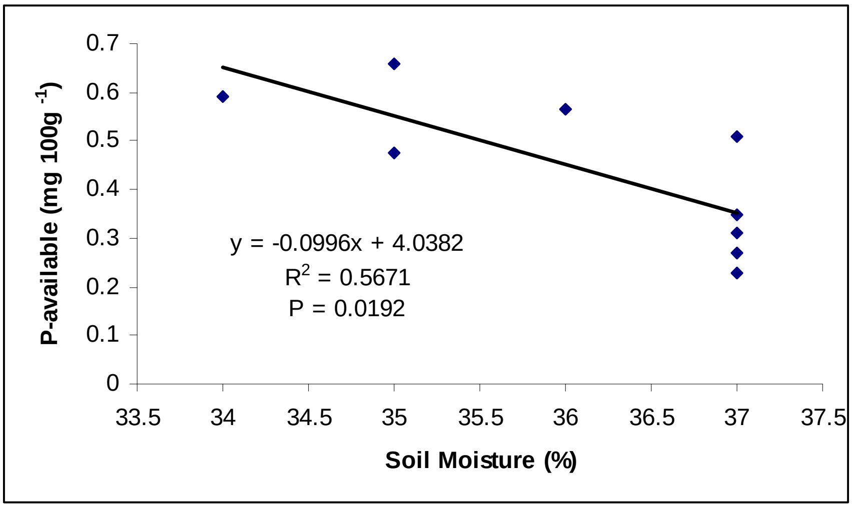

Figure 5.22 The relationship between available P and soil moisture during the dry and the wet seasons across all zones at the KV and MO sites in the Can Gio Biosphere Reserve.

Table 5.4 ANOVA table of OM, total N, N-NH_4^+, total P, and available P at the study sites in the Can Gio Mangrove Biosphere Reserve. (*) indicates significant effect at $P \leq 0.05$.

		OM		Total N		N-NH_4^+		Total P		P available	
Source	DF	F-ratio	Prob > F	F-ratio	Prob > F	F-ratio	Prob > F	F-ratio	Prob > F	F-ratio	Prob > F
Site (Si)	1	317.34	<0.0001*	95.88	<0.0001*	10.29	0.0024*	2.79	0.1011	18.43	<0.0001*
Season (Se)	1	25.09	<0.0001*	19.92	<0.0001*	4.51	0.0389*	2.29	0.1361	10.03	0.0027*
Si x Se	1	6.75	0.0124*	10.97	0.0018*	0.41	0.5249	0.07	0.7867	0.26	0.6109
Zone (Zo)	2	51.95	<0.0001*	22.02	<0.0001*	2.18	0.1238	0.69	0.5034	12.60	<0.0001*
Si x Zo	2	35.83	<0.0001*	3.54	0.0366*	1.86	0.1660	1.59	0.2128	3.29	0.0457*
Se x Zo	2	3.45	0.0397*	6.41	0.0034*	0.95	0.3929	0.38	0.6800	1.00	0.3746
Si x SeZo	2	0.07	0.9283	3.30	0.0453*	0.08	0.9155	1.35	0.2686	0.46	0.6298
Depth (De)	1	15.73	0.0002*	0.23	0.6334	10.55	0.0021*	1.02	0.3172	3.24	0.0778
Si x De	1	25.09	<0.0001*	2.35	0.1311	1.32	0.2550	0.21	0.6430	0.68	0.4116
Se x De	1	4.00	0.0512*	7.48	0.0087*	0.06	0.7926	0.48	0.4875	1.33	0.2723
Si x Se x De	1	5.31	0.0255*	6.47	0.0142*	0.08	0.7740	1.18	0.2818	0.73	0.4861

(table con'd)

Zo x De	2	0.32	0.7268	1.35	0.2684	0.50	0.6087	0.50	0.6075	1.33	0.2723
Si x Zo x De	2	0.45	0.6358	2.26	0.1149	4.84	0.0121*	2.12	0.1300	0.73	0.4861
Se x Zo x De	2	0.12	0.8835	1.22	0.3017	1.10	0.3381	0.72	0.4910	1.47	0.2388
Si x Se x Zo x De	2	0.46	0.6299	0.36	0.6995	0.44	0.6446	0.95	0.3921	0.68	0.5107

Table 5.5 Mean comparisons of OM, total N, N-NH_4^+, total P and available P at the study sites in the Can Gio mangrove Biosphere Reserve. The means ± standard errors with different letter are significantly different at alpha = 0.05.

Source	OM (% C)	Total N (% N)	N-NH_4^+ (mg/kg)	Total P (% P_2O_5)	P-available (mg/100g)
Site (Si)					
KV	4.11 ± 0.15 b	0.19 ± 0.01 a	12.25 ± 1.05 b	0.10 ± 0.01 a	0.52 ± 0.04 a
MO	9.17 ± 0.58 a	0.31 ± 0.02 b	18.32 ± 1.86 a	0.08 ± 0.02 a	0.33 ± 0.03 b
Season (Se)					
Dry season	5.93 ± 0.50 b	0.22 ± 0.01 a	13.28 ± 1.71 b	0.10 ± 0.01 a	0.36 ± 0.04 b
Wet season	7.35 ± 0.67 a	0.28 ± 0.02 b	17.30 ± 1.38 a	0.08 ± 0.02 a	0.50 ± 0.04 a
Si * Se					
KV – Dry	3.77 ± 0.21 c	0.19 ± 0.01 c	10.84 ± 1.24 b	0.11 ± 0.01 a	0.40 ± 0.05 ab
KV – Wet	4.45 ± 0.21 c	0.20 ± 0.01 c	13.65 ± 1.66 b	0.09 ± 0.01 a	0.60 ± 0.06 a
MO – Dry	8.09 ± 0.68 b	0.26 ± 0.01 b	15.71 ± 3.14 ab	0.09 ± 0.01 a	0.27 ± 0.06 c
MO – Wet	10.25 ± 0.90 a	0.35 ± 0.03 a	20.94 ± 1.89 a	0.06 ± 0.03 a	0.39 ± 0.05 bc

(table con’d)

Zone (Zo)					
Zone 1	4.60 ± 0.39 b	0.20 ± 0.01 b	12.58 ± 1.49 a	0.08 ± 0.01 a	0.27 ± 0.02 b
Zone 2	7.76 ± 0.87 a	0.29 ± 0.03 a	16.02 ± 1.52 a	0.10 ± 0.03 a	0.52 ± 0.06 a
Zone 3	7.57 ± 0.69 a	0.26 ± 0.01 a	17.26 ± 2.56 a	0.09 ± 0.01 a	0.49 ± 0.05 a
Si * Zo					
KV - Z1	3.71 ± 0.25 c	0.15 ± 0.01 d	10.06 ± 1.90 b	0.09 ± 0.01 a	0.29 ± 0.18 b
KV - Z2	4.03 ± 0.33 bc	0.21 ± 0.01 c	14.92 ± 2.20 ab	0.10 ± 0.01 a	0.66 ± 0.05 a
KV - Z3	4.59 ± 0.14 bc	0.21 ± 0.01 c	11.70 ± 0.96 b	0.11 ± 0.01 a	0.62 ± 0.06 a
MO - Z1	5.48 ± 0.65 b	0.25 ± 0.02 bc	15.11 ± 2.13 ab	0.07 ± 0.02 a	0.26 ± 0.03 b
MO - Z2	11.50 ± 0.74 a	0.37 ± 0.04 a	17.11 ± 2.15 ab	0.10 ± 0.04 a	0.37 ± 0.10 b
MO - Z3	10.54 ± 0.61 a	0.30 ± 0.01 b	22.75 ± 4.58 a	0.06 ± 0.01 a	0.37 ± 0.05 b
Se * Zo					
Dry - Z1	4.06 ± 0.34 d	0.19 ± 0.01 c	12.26 ± 2.39 a	0.08 ± 0.01 a	0.24 ± 0.02 b
Dry - Z2	6.53 ± 1.05 bc	0.24 ± 0.02 bc	12.51 ± 1.77 a	0.12 ± 0.02 a	0.41 ± 0.08 ab
Dry - Z3	7.20 ± 0.85 b	0.24 ± 0.02 bc	15.06 ± 4.33 a	0.10 ± 0.02 a	0.42 ± 0.07 ab
Wet - Z1	5.13 ± 0.68 cd	0.21 ± 0.02 c	12.91 ± 1.89 a	0.08 ± 0.02 a	0.30 ± 0.03 b

(table con’d)

Wet - Z2	8.99 ± 1.35 a	0.35 ± 0.05 a	19.52 ± 2.07 a	0.08 ± 0.05 a	0.62 ± 0.08 a
Wet - Z3	7.94 ± 1.12 ab	0.27 ± 0.02 b	19.46 ± 2.79 a	0.08 ± 0.02 a	0.57 ± 0.05 a
Si * Se * Zo					
KV - Dry - Z1	3.49 ± 0.27 d	0.15 ± 0.01 d	10.37 ± 2.85 ab	0.09 ± 0.01 a	0.27 ± 0.03 c
KV - Dry - Z2	3.24 ± 0.34 d	0.20 ± 0.01 cd	11.52 ± 2.10 ab	0.10 ± 0.01 a	0.52 ± 0.03 abc
KV - Dry - Z3	4.57 ± 0.21 cd	0.21 ± 0.01 cd	10.65 ± 1.72 ab	0.14 ± 0.01 a	0.53 ± 0.11 abc
KV - Wet - Z1	3.92 ± 0.43 d	0.15 ± 0.01 d	9.74 ± 2.77 b	0.09 ± 0.01 a	0.30 ± 0.03 c
KV - Wet - Z2	4.81 ± 0.34 cd	0.23 ± 0.01 cd	18.32 ± 3.49 ab	0.09 ± 0.01 a	0.81 ± 0.04 a
KV - Wet - Z3	4.62 ± 0.21 cd	0.22 ± 0.01 cd	12.89 ± 0.75 ab	0.09 ± 0.01 a	0.70 ± 0.05 ab
MO - Dry - Z1	4.63 ± 0.55 cd	0.23 ± 0.01 bcd	14.15 ± 3.95 ab	0.07 ± 0.01 a	0.21 ± 0.02 c
MO - Dry - Z2	9.82 ± 0.64 b	0.28 ± 0.03 bc	13.50 ± 3.02 ab	0.14 ± 0.03 a	0.31 ± 0.16 c
MO - Dry - Z3	9.83 ± 0.58 b	0.28 ± 0.02 bc	19.47 ± 8.46 ab	0.06 ± 0.02 a	0.30 ± 0.08 c
MO - Wet - Z1	6.34 ± 1.12 c	0.26 ± 0.03 bc	16.07 ± 2.01 ab	0.06 ± 0.03 a	0.30 ± 0.05 c
MO - Wet - Z2	13.18 ± 0.94 a	0.47 ± 0.06 a	20.73 ± 2.47 ab	0.07 ± 0.06 a	0.44 ± 0.13 abc
MO - Wet - Z3	11.25 ± 1.06 ab	0.33 ± 0.02 b	26.03 ± 4.06 a	0.06 ± 0.01 a	0.43 ± 0.05 bc

(table con’d)

Depth					
Subsoil	7.20 ± 0.48 a	0.25 ± 0.02 a	18.36 ± 1.25 a	0.08 ± 0.02 a	0.43 ± 0.05 a
Topsoil	6.08 ± 0.69 b	0.25 ± 0.01 a	12.21 ± 1.73 b	0.10 ± 0.01 a	0.42 ± 0.03 a
Si * De					
KV - Subsoil	3.96 ± 0.20 c	0.19 ± 0.01 b	8.08 ± 0.97 b	0.09 ± 0.01 a	0.51 ± 0.06 ab
KV - Topsoil	4.26 ± 0.24 c	0.20 ± 0.01 b	16.41 ± 1.23 a	0.11 ± 0.01 a	0.53 ± 0.05 a
MO - Subsoil	10.45 ± 0.83 a	0.32 ± 0.03 a	16.34 ± 1.86 a	0.07 ± 0.03 a	0.36 ± 0.07 bc
MO - Topsoil	7.90 ± 0.72 b	0.29 ± 0.02 a	20.31 ± 3.21 a	0.08 ± 0.02a	0.31 ± 0.02 c
Se * De					
Dry - Subsoil	6.21 ± 0.80	0.21 ± 0.01 c	10.45 ± 1.84 b	0.10 ± 0.01 a	0.33 ± 0.06 b
Dry Topsoil	5.65 ± 0.63	0.24 ± 0.01 bc	16.10 ± 2.79 ab	0.10 ± 0.01 a	0.39 ± 0.04 ab
Wet - Subsoil	8.20 ± 1.10	0.29 ± 0.03 a	13.97 ± 1.64 ab	0.07 ± 0.03 a	0.54 ± 0.07 a
Wet - Topsoil	6.51 ± 0.74	0.26 ± 0.02 ab	20.62 ± 1.98 a	0.09 ± 0.02 a	0.45 ± 0.05 ab
Si * Se * De					
KV - Dry – Subsoil	3.66 ± 0.28 c	0.18 ± 0.01 c	6.66 ± 1.04 b	0.10 ± 0.01 a	0.41 ± 0.07 abc
KV - Dry - Topsoil	3.87 ± 0.32 c	0.19 ± 0.01 c	15.03 ± 1.02 ab	0.12 ± 0.01 a	0.47 ± 0.06 abc

(table con’d)

KV - Wet - Subsoil	4.26 ± 0.26 c	0.19 ± 0.02 c	9.51 ± 1.56 b	0.08 ± 0.02 a	0.62 ± 0.09 a
KV - Wet - Topsoil	4.64 ± 0.32 c	0.20 ± 0.01 c	17.80 ± 2.22 ab	0.10 ± 0.01 a	0.59 ± 0.07 ab
MO - Dry - Subsoil	8.76 ± 0.01 b	0.24 ± 0.01 bc	14.24 ± 3.11 ab	0.10 ± 0.01 a	0.24 ± 0.10 c
MO - Dry - Topsoil	7.43 ± 0.90 b	0.28 ± 0.02 b	17.17 ± 5.63 ab	0.08 ± 0.02 a	0.31 ± 0.05 c
MO - Wet - Subsoil	12.14 ± 0.09 a	0.39 ± 0.05 a	18.43 ± 1.99 ab	0.05 ± 0.05 a	0.47 ± 0.09 abc
MO - Wet Topsoil	8.37 ± 0.16 b	0.31 ± 0.03 b	23.45 ± 3.10 b	0.08 ± 0.02 a	0.31 ± 0.01 bc
Zo * De					
Z1 - Subsoil	5.01 ± 0.71 c	0.21 ± 0.02 b	10.07 ± 2.50 b	0.06 ± 0.02 a	0.25 ± 0.03 c
Z1 - Topsoil	4.18 ± 0.29 c	0.19 ± 0.01 b	15.10 ± 1.37 ab	0.09 ± 0.01 a	0.30 ± 0.01 bc
Z2 - Subsoil	8.34 ± 1.48 a	0.30 ± 0.05 a	13.72 ± 2.30 ab	0.10 ± 0.05 a	0.58 ± 0.10 a
Z2 - Topsoil	7.18 ± 0.98 ab	0.28 ± 0.02 a	18.32 ± 1.85 ab	0.10 ± 0.02 a	0.46 ± 0.07 abc
Z3 - Subsoil	8.26 ± 1.10 ab	0.25 ± 0.02 ab	12.85 ± 1.63 ab	0.08 ± 0.02 a	0.48 ± 0.08 ab
Z3 - Topsoil	6.87 ± 0.84 b	0.27 ± 0.02 a	21.67 ± 4.60 a	0.10 ± 0.02 a	0.50 ± 0.05 ab
Si * Zo * De					
KV - Z1 - Subsoil	3.28 ± 0.22 e	0.14 ± 0.01 d	4.37 ± 0.80 c	0.09 ± 0.01 a	0.25 ± 0.03 c
KV - Z1 - Topsoil	4.13 ± 0.40 e	0.17 ± 0.01 d	15.74 ± 0.90 abc	0.10 ± 0.01 a	0.32 ± 0.02 abc

(table con’d)

KV - Z2 - Subsoil	3.84 ± 0.30 e	0.21 ± 0.02 cd	9.44 ± 0.92 bc	0.07 ± 0.02 a	0.67 ± 0.08 a
KV - Z2 - Topsoil	4.22 ± 0.61 e	0.22 ± 0.01 cd	20.40 ± 1.94 ab	0.12 ± 0.01 a	0.65 ± 0.06 a
KV - Z3 - Subsoil	4.77 ± 0.21 de	0.21 ± 0.01 cd	10.44 ± 1.10 bc	0.11 ± 0.01 a	0.62 ± 0.10 ab
KV - Z3 - Topsoil	4.42 ± 0.19 de	0.22 ± 0.01 cd	13.11 ± 0.66 bc	0.12 ± 0.01 a	0.61 ± 0.08 abc
MO - Z1 - Subsoil	6.74 ± 1.00 d	0.28 ± 0.03 bc	15.76 ± 2.58 abc	0.04 ± 0.02 a	0.25 ± 0.06 c
MO - Z1 - Topsoil	4.22 ± 0.47 e	0.22 ± 0.01 cd	14.46 ± 1.80 abc	0.09 ± 0.01 a	0.27 ± 0.01 bc
MO - Z2 - Subsoil	12.85 ± 1.17 a	0.40 ± 0.08 a	17.99 ± 2.67 abc	0.13 ± 0.08 a	0.48 ± 0.19 abc
MO - Z2 - Topsoil	10.15 ± 0.56 bc	0.35 ± 0.03 ab	16.23 ± 1.70 abc	0.08 ± 0.03 a	0.27 ± 0.04 bc
MO - Z3 - Subsoil	11.76 ± 0.64 ab	0.28 ± 0.02 bc	15.26 ± 1.87 bc	0.04 ± 0.02 a	0.34 ± 0.09 abc
MO - Z3 - Topsoil	9.32 ± 0.81 c	0.32 ± 0.01 ab	30.23 ± 5.61 a	0.08 ± 0.01 a	0.40 ± 0.05 abc
Se * Zo * De					
Dry - Z1 - Subsoil	4.16 ± 0.64 d	0.19 ± 0.02 c	11.57 ± 4.67 a	0.06 ± 0.02 a	0.21 ± 0.03 c
Dry - Z1 - Topsoil	3.97 ± 0.31 d	0.20 ± 0.02 c	12.95 ± 1.78 a	0.10 ± 0.02 a	0.28 ± 0.02 c
Dry - Z2 - Subsoil	6.92 ± 1.70 bc	0.22 ± 0.02 bc	10.73 ± 2.98 a	0.14 ± 0.02 a	0.46 ± 0.15 abc
Dry - Z2 - Topsoil	6.14 ± 1.37 cd	0.25 ± 0.03 bc	14.28 ± 1.94 a	0.10 ± 0.03 a	0.37 ± 0.08 abc
Dry - Z3 - Subsoil	7.55 ± 1.38 abc	0.23 ± 0.02 bc	9.05 ± 1.78 a	0.09 ± 0.02 a	0.31 ± 0.11 bc

(table con'd)

Dry - Z3 - Topsoil	6.85 ± 1.09 bc	0.26 ± 0.02 bc	21.07 ± 8.05 a	0.11 ± 0.02 a	0.52 ± 0.08 abc
Wet - Z1 - Subsoil	5.87 ± 1.24 cd	0.23 ± 0.04 bc	8.57 ± 2.21 a	0.07 ± 0.04 a	0.29 ± 0.05 bc
Wet - Z1 - Topsoil	4.39 ± 0.51 d	0.19 ± 0.01 c	17.24 ± 1.81 a	0.09 ± 0.01 a	0.31 ± 0.02 bc
Wet - Z2 - Subsoil	9.76 ± 2.42 a	0.39 ± 0.08 a	16.70 ± 3.30 a	0.07 ± 0.08 a	0.70 ± 0.13 a
Wet - Z2 - Topsoil	8.23 ± 1.37 abc	0.31 ± 0.04 ab	22.35 ± 2.19 a	0.10 ± 0.04 a	0.55 ± 0.10 abc
Wet - Z3 - Subsoil	8.98 ± 1.80 ab	0.27 ± 0.03 bc	16.55 ± 1.67 a	0.06 ± 0.03 a	0.65 ± 0.06 ab
Wet - Z3 - Topsoil	6.90 ± 1.38 bc	0.28 ± 0.02 bc	22.2 ± 5.32 a	0.09 ± 0.02 a	0.48 ± 0.08 abc
Si * Se * Zo * De					
KV - Dry - Z1 - Subsoil	3.15 ± 0.32 e	0.13 ± 0.01 e	5.10 ± 2.40 b	0.08 ± 0.01 a	0.24 ± 0.04 a-d
KV - Dry - Z1 - Topsoil	3.83 ± 0.37 e	0.16 ± 0.01 de	15.63 ± 2.65 ab	0.10 ± 0.01 a	0.30 ± 0.02 a-d
KV - Dry - Z2 - Subsoil	3.31 ± 0.41 e	0.19 ± 0.01 cde	7.33 ± 1.87 ab	0.07 ± 0.02 a	0.50 ± 0.06 a-d
KV - Dry - Z2 - Topsoil	3.17 ± 0.63 e	0.21 ± 0.02 cde	15.70 ± 1.01 ab	0.12 ± 0.02 a	0.53 ± 0.01 a-d
KV - Dry - Z3 - Subsoil	4.53 ± 0.28 e	0.21 ± 0.02 cde	7.53 ± 1.39 ab	0.13 ± 0.02 a	0.50 ± 0.17 a-d
KV - Dry - Z3 - Topsoil	4.61 ± 0.38 de	0.21 ± 0.02 cde	13.77 ± 1.78 ab	0.14 ± 0.02 a	0.57 ± 0.17 a-d
KV - Wet - Z1 - Subsoil	3.41 ± 0.34 e	0.14 ± 0.01 e	3.64 ± 0.32 b	0.09 ± 0.01 a	0.26 ± 0.04 a-d
KV - Wet - Z1 - Topsoil	4.43 ± 0.75 e	0.17 ± 0.01 de	15.84 ± 1.01 ab	0.09 ± 0.01 a	0.34 ± 0.02 a-d

(table con'd)

KV - Wet - Z2 - Subsoil	4.36 ± 0.04 e	0.23 ± 0.03 cde	11.54 ± 0.72 ab	0.08 ± 0.03 a	0.84 ± 0.05 a
KV - Wet - Z2 - Topsoil	5.26 ± 0.62 e	0.22 ± 0.01 cde	25.10 ± 3.81 ab	0.11 ± 0.01 a	0.77 ± 0.07 ab
KV - Wet - Z3 - Subsoil	5.00 ± 0.27 de	0.21 ± 0.01 cde	13.34 ± 1.36 ab	0.09 ± 0.01 a	0.74 ± 0.08 abc
KV - Wet - Z3 - Topsoil	4.24 ± 0.08 e	0.22 ± 0.01 cde	12.44 ± 0.89 ab	0.09 ± 0.01 a	0.65 ± 0.06 a-d
MO - Dry - Z1 - Subsoil	5.16 ± 0.96 de	0.24 ± 0.02 b-e	18.03 ± 7.84 ab	0.04 ± 0.02 a	0.18 ± 0.02 cd
MO - Dry - Z1 - Topsoil	4.10 ± 0.57 e	0.23 ± 0.01 cde	10.27 ± 1.26ab	0.10 ± 0.01 a	0.25 ± 0.02 bcd
MO - Dry - Z2 - Subsoil	10.54 ± 1.10 bc	0.25 ± 0.04 b-e	14.13 ± 5.41 ab a	0.20 ± 0.04 a	0.41 ± 0.33 a-d
MO - Dry - Z2 - Topsoil	9.10 ± 0.51 c	0.30 ± 0.03 bcd	12.87 ± 3.97ab	0.07 ± 0.03 a	0.20 ± 0.06 bcd
MO - Dry - Z3 - Subsoil	10.57 ± 0.61 bc	0.24 ± 0.03 b-e	10.57 ± 3.41 ab	0.05 ± 0.03 a	0.13 ± 0.01 c
MO - Dry - Z3 - Topsoil	9.09 ± 0.88 c	0.31 ± 0.01 bcd	28.37 ± 16.34 ab	0.07 ± 0.01 a	0.47 ± 0.07 a-d
MO - Wet - Z1 - Subsoil	8.33 ± 1.26 cd	0.31 ± 0.04 bcd	13.49 ± 0.29 ab	0.04 ± 0.04 a	0.31 ± 0.01 a-d
MO - Wet - Z1 - Topsoil	4.35 ± 0.87 e	0.21 ± 0.01 cde	18.46 ± 3.67ab	0.08 ± 0.01 a	0.28 ± 0.26 a-d
MO - Wet - Z2 - Subsoil	15.15 ± 0.51 a	0.54 ± 0.10 a	21.85 ± 5.23 ab	0.06 ± 0.10 a	0.55 ± 0.26 a-d
MO - Wet - Z2 - Topsoil	11.20 ± 0.46 bc	0.39 ± 0.01 ab	19.60 ± 1.39 ab	0.08 ± 0.02 a	0.33 ± 0.02 a-d
MO- Wet - Z3 - Subsoil	12.95 ± 0.52 ab	0.33 ± 0.01 bc	19.95 ± 1.13 ab	0.04 ± 0.01 a	0.55 ± 0.03 a-d
MO - Wet - Z3 - Topsoil	9.55 ± 1.56 bc	0.33 ± 0.01 bc	32.10 ± 6.64 a	0.08 ± 0.01 a	0.32 ± 0.02 a-d

5.4. Conclusions

The soil texture at both the KV and MO sites was dominated by silt and clay, which together comprised more than 95% of the soil by weight. The proportion of sand was positively correlated with elevation. The site of MO had a higher sand proportion than KV and zones with high elevation had greater sand proportion than others, (zone 2 and 3 of the MO site), and the subsoil had a higher sand proportion than the topsoil. The proportion of silt was lower at the MO site compared to the KV site and in the topsoil compared to the subsoil while proportion of clay was higher in the topsoil and highest in zone with low elevation, zone 1 of the KV site. Soil bulk density had a relationship with soil moisture with soil bulk density being higher during the dry season than the wet season. Soil bulk density was also found to have a relationship with OM, zones with lower OM had high soil bulk density. Soil organic matter was high in zones with high elevation and more landward areas. OM was higher in the wet season than in the dry season.

Hydrological regime had an effect on soil pH and Eh. High pH was found at locations with high elevation and low flooding frequency. In contrast, low Eh was found at locations with low elevation and high water inundation. EC was highly affected by season and by elevation. Higher EC was found in the high elevation zones, in the subsoil, and in the dry season. High CEC occurred during the wet season, in the topsoil, and in zones with high elevation.

Total N and $N\text{-}NH_4^+$ had a strong relationship with elevation and also with OM in the soil. In this study, total N and available N were high in areas with high elevation and high OM content. No effect was found on total P. Available P was high in the wet season and in areas with high reducing conditions and high OM content.

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CHAPTER 6

EFFECT OF HYDROLOGY ON SEDIMENTATION IN CAN GIO MANGROVE BIOSPHERE RESERVE

6.1 Introduction

Mangrove forests prosper on tropical shorelines. They are present extensively in intertidal zones where there is an abundance of fine-grain sediment and the potential for sediment accumulation (Chapman 1976). Sedimentation influences mangrove ecosystems by promoting mangrove expansion along coastlines and by influencing zonation and succession. The establishment of mangrove vegetation and species distribution are directly influenced by physical changes resulting from sedimentation (Woodroffe 1992, Woodroffe 2002).

The zonation and succession of mangrove species reflect the ecological and physiological responses of the plants to the environment, which includes the sedimentary environment resulting from sediment deposition. The colonization of mangrove species in the lowest intertidal zone is a result of sedimentation having occurred to a degree that provides an intertidal environment suitable for the establishment and growth of mangroves. Once enough sediment accretes, mangrove species are able to colonize (Smith III 1992). Lugo (1980) and McKee (1996), indicating that mangroves are typically steady-state cyclical systems. Sedimentation rate is a factor that affects the expansion of mangrove forests toward or regression away from the sea.

Fine sediments, and their associated nutrients, promote root system growth and the capacity of mangrove roots for sediment stabilization, helping mangroves to develop. In addition, the bed and bank of rivers and estuaries are generally formed of riverine sediment (Simons et al. 2000) that serves as a nutrient source for flora and fauna in mangrove systems, which in turn influence soil biogeochemistry. These muddy sediments have high concentrations of organic carbon and nitrogen (Boto and Wellington 1984, Alongi 1987),

which can support the growth of mangrove vegetation and aquatic species in the mangrove swamps. Alongi et al. (2005) suggested that the linkage between sediments and mangroves is an important process for the cycling of carbon and nutrients within the forest floor. Complex bacterial communities, resulting from sediment transport processes, support the decomposition progress of organic matter and inorganic particles (Alongi et al. 2005).

Sediment texture varies depending on mangrove morphology. For example, in riverine systems, where fringe forests are present, sediments are predominately composed of fine sand and covered by mud veneer. Thus, often the sediments in fringe forests are more oxidized and compacted than the sediments in other mangrove zones with finer deposits (Alongi et al. 1992). The plant root system can modify the chemical characteristics of the sediment through the release of gases (e.g., oxygen) and organic solutes to the soil and by the uptake of nutrients (Boto 1984, Alongi et al. 2005).

Sediment deposition in mangroves is termed allochthonous because the sediment originates from outside the mangrove ecosystem, (Woodroffe 1992). These sources of sediment originate from the erosion of agricultural soils within catchments (Alongi et al. 2005). Both physical and biological processes are important in controlling the rates of sediment (Mendelssohn and McKee 2000). The accumulation rates of sediment are rapid, especially in Asia (Twilley et all. 1992), but change depending on gradients of the intertidal zone. Sediment accumulates at a faster rate and in greater quantity in low intertidal zones and disperses as the intertidal zone gradient increases (Alongi et al. 2005). Sediment deposits are different between summer and winter (Redfield 1972, Allen 1990). The extreme variation in water temperature is a major factor contributing to the difference in seasonally deposited sediments (Allen 1990, Mohd-Lokman and Pethick 2001). Monsoonal rains can drastically alter the grain size of sediments (Alongi 1987). Other features of mangrove sediments in the tropical marine and estuarine environment include low concentration of dissolved nutrients

such as ammonium (Holmboe and Kristensen 2002), nitrate and phosphate, and presence of condensed tannins in intertidal water that derives from root leakages and litter on the forest floor (Alongi et al. 1992).

Sediment deposition in the mangrove ecosystems of Vietnam and specifically, in the Can Gio mangrove forests, has received little scientific attention. Thus, the objective of this research chapter was to determine differences in sediment deposition within the mangrove forest and to study the function of sediment in the Can Gio mangrove ecosystem.

6.2 Materials and Methods

Plastic petri dishes measuring 12 cm in diameter and 2 cm in height were used to trap sediment deposition. Holes with 1 mm diameters were drilled at the bottom of the petri dishes and covered by filter paper so that water could leak easily. Six petri dishes were installed on each zone for each transect. A total 18 petri dishes were installed on each transect. The procedure was repeated for the other transects on each site. The petri dishes were installed horizontally on the soil surface to keep them stable over time. The sediment samples were collected every week for four weeks in the dry season from March 12 to April 30 of 2005 and in the wet season from July 22 to Sept 10 of 2005. The sediment samples were dried in the oven at 105^{o}C until no change in weight was observed. The samples were then analyzed for their dry weight in grams per square meter per day.

A test was conducted to compare the rates of sediment deposition in the water columns at Dong Tranh River. Four observation points (P) were chosen for the collection of water samples: P1, P2, P3, and P4. P1 was located in the Dong Tranh River near zone 1 at the MO site. P2 occurred in the middle of the Dong Tranh River at the KV site. P3 was located in the mangrove creek, and P4 occurred near zone 1 at the MO site. Three individual samples of one liter of water each was collected at each point. Sediment in the water sample was filtered

and dried at 105^{o}C until no change in weight was observed. The dry weight of the sediment was calculated in grams per liter of water.

A factorial design was used to statistically analyze the main effects and their interactions on sediment deposition between KV and MO, between the dry and the wet seasons, and among zone 1, zone 2 and zone 3. JMP statistical software was used to analyze the soil data. Significant differences among means were determined by the Tukey – Kramer post – hoc test.

Table 6.1 Comparison of sediment concentration in the water column of four points at the Dong Tranh River in the Can Gio Mangrove Biosphere Reserve.

Observation points	Sediment (g/l)
P 1	0.26
P 2	0.31
P 3	0.30
P 4	1.02

*Note: P1 was a point near zone 1 at the MO site. P2 was a point in the middle of the river. P3 was a point in the mangrove creek near the KV site. P4 was a point near zone 1 of KV site.

6.3 Results and Discussions.

6.3.1 General Description

The sedimentation measurements were conducted at both the Khe Vinh (KV) and Mui O (MO) study sites. However, because of lower flooding frequency at MO (Figure 4.15), sediment accumulation was often zero at MO. The large number of samples with no sediment prevented statistical analysis of the data. Another reason why sediment accumulation was minimal at the MO site was the relatively low sediment concentrations in the water adjacent to MO. Table 6.1 presents the sediment concentration in the water bodies near the two study sites. P1 had the lowest sediment concentration compared to other points while P4 had the highest. Zone 1 of the KV site is situated near the river mouth where it is

strongly affected by the wave energy from the sea. As a result, there is a substantial amount of sediment deposition in this area due to sediment being highly suspended in the water column. MO site is situated further inland where it received no sediment deposition and was not affected by the wave energy from the sea, thus sediment was not re-suspended in the water columns. Therefore, because of low flooding frequency and the low sediment concentration, the sedimentation rate at the MO site could not be determined. Only the sedimentation rate at the KV site was statistically analyzed.

6.3.2 Sediment Deposition (KV Site Only)

The sediment deposition rate was affected by the main effect of zone. The main effect of season and the two-way interaction of season x zone had marginally significant effects on sedimentation rate (Table 6.2).

The sediment deposition rate was significantly greater in zone 1 compared to zones 2 and 3 (Figure 6.1). In addition, sedimentation rate tended to be greater in the wet season than in the dry season, but only in zone 1 (Figure 6.2), and the interactive effect of season and zone had no effect on sedimentation rate.

Table 6.2 ANOVA table of sediment deposition rates at the KV site in the Can Gio Mangrove Biosphere Reserve, (*) indicates statistical significance at alpha = 0.05.

Source	DF	F-ratio	Prob >F
Season (Se)	1	3.4952	0.0861
Zone (Zo)	2	70.3647	< 0.0001*
Se x Zo	2	2.8410	0.0977

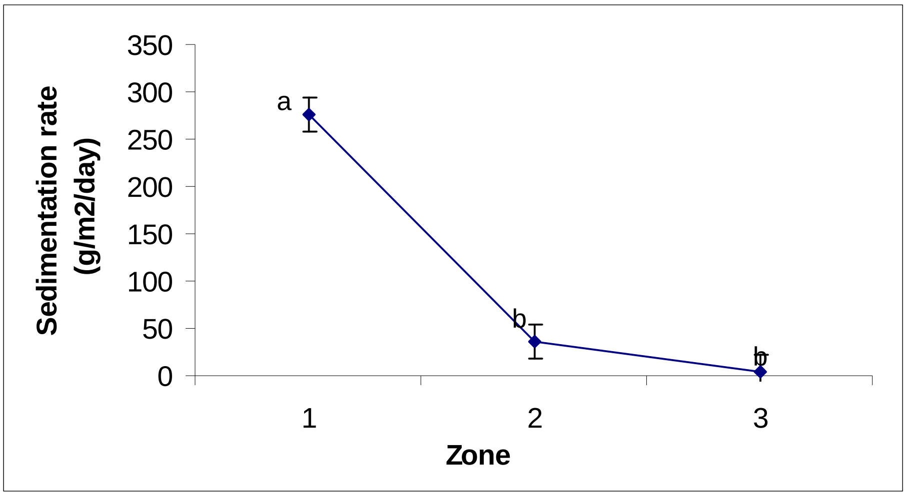

Figure 6.1 Comparison of sedimentation rate (mean ± SE) among zones at the KV site in the Can Gio Mangrove Biosphere Reserve. Means with different letter are significantly different at P <0.05.

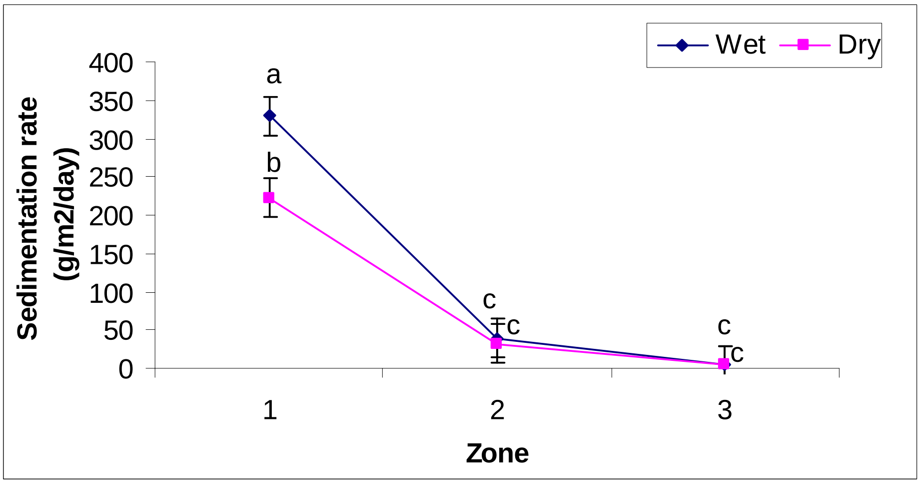

Figure 6.2 Comparison of sedimentation rate (mean ± SE) as a function of season and zone at the KV site in the Can Gio Mangrove Biosphere Reserve. Means with different letter are significantly different at P <0.05.

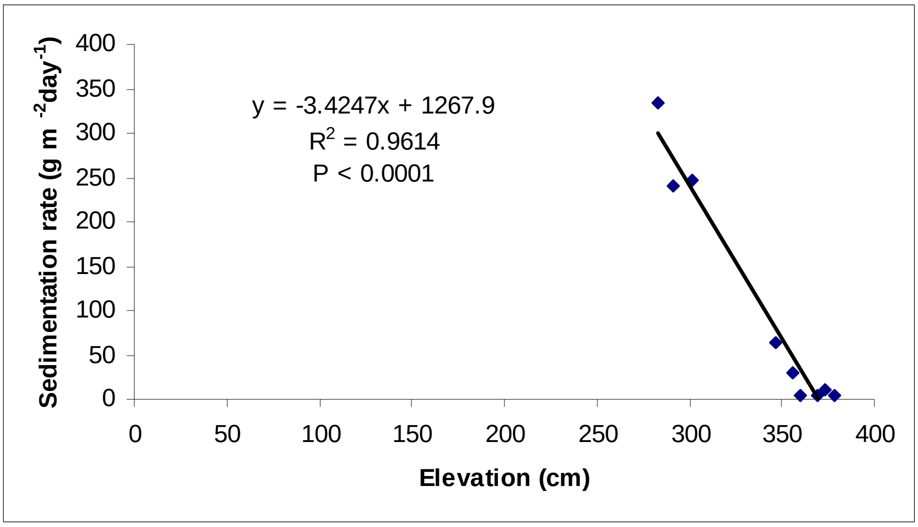

Figure 6.3 The relationship between sediment deposition rate and elevation across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

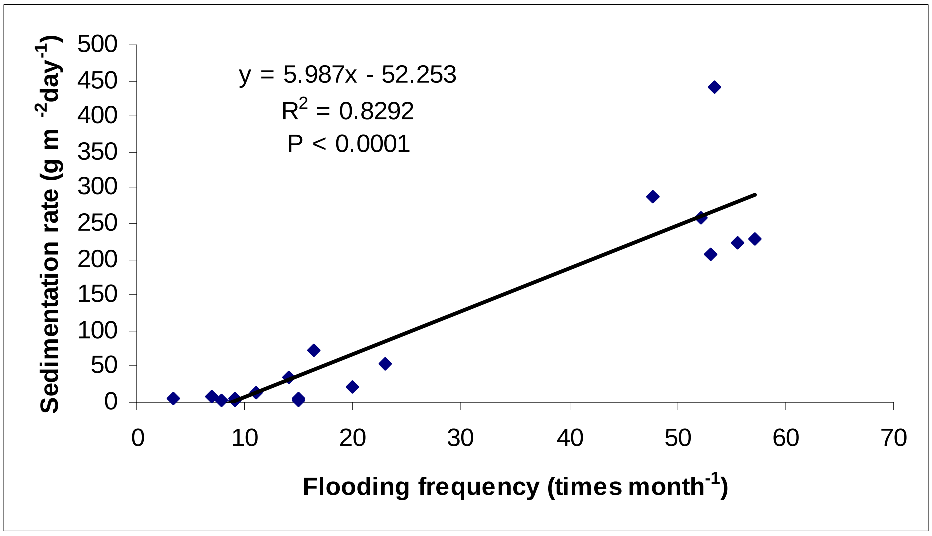

Figure 6.4 The relationship between sedimentation rate and flooding frequency during the dry and the wet seasons across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

The sediment deposition rate was found to have strong relationship with elevation and flooding frequency. In which sediment rate was negative correlation with elevation ($r = -0.8920$, $P < 0.0001$) (Figure 6.3) and positive correlation with flooding frequency ($r = 0.9106$, $p < 0.0001$) (Figure 6.4). Zones with low elevation and high flooding frequency (Zone 1) had high sediment rate than zone higher elevation and lower flooding frequency (zone 2 and 3).

6.3.3 Discussion

Mangrove forests are best developed along shorelines where there is an abundant supply of fine sediment and extensive intertidal zones, where conditions are favorable to mangrove colonization and expansion (Walsh 1974). The soil texture of the Can Gio mangrove forest is composed predominantly of silt and clay with a large quantity of fine and fibrous root matter. These characteristics are the result of sedimentation and hydrologic processes. At KV and MO, the study sites located within the Can Gio mangrove forest, soil texture was also composed mainly of clay and silt (Table 5.1). Boto and Wellington (1984) is also noted the dominance of clay and silt at their study.

The sedimentation rate at the Khe Vinh site was affected by the hydrologic regime of the Saigon and Dong Nai Rivers. The flow of water from the Saigon and Dong Nai Rivers carries with it sediment that empties out via the Dong Tranh estuary (Tuan et al. 2002). Because KV study site is situated near the mouth of the Dong Tranh estuary, it receives the majority of the sediment (Simons et al. 2000) deposited by the alluvium from the Saigon and Dong Nai Rivers. .

Sediment deposition rates at the KV and MO sites varied considerably due to the effects of the tidal regime. The amount of alluvium in the water column decreased from the KV site to the MO site because of their location (Table 6.1). Because zone 1 at the KV site is located nearly the river mouth, sediment was re-suspended by the wave action from the China Sea. The wave action brought the sediment back into the KV site during high tides. Because

of the low elevation (Figure 4.10), KV also flooded more frequently (Figure 4.16) and was able to retain more sediment during each flooding event. Unlike the KV site, the MO site was located away from the river mouth and was at a higher in elevation. Therefore, MO received no sedimentation from either wave action or the frequent flooding that occurred at the KV site.

The sediment rate at the KV site was found to have a high negative correlation with elevation (Figure 6.3) and a high positive correlation with flooding frequency (Figure 6.4). This may be explained by the results of Alongi et al. (2005), who found that the sediment deposition rate increases as elevation decreases. In this study, zone 1 of the KV site had a combination of low elevation and high flooding frequency, which allowed for high sedimentation.

Sedimentation rate is different between seasons due to extreme environmental differences (Redfield 1972 and Allen 1990). The high variation in water temperature between seasons is a main reason for the differences in the characteristics of seasonally deposited sediment (Allen 1990, Mohd-Lokman and Pethick 2001, Redfield 1972). However, in this study, not much difference was found in the water temperature between the dry and the wet seasons. Thus the sediment deposition rate at the KV site was not different between the dry and the wet season (Figure 6.1), except in zone 1, where differences were marginally significant.

6.4 Conclusions

Sedimentation at the KV and MO sites was affected by the tidal regimes of the China Sea and the Dong Tranh River. No sufficient sediment was available at the MO site for data collection because of its low flooding frequency and high elevation. At the KV site, the sediment was mainly composed of silt and clay and a low percentage of sand. The sediment rate at the KV site was significantly greater in zone 1 than zones 2 and 3, which did not

differ. Season had a marginally significant effect (Table 6.2) on sedimentation, but only in zone 1. Zone 1 of the KV site received the highest sedimentation because of its low elevation and high flooding frequency. Overall, low elevation and high flooding frequency allowed for greater sediment deposition.

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CHAPTER 7

EFFECT OF HYDROLOGY ON LITTER DECOMPOSITION IN CAN GIO MANGROVE BIOSPHERE RESERVE

7.1 Introduction

Mangrove forests are recognized as highly productive ecosystems that contain a vast amount of organic matter (OM). Organic matter in mangrove ecosystems is exported to adjacent areas and supports a variety of organisms (Odum and Heald 1975, Lee 1989, Nga 2004). The quantity and quality of the OM affect marine food webs (Alongi et al. 1989, Alongi 1990, Nga 2004). Mackey and Smail (1996) suggested that the decomposition of mangrove litter composed of leaves, stems and roots plays an important role as a source of food and energy for organisms in the mangrove system. Litter decomposition can also improve sediment quality and support food webs in estuarine and coastal regions by providing additional nutrients (Benner et al. 1986, Tam et al. 1990). Mangrove forests not only contribute organic matter via decomposition of litter fall (Day et al. 1987), but they also serve as a nursery and habitat for commercially important fish and shellfish (Tomlinson 1986).

However, the decomposition of mangrove litter can have detrimental effects on the mangrove ecosystem by the release of toxic substances and the consumption of oxygen during the decomposition process (Roijacker and Nga 2002, Nga 2004). Toxin generation and oxygen consumption can cause biological stresses and lower productivity in the mangrove system (Nga 2004).

Robertson et al. (1992) indicated that the decomposition process is comprised of three stages: (1) the fragmentation stage that consists of the breakdown of materials by various biotic and abiotic factors; (2) the leaching stage that occurs when soluble materials leach from the litter; and (3) the decay stage, when microbial organisms degrade the organic matter via their metabolic activities. The rate of decomposition is dependent on various abiotic and

biotic factors such as degree and frequency of water inundation, temperature, available oxygen, species type, and presence or absence of litter consuming fauna in the ecosystem (Benner and Hodson 1985, Twilley et al. 1986, Robertson 1989, Mackey and Smail 1996, Nga 2004). The presence and abundance of crabs and other invertebrates in mangrove wetlands are mentioned by Robertson and Daniel (1989), Camilleri (1992), Twilley et al. (1997), and Mitsch and Gosselink (2000) as having an important role in the litter decomposition process due to their ability to shred litter into smaller particles and their litter consumption.

Organic matter in wetland soils is formed by the remains of leaf litter and root production in various stages of decomposition (Mitsch and Gosselink 2000). The origin of the organic materials and the degree of decomposition are two important characteristics of organic soils in wetland. Recent studies showed that leaves of different mangrove species have different decomposition rates. Depending on the extent of decomposition or water saturation of wetland soils, plant organic matter is changed physically and chemically until the resulting organic materials are the same as the parent materials (Mitsch and Gosselink 2000).

Environmental conditions may also be important in controlling belowground decomposition. The tidal gradient is an environmental factor within the mangrove ecosystem that may be as, or even more important than the nutrient, structural and chemical quality of litter in controlling the decomposition rate. Decomposition rates vary depending on water depth and tidal elevation. Salinity is an important environmental factor affecting not only total litter fall (Day et al. 1982) but also the decomposition process (Roijackers and Nga 2002).

Litter decomposition in the Can Gio mangrove forest as well as in other mangrove forests in Vietnam are not well studied. The purpose of this research was to determine the

effect of the hydrologic regime and various other environment factors on litter decomposition in the Can Gio Biosphere Reserve.

7.2 Materials and Methods

Decomposition bags, 20 cm by 20 cm, were constructed from mosquito netting (Figure 7.1) and used to store root and leaf samples for the decomposition study. About 20 to 30 grams of yellow to brown matured leaves that fell onto the soil surface were collected for the determination of decomposition rate. Also, about 30 to 40 grams of roots were harvested from underground and cut into about 5-cm pieces. The samples were segregated according to their place of origin, as each species was unique and native to each zone (zone 1, zone 2 and zone 3).

The decomposition of leaves and roots were studied for their decomposition characteristics over a period of eight months from January 2005 to August 2005. Also, differences in decomposition rate between dry and the wet seasons were evaluated during a two-month time period. To assess the effect of zone on decomposition, 20 leaf sample bags and 20 root sample bags of species native to each zone were installed back into the same zone on each transect. Ten of the leaf samples were placed on the topsoil and ten were buried in the subsoil at a 25 to 30 cm depth. Ten of the root samples were placed on the topsoil and ten were installed into the subsoil at a 25 to 30 cm deep. This procedure was repeated for the three zones on each transect and replicated on three transects at the KV site and MO site. The leaf and root samples remained on the topsoil and in the subsoil for a period of eight months. Every two months, two samples per zone on each transect were retrieved for the determinations of the percent of the initial material remaining after the decomposition period and for the decomposition rate (K as discussed below).

The decomposition rates of roots and leaves between the dry and the wet season were also studied. Twelve leaf sample bags and 12 root sample bags of each species native to each

zone were installed back into the same zone. Six of the leaf samples were placed on the topsoil and the remaining six were installed in the subsoil at a 25 to 30 cm depth. Six of the root samples were placed on the topsoil and the remaining six were buried in the subsoil at a 25 to 30 cm depth. The procedures were repeated for each zone in each transect. The samples were allowed to decompose undisturbed for two months in each season.

For the eight month decomposition rate study, the leaf and root tissues were collected and the percentage of tissues that remained in the litter bags after two months as well as the decomposition rate were calculated. This procedure was repeated every two months for eight months. The percentage of tissues remaining and the decomposition rates were also examined for seasonal effects.

The leaf and root tissues remaining in the litter bags were collected by gently washing with water in a metal net basket in order to remove soils and other materials that had attached onto the leaves or roots during the decomposition process. After washing, the samples were dried in an oven at 65°C until they reached a stable weight. The decomposition rates and the percentage of tissue mass remaining were calculated using the formula $X_{(\%)} = X_o * e^{-KT}$ where $X_{(\%)}$ is the percentage of tissue remaining, X_o is percent remaining before decomposition (100 %), K is the instantaneous decay rate, and T is the time in days. Statistical analysis was carried out using JMP statistical software and significant differences among means were determined using the Tukey-Kramer post-hoc test. Differences in decomposition rate were compared between the dry and the wet season and between the topsoil and the subsoil. The effect of site and zone on decomposition rate was also compared but these comparisons were only possible through the grouping of similar species native to each zone. Not all species occurred in the same zone. For example, *Avicennia alba* was native only to zone 1 and zone 2 of the KV site. Therefore, decomposition rates were

compared between zone 1 and zone 2 of the KV site. Table 7.1 shows a complete listing of species and their zones.

Table 7.1 Plant species and their location (zone) at the KV and MO study sites in the Can Gio Mangrove Bioshpere Reserve.

Species	**Native Zone**	**Site**	**Symbol**
Avicennia alba	Zone 1	Khe Vinh	Avi (KV1)
Avicennia alba	Zone 2	Khe Vinh	Avi (KV2)
Rhizophora apiculata	Zone 2	Khe Vinh	Rhi (KV2)
Rhizophora apiculata	Zone 3	Khe Vinh	Rhi (KV3)
Rhizophora apiculata	Zone 3	Mui O	Rhi (MO3)
Ceriops decandra	Zone 2	Khe Vinh	Ceriops (KV2)
Ceriops decandra	Zone 2	Mui O	Ceriops (MO2)
Phoenix paludosa	Zone 1	Mui O	Phoe (MO1)

Figure 7.1 Decomposition bags containing leaf and root samples

7.3 Results and Discussion

7.3.1 Two Months Decomposition During Dry and Wet Season

7.3.1.1 Leaf Decomposition

Leaf decomposition was quantified by the amount of leaf tissue remaining. The amount of leaf tissue remaining after two months of incubation during the dry and the wet seasons were affected by the main effect of depth and highly affected by the main effect of zone. The main effect of season and both the two-way and the three-way interactions had no effect on the amount of leaf tissue remaining (Table 7.2).

Differences in the amount of leaf tissue remaining were dependent on the type of species and their location. *Ceriops decandra* in zone 2 [Ceriops (MO2)] and *Phoenix paludosa* in zone 1 [Phoe (MO1)] at the MO site had significantly higher amounts leaf tissue remaining compared to all of the other species (Figure 7.2). *Avicennia alba* in both zone 1 [Avi (KV1)] and zone 2 [Avi (KV2)] of the KV site had significantly lower amounts of leaf tissue remaining compared to all of the other species (Figure 7.2). No difference in the percentage of leaf tissue remaining was found among the remaining species (Figure 7.2).

The percentage of leaf tissue remaining significantly decreased from the topsoil to the subsoil (Figure 7.3).

The percentage of leaf tissue remaining and the leaf decomposition rates were not different between the dry and the wet seasons. This can be explained by the high flooding frequency that occurred similarly in both the dry and wet seasons at the study sites. The fragmentation stage (caused by abiotic factors) of the decomposition process (Robertson et al. 1992) did not change between the dry and the wet seasons because the soil was always moist from frequent flooding. Leaf decomposition was different for species depending on the zones that they were located in and on their tissue structure. Leaf decomposition was different between the topsoil and the subsoil due to differences in soil moisture (Nga 2004). Leaf

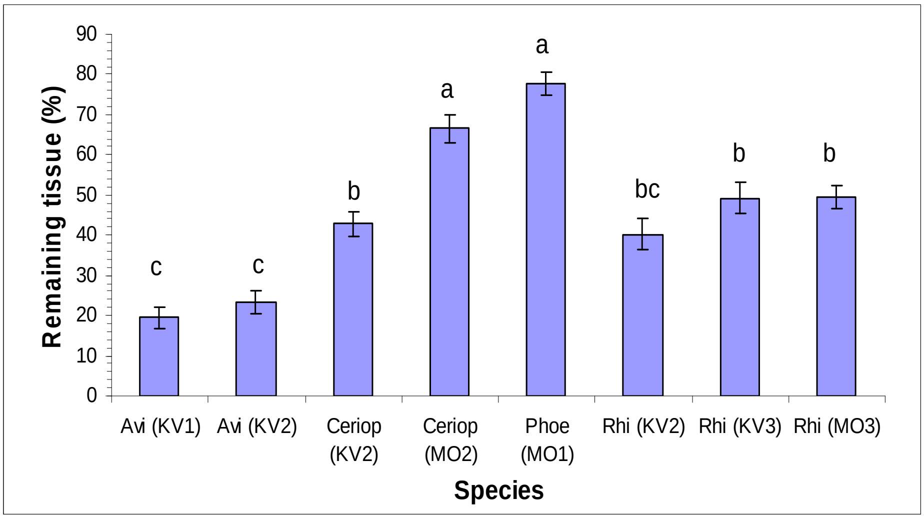

Figure 7.2 Comparison of the percentage of leaf tissue remaining (mean ± SE) among species after two months of incubation in the dry and the wet season at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant differences at P ≤ 0.05.

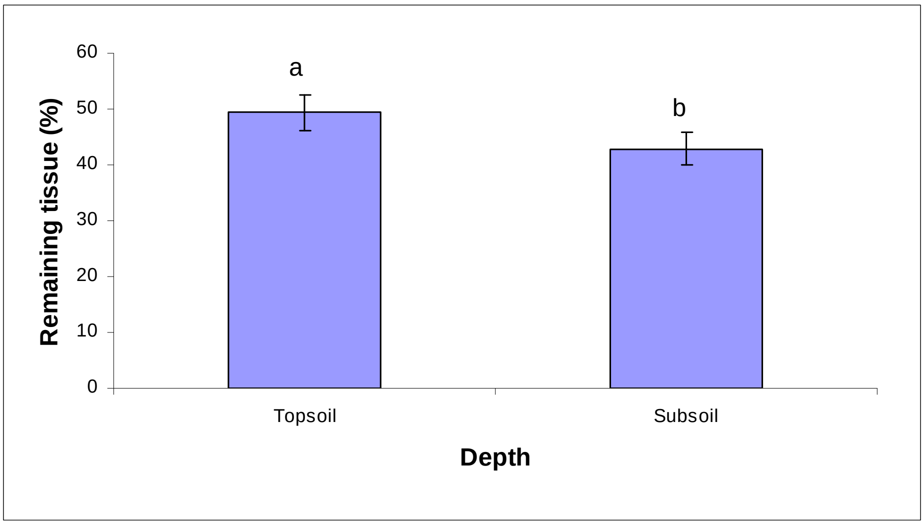

Figure 7.3 Comparisons for percentage of leaf tissue remaining (mean ± SE) between the top and the sub soil after two months of incubation in the dry and the wet season at study sites in Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant differences at P ≤ 0.05.

tissue in the subsoil was exposed to higher soil moisture during the fragmentation stage. This situation provided a better growth condition for the belowground microbial community, hence maximizing the mineralization process.

In this study, low amount of leaf tissue remaining were found in species that had thin leaves and soft tissues. These species, such as *Avicennia alba* in zone 1 [Avi (KV1)] and in zone 2 [Avi (KV2)], occurred at the KV site. In contrast, species that had thick leaves and hard tissues had higher percentages of leaf tissue remaining. These species occurred in zone 2 at the MO site [Ceriops (MO2)] and in zone 1 at the MO site [Phoe (MO1)].

The effects of zone on leaf decomposition could not be clearly determined (Figure 7.2 and 7.3). This was because the percentage of leaf tissue remaining of *Ceriops decandra* in zone 2 of the KV site was less than the percentage of leaf tissue remaining in zone 2 of the MO site, which was due to the greater flooding frequency in zone 2 at the KV site. However, no difference was found in the percentage of leaf tissue remaining for *Avicennia alba* between zones 1 and 2 of the KV site even though zone 1 of the KV site had a higher flooding frequency than zone 2 of the KV site. No difference was found in the leaf tissue remaining of *Rhizophora apiculata* in zone 2 of the KV site, zone 3 of the KV site, and zone 3 of the MO site. This may be due to the similarly in original species (*Rhizophora apiculata*) among the three zones and the difference in soil moisture among zones 2 and 3 at the KV site and zone 3 at the MO site (Table 5.3).

7.3.1.2 Root Decomposition

The amount of root tissue remaining after two months of incubation in the dry and the wet season was highly affected by the main effects of zone and season, but was minimally affected by depth (Table 7.2). The three-way interaction of species x season x depth also had a significant effect on the percentage of root tissue remaining (Table 7.2).

The percentage of root tissue remaining was dependent on the interactive effect of zone, season and depth. During the dry season, and in the topsoil, no difference in the percentage of root tissue remaining among species within their native zones was found except for the species *Avicennia alba* in zone 1 at the KV site [Avi (KV1)], which had a significantly lower percentage of root tissue remaining than all of the others (Table 7.3). Similar to the topsoil, there was no difference in the subsoil of the percentage of root tissue remaining, except for *Ceriops decandra* in zone 2 at the MO site [Ceriops (MO2)] and *Rhizophora apiculata* in zone 3 at the MO site [Rhi (MO3)], which were significantly greater than that of *Avicennia alba* in zone 1 at the KV site [Avi (KV1)] (Table 7.3). No difference in the percentage of root tissue remaining was found between the topsoil and the subsoil for each species (Table 7.3). During the wet season, in both the topsoil and the subsoil, the percentage of root tissue remaining of *Avicennia alba* in both zone 1 [Avi (KV1)] and zone 2 [Avi (KV2)] of the KV site was significantly lower than that of all the other species (Table 7.3). Similar to the dry season, no difference in the percentage of root tissue remaining was found between the topsoil and the subsoil for each species (Table 7.3). The percentage of root tissue remaining was significantly lower in the wet season than in the dry season in both the topsoil and the subsoil, but only for *Avicennia alba* in zone 2 at the KV site [Avi (KV2)] (Table 7.3).

The percentage of root tissue remaining was significantly greater in the wet season than the dry season, but only for *Avicenia alba* in zone 2 at the KV site [Avi (KV2)] (Table 7.3).

The interactive effect of zone, season and depth on the decomposition rate again demonstrated that the particular species and their location had effects on the decomposition process. Steike and Charles (1986), Roijackers and Nga (2002), and Nga (2004) found that mangrove zones with high elevation and low flooding frequency (often with high salinity) contributed to relatively low decomposition rates in these zones. Mitsch and Gosselink

(2000) also suggested that decomposition rate depends on the chemical composition and structure of the plant material, which is changed physically and chemically until the resulting litter resembles the parent material. In this study, we found that most species, especially those with soft root tissues located in the subsoil in low elevation zones during the wet season, had a high root decomposition rate and low percentage of tissue remaining. For example, *Avicennia alba,* a species with soft root tissues located in the subsoil of zone 1 and zone 2 (low elevation zones) in the wet season, fit this pattern of high decomposition.

In contrast, species in high elevation zones and with hard root tissues had a high percentage of root tissue remaining for a given period of time. For example, *Ceriops decandra* in zone 2 of the MO site and *Phoenix paludosa* in zone 1 of the MO site had a high percentage of remaining tissue. Both of these species have thick and hard root tissues. Also, these species occur in high elevation zones with low flooding frequencies. All of these characteristics contributed to the high percentage of remaining root tissues as discussed by Roijackers and Nga (2002), and Nga (2004).

I also found that the decomposition rate of mangrove litter after two months, during the dry and wet seasons, was significantly correlated with certain environmental factors. However, these relationships were not statistically significant for all species. The percentage of leaf tissue remaining of *Avicennia alba* in the topsoil during the dry season was negatively correlated with elevation ($r = -0.8658$, $P = 0.0258$) (Figure 7.4) and positively correlated with flooding frequency ($r = 0.8396$, $P = 0.0365$) (Figure 7.5), and the percentage of tissue remaining of *Rhizophora apiculata* in the subsoil during the wet season had a positive correlation with soil drainage ($r = 0.7379$, $P = 0.0232$) (Figure 7.6).

When decomposition was compared among the different native zones for both *Avicennia alba* and *Rhizophora apiculata*, the relationship between decomposition and various environment factors differed depending on the species and the depth at which

decomposition occurred. In the topsoil, the leaf tissue remaining of *Avicennia alba* had a negative correlation with elevation (Figure 7.4) and a positive correlation with flooding frequency (Figure 7.5). Therefore, areas with higher elevations, lower flooding frequencies (KV-Zone 2) and higher oxygen content in the topsoil are more favorable for the decomposition of *Avicennia alba* than areas with low elevation, high flooding frequency (KV-Zone 1) and low oxygen content in the topsoil. In contrast, the decomposition of the root tissue of *Rhizophora apiculata* did not show a significant relationship with the above environmental factors, but in the subsoil was positively correlated with soil drainage. Zones with low soil drainage (KV-zone 2) had low percentage of root tissue remaining in the subsoil and zones with high soil drainage (MO-Zone 3) had a higher percentage of root tissue remaining in the subsoil. Thus, *Rhizophora apiculata* appears to decompose somewhat faster when the soil stays moist because soil drainage is minimal.

Table 7.2 F values and probability levels from analysis of variance of zone, season, depth, and their interactions for the percentage of remaining leaf tissue and the percentage of remaining root tissue, during a two month incubation period in the dry and the wet seasons at the study sites in the Can Gio Mangrove Biosphere Reserve. (*) indicates statistical significance at alpha = 0.05.

		Leaf tissue remaining		Root tissue remaining	
Source	DF	F-ratio	Prob > F	F-ratio	Prob > F
Zone (Zo)	7	37.1833	<0.0001*	46.6201	<0.0001*
Season (Se)	1	0.2422	0.6243	41.8688	<0.0001*
Zo x Se	7	1.0188	0.4268	9.6675	<0.0001*
Depth (De)	1	7.8822	0.0066*	4.8342	0.0315*
Sp x De	7	0.8494	0.5510	2.0743	0.0591
S x De	1	0.0746	0.7857	0.1562	0.6940
Zo x Se x De	7	1.2380	0.4234	2.7970	0.0133*

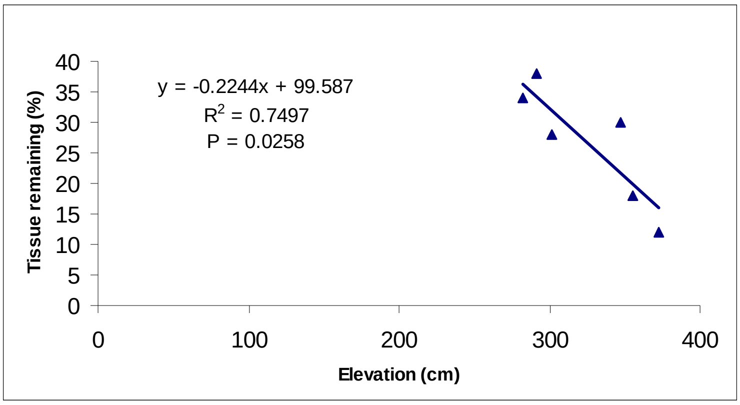

Figure 7.4 The relationship between the percentage of leaf tissue remaining of *Avicennia alba* and elevation after two months during the dry season for samples collected from the topsoil at the study sites in the Can Gio Mangrove Biosphere Reserve.

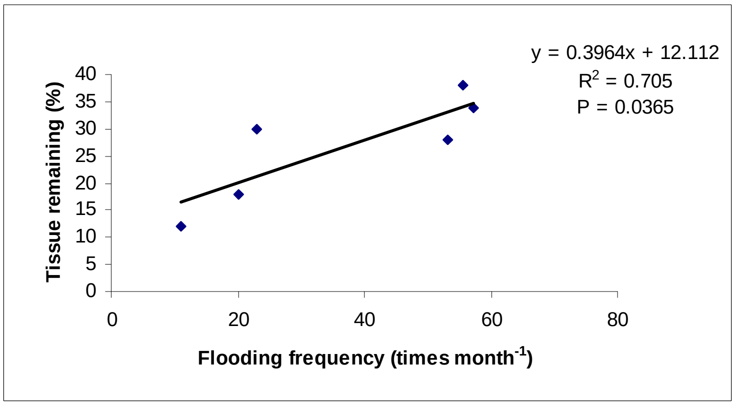

Figure 7.5 The relationship between the percentage of leaf tissue remaining of *Avicennia alba* and flooding frequency after two months during the dry season for samples collected from the topsoil at the study sites in the Can Gio Mangrove Biosphere Reserve.

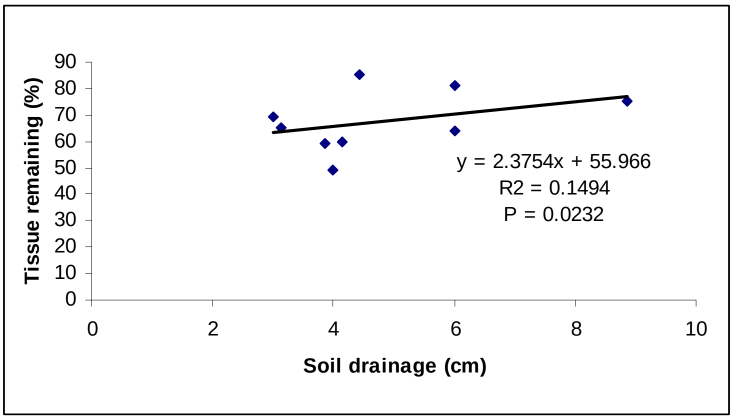

Figure 7.6 The relationship between the percentage of root tissue remaining of *Rhizophora apiculata* and soil drainage after two months during the wet season for samples collected from the subsoil at the study sites in the Can Gio Mangrove Biosphere Reserve.

Table 7.3 Means (± SE) of the percentage of root tissue for the interaction of zone x season x depth after two months of incubation during the dry and the wet seasons at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant differences at $P \leq 0.05$.

Season	Depth	Zone	Percentage Tissue Remaining
Dry	Topsoil	Avi (KV1)	30.98 ± 8.72 e
		Avi (KV2)	63.65 ± 4.71 a-d
		Ceriops (KV2)	68.31 ± 0.33 a-d
		Ceriops (MO2)	87.99 ± 2.08 a
		Phoe (MO1)	87.99 ± 2.31 a
		Rhi (KV2)	72.99 ± 3.79 a-d
		Rhi (KV3)	82.66 ± 3.38 abc
		Rhi (MO3)	84.99 ± 1.53 abc
	Subsoil	Avi (KV1)	48.98 ± 6.66 de
		Avi (KV2)	67.32 ± 7.31 a-d
		Ceriops (KV2)	72.99 ± 6.42 a-d
		Ceriops (MO2)	83.99 ± 2.52 abc
		Phoe (MO1)	66.32 ± 4.91 a-d
		Rhi (KV2)	63.65 ± 9.70 a-d
		Rhi (KV3)	65.32 ± 3.39 a-d
		Rhi (MO3)	86.66 ± 2.02 ab
Wet	Topsoil	Avi (KV1)	29.31 ± 2.03 e
		Avi (KV2)	30.98 ± 0.58 e
		Ceriops (KV2)	63.32 ± 4.37 a-d
		Ceriops (MO2)	68.65 ± 2.43 a-d
		Phoe (MO1)	82.32 ± 0.88 abc
		Rhi (KV2)	78.32 ± 6.33 abc
		Rhi (KV3)	72.32 ± 5.49 a-d
		Rhi (MO3)	72.32 ± 9.82 a-d
	Subsoil	Avi (KV1)	27.98 ± 4.04 e
		Avi (KV2)	25.65 ± 1.76 e
		Ceriops (KV2)	58.98 ± 5.13 cd
		Ceriops (MO2)	67.65 ± 4.91 a-d
		Phoe (MO1)	79.99 ± 4.36 abc
		Rhi (KV2)	61.31 ± 1.86 a-d
		Rhi (KV3)	80.32 ± 2.91 abc
		Rhi (MO3)	60.65 ± 6.01 bcd

7.3.2 Eight Months Decomposition for Zone and Depth Effects

7.3.2.1 Leaf Tissue Remaining and Leaf Decomposition Rate (K)

The percentage of leaf tissue remaining after eight months was affected by the main effect of zone whereas the main effect of depth and the two-way interaction of zone by depth had no effect on the amount of leaf tissue remaining (Table 7.4). Leaf decomposition rate (K) during the eight months of incubation was also significantly affected by the main effect of zone and the main effect of depth (Table 7.4). The two-way interaction of zone by depth had no effect on the leaf decomposition rate (Table 7.4).

Because all mangrove species did not occur in each zone, the effect of zone cannot always be separated from the effect of species. At the KV site, *Rhizophora apiculata* in zone 3 [Rhi (KV3)] had a significantly higher percentage of leaf tissue remaining than that of *Avicennia alba* in zone 1 [Avi (KV1)] and zone 2 [Avi (KV2)] (Figure 7.7). At the MO site, *Phoenix paludosa* in zone 1 [Phoe (MO1)] had the highest percentage of leaf tissue remaining when compared to *Ceriops decandra* in zone 2 [Ceriops (MO2)] and *Rhizophora apiculata* in zone 3 [Rhi (MO3)] (Figure 7.7). Overall, there is no different in the percentage of leaf tissue remaining between *Avicenia alba* in zone 1 [Avi (KV1)] and zone 2 [Avi (KV2)] at the KV site and between *Rhizophora apiculata* in zone 2 [Rhi (KV2)] and zone 3 [Rhi (KV3)] at the KV site (Figure 7.7). No significant difference in the percentage of leaf tissue remaining was found between *Rhizophora apiculata* in zone 3 at the KV site [Rhi (KV3)] and zone 3 at the MO site [Rhi (MO3)] (Figure 7.7). However, the percentage of leaf tissue remaining of *Ceriops decandra* in zone 2 at the KV site [Ceriops (KV2)] was found to be lower than in zone 2 at the MO site [Ceriops (MO2)] (Figure 7.7).

Leaf decomposition rate (k) also significantly differed as a function of the combined effects of zone and species. In zone 1 and zone 2 at the KV site, *Avicennia alba* [Avi (KV1)] and *Avicennia alba* [Avi (KV2)] were found to have the greatest leaf decomposition rate

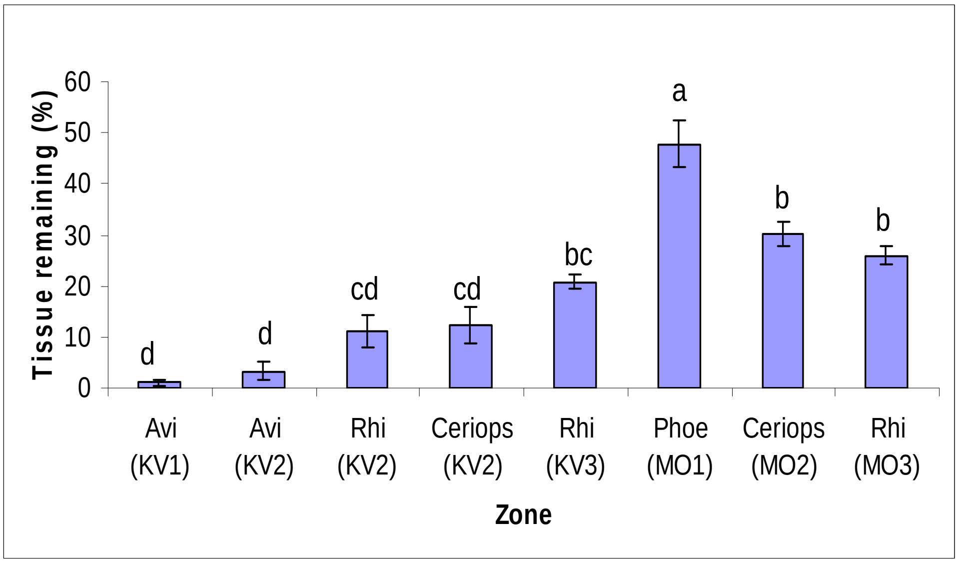

Figure 7.7: Comparison of the percentage of leaf tissue remaining (mean ± SE) among zones at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant differences at $P \leq 0.05$.

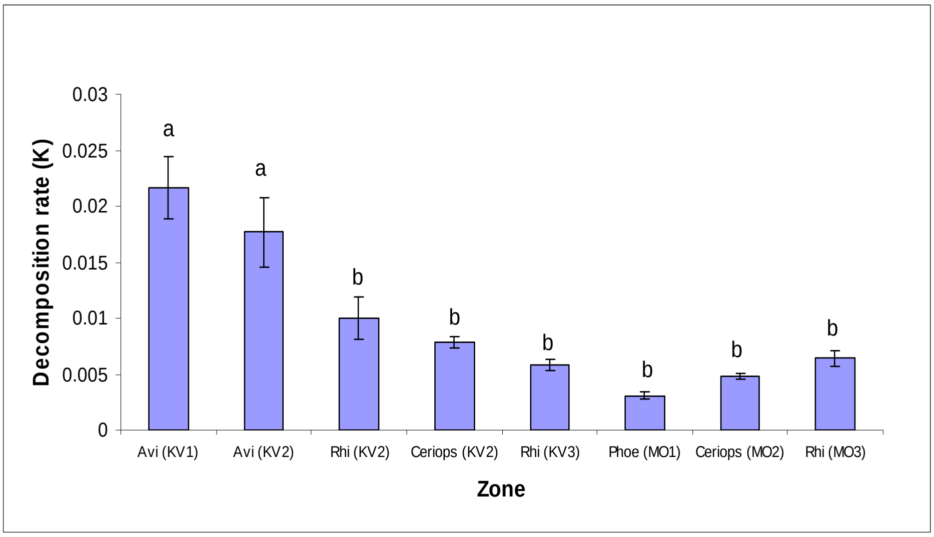

Figure 7.8: Comparison of the leaf decomposition rate (mean ± SE) among zones at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant differences at $P \leq 0.05$.

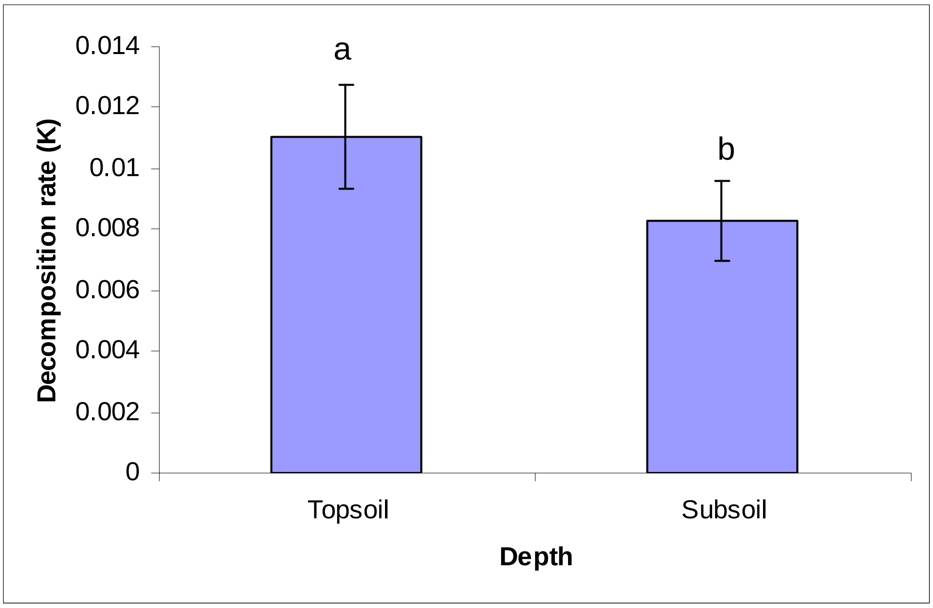

Figure 7.9: Comparison of leaf decomposition rates (mean ± SE) between the topsoil and the subsoil, averaged over all zones, at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant difference at $P \leq 0.05$.

when compared to other zones (Figure 7.8). The remaining zones did not differ in their leaf decomposition rates. No significant difference in the leaf decomposition rate was found in any of the zones at the MO site (Figure 7.8). In addition, leaf decomposition rate of the topsoil was significantly higher than leaf decomposition rate of the subsoil, when averaged over all zones (Figure 7.9).

7.3.2.2. Root Tissue Remaining and Root Decomposition Rate (k)

The percentage of root tissue remaining was affected by the main effect of zone and the two-way interaction of zone by depth (Table 7.4). The main effect of depth did not affect the percentage of root tissue remaining (Table 7.4).

At the KV site, *Avicennia alba* in zone 1 [Avi (KV1)] and zone 2 [Avi (KV2)] (Figure 7.10) and *Rhizophora apiculata* in zone 2 [Rhi (KV2)] did not differ in the percentage of root tissue remaining, but their percent remaining were significantly lower than that of *Rhizophora apiculata* in zone 3 [Rhi (KV3)] and *Ceriops decandra* in zone 2 [Ceriops (KV2)] (Figure 7.10). At the MO site, no difference in the percentage of root tissue remaining

was found among *Phoenix paludosa* in zone 1[Phoe (MO1)], *Ceriops decandra* in zone 2 [Ceriops (MO2)] and *Rhizophora apiculata* in zone 3 [Rhi (MO3)] (Figure 7.10).

The effect of depth on the percentage of root tissue remaining was dependent on zone. At the KV site, *Ceriops decandra* in zone 2 had a lower percentage of root tissue remaining on the topsoil than on the subsoil. There were no other significant differences in the amount of root tissue remaining between the topsoil and the subsoil for the remaining zones at the KV site (Figure 7.11). At the MO site, *Ceriops decandra* in zone 2 [Ceriops (MO2)] had the highest percentage of root tissue remaining on the topsoil compared to other zones, but was not different from *Phoenix paludosa* in zone 1 at the MO site [Phoe (MO1)] or *Rhizophora apiculata* in zone 3 at the KV site [Rhi (KV3)] (Figure 7.11). Among zones, *Avicenia alba* in zone 1 [Avi (KV1)] had a significantly lower percentage of root tissue remaining than *Ceriops decandra* in zone 2 [Ceriops (KV2)]. No difference was found in the percentage of root tissue remaining in the subsoil of *Avicenia alba* in zone 1 [Avi (KV1)] and zone 2 [Avi (KV2)] and *Rhizophora apiculata* in zone 2 [Rhi (KV2)] at the KV site. However, there was a lower percentage of root tissue remaining compared to other zones (Figure 7.11).

The root decomposition rate after eight months of incubation was highly affected by the main effect of zone (Table 7.6). Root decomposition rate was not significantly affected by the main effect of depth and the two-way interaction of zone by depth (Table 7.6).

As for the leaf decomposition, root decomposition rates differed as a function of the combined effects of zone and species. At the KV site, *Ceriops decandra* in zone 2 [Ceriops (KV2)] had the lowest root decomposition rate compared to other zones (Figure 7.12). At the MO site, root decomposition rate was not significantly different among species and zones (Figure 7.12). Overall, root decomposition rates of *Rhizophora apiculata* at the KV site in zone 2 [Rhi (KV2)] and zone 3 [Rhi (KV3)] were not significantly different from *Rhizophora apiculata* in zone 3 at the MO site [Rhi (MO3)] (Figure 7.12). The root decomposition rate of

Ceriops decandra in zone 2 at the KV site [Ceriops (KV2)] was not significantly different from zone 2 at the MO site [Ceriops (MO2)] (Figure 7.12).

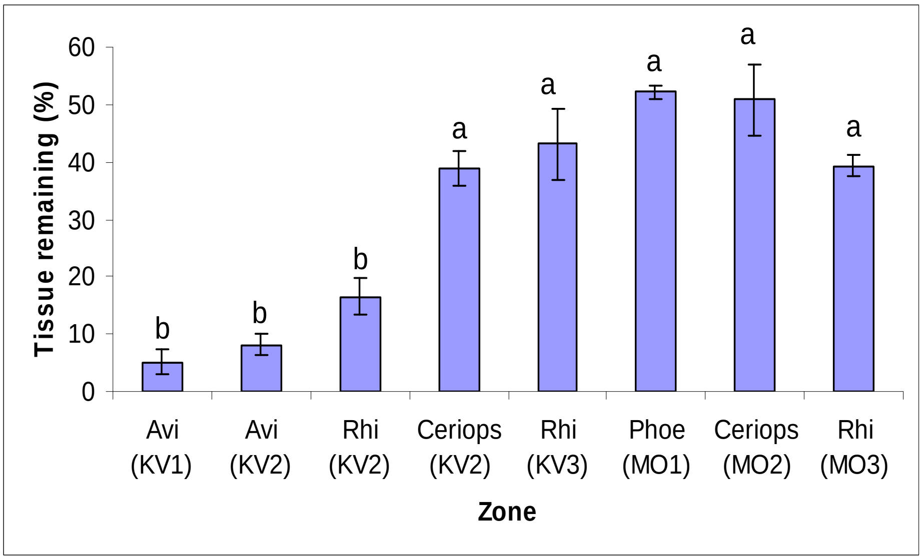

Figure 7.10: Comparison of the percentage of root tissue remaining (mean ± SE) among zones at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant differences at P ≤ 0.05.

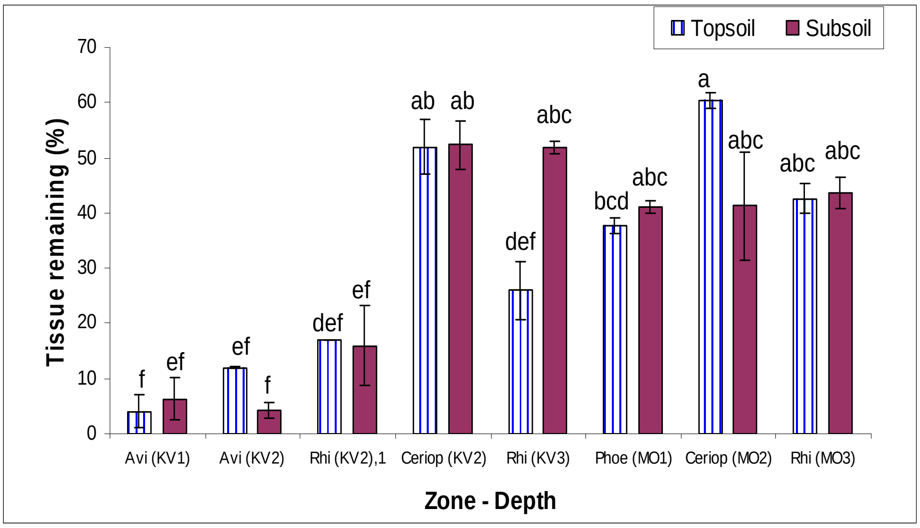

Figure 7.11: Comparison of the percentage of root tissue remaining (mean ± SE) by depth among zones at the study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant differences at P ≤ 0.05.

Table 7.4: F values and probability levels from the analysis of variance of zone and depth and their interaction on percentage tissue remaining and decomposition rate of leaf and root material during the eight month incubation period at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. (*) indicates statistical significance at alpha = 0.05.

		Leaf decomposition				Root decomposition			
		Tissue remaining		Decomposition rate		Tissue remaining		Decomposition rate	
Source	DF	F-ratio	Prob > F	F-ratio	Prob > F	F-ratio	Prob > F	F-ratio	Prob > F
Zone	7	35.0264	< 0.0001*	17.5253	< 0.0001*	43.2427	< 0.0001*	5.9282	0.0002*
Depth	1	0.4784	0.4941	6.0617	0.0194*	0.1074	0.7452	0.4928	0.4877
Zone x Depth	7	1.8394	0.1136	1.3795	0.2477	4.7760	0.0009*	0.1657	0.9903

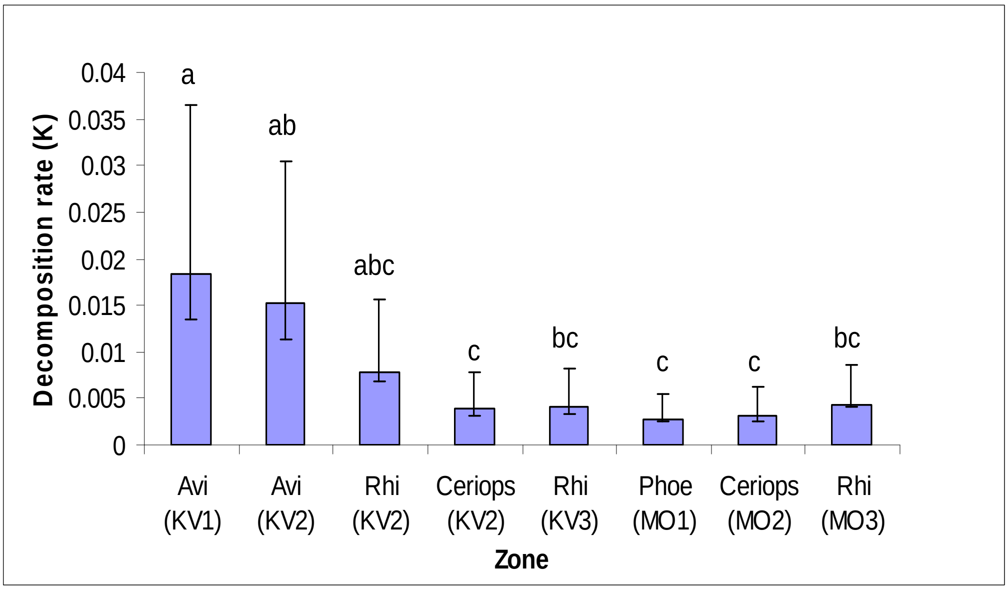

Figure 7.12: Comparison of the root decomposition rate (mean ± SE) among zones at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant difference at $P \leq 0.05$.

7.3.2.3. Relationship Between Environmental Factors and Eight Month Decomposition

I found that the decomposition of the plant tissue was statistically correlated with various environmental factors such as elevation, soil drainage, groundwater EC, and soil EC. However, these relationships were dependent on the particular index of decomposition, the type of tissue (leaf or root), the depth of incubation (topsoil and subsoil) as well as the mangrove species native to the particular zone.

Elevation had a negative correlation with leaf decomposition rate of *Avicennia alba* in zone 1 and zone 2 at the KV site ($r = -0.8303$, $P = 0.0405$) and a positive correlation with root tissue remaining ($r = 0.8586$, $P = 0.0402$) (Figure 7.13), all in the topsoil. In addition, there was a negative correlation between the amount of root tissue remaining of *Avicennia alba* in the topsoil and the flooding frequency ($r = - 0.8276$, $P = 0.0420$) (Figure 7.14).

For the topsoil, root decomposition of *Rhizophora apiculata* in zone 3 at the MO site as well as in zone 2 and zone 3 at the KV site was negatively correlated with soil drainage

(r = -0.6968, P = 0.0370) (Figure 7.15). For the subsoil, EC of groundwater was positively correlated with the leaf decomposition rate of *Rhizophora apiculata* (r = 0.8404, P = 0.0046), but it was negatively correlated with the leaf tissue remaining (r = -0.8276, P = 0.0059) (Figure 7.16).

The groundwater EC had a negative correlation with leaf tissue remaining of *Ceriops decandra* in both the topsoil (r = -0.9362, P = 0.0067) and the subsoil (r = -0.8500, P = 0.0320) (Figure 7.17) as well as with the root tissue remaining in the topsoil (r = -0.8893, P = 0.0177) (Figure 7.17). However, groundwater EC was positively correlated with leaf decomposition rate (r = 0.9120, P = 0.0113) (Figure 7.17). Soil EC had a negative correlation with the leaf decomposition rate of *Ceriops decandra* (r = -0.8381, P = 0.0372) and a positive correlation with the leaf tissue remaining (r = 0.8794, P = 0.0209) (Figure 7.18). In contrast, soil EC was positively correlated with the root decomposition rate of *Ceriops decandra* (r = 0.8568, P = 0.0293) and negatively correlated with the root tissue remaining (r = -0.8411, P = 0.0358) (Figure 7.19).

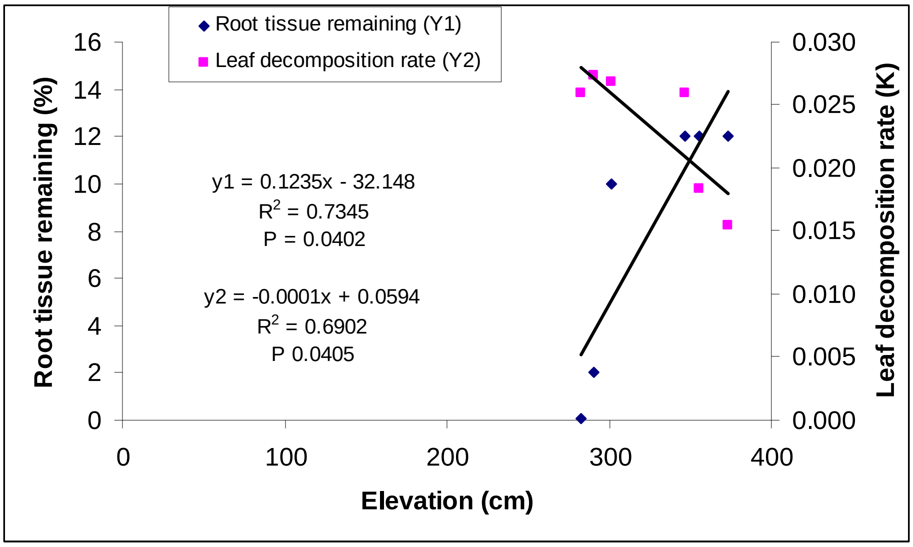

Figure 7.13: The relationship between elevation and root tissue remaining and leaf decomposition rate of *Avicennia alba* after eight months on the topsoil at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve.

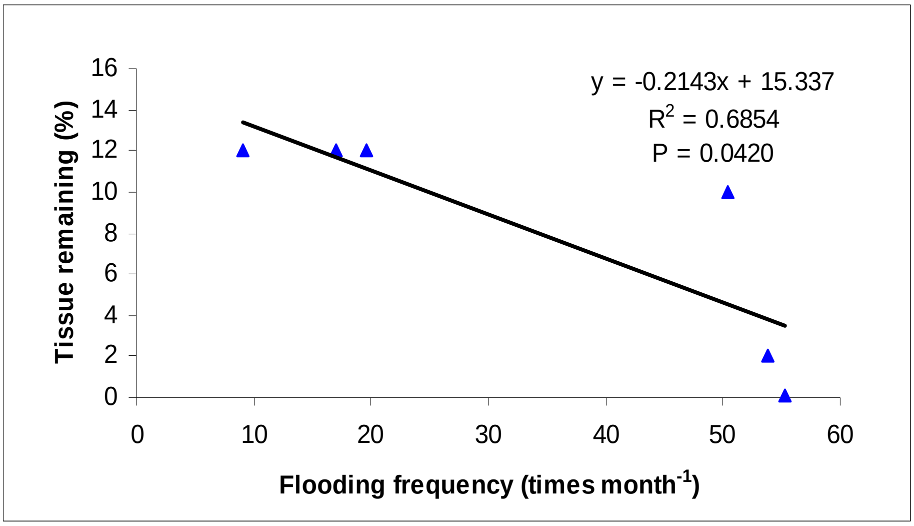

Figure 7.14: The relationship between flooding frequency and root tissue remaining of *Avicennia alba* after eight months on the topsoil at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve.

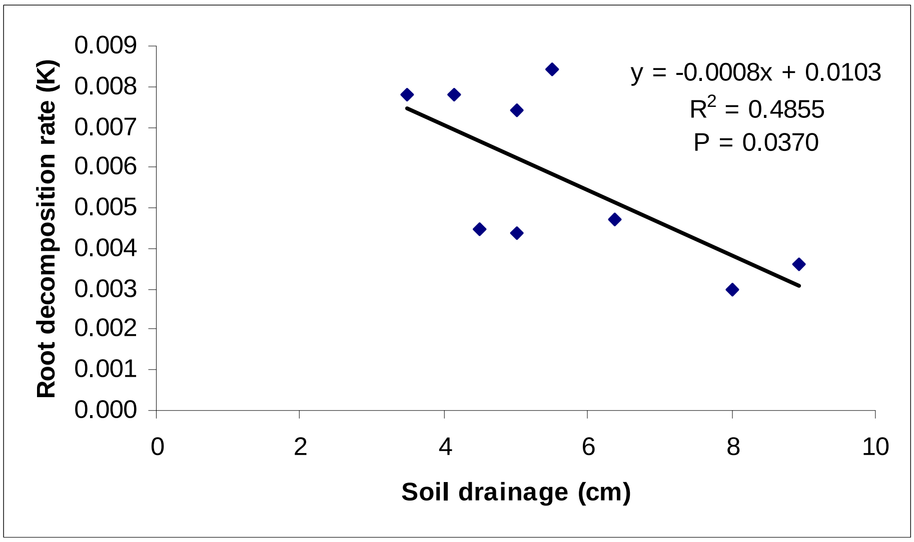

Figure 7.15: The relationship between soil drainage and root decomposition rate of *Rhizophora apiculata* after eight months on the topsoil at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve.

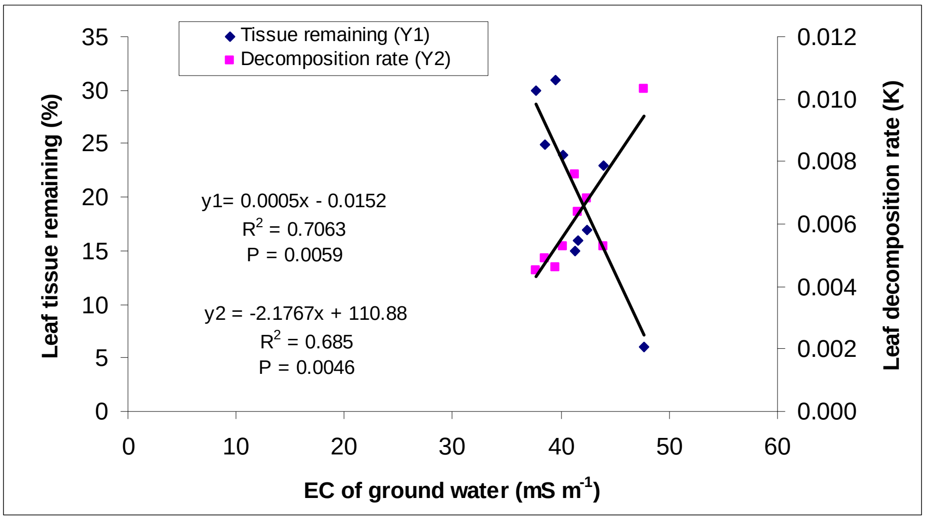

Figure 7.16: The relationship between groundwater EC and leaf tissue remaining and leaf decomposition rate of *Rhizophora apiculata* after eight months in the subsoil at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve.

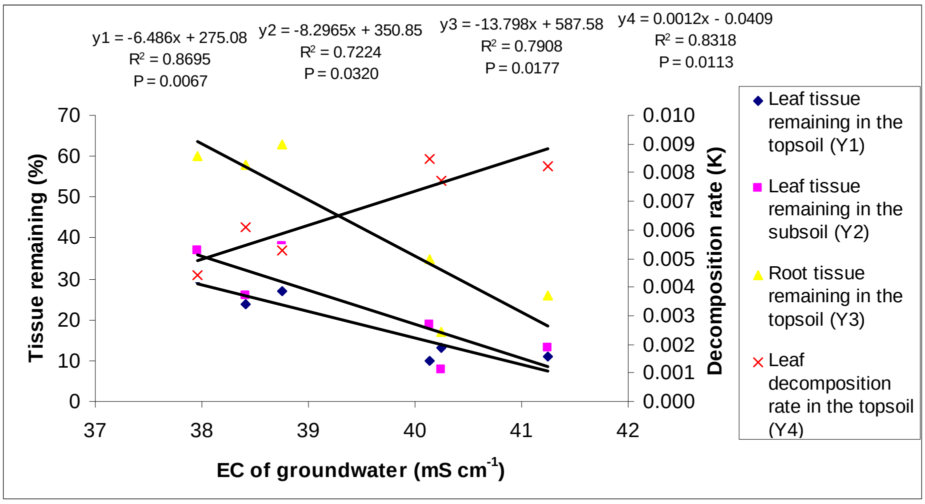

Figure 7.17: The relationship between groundwater EC and leaf tissue remaining in the topsoil and the subsoil, root tissue remaining in the topsoil and leaf decomposition rate in the topsoil of *Ceriops decandra* after eight months in the subsoil at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve.

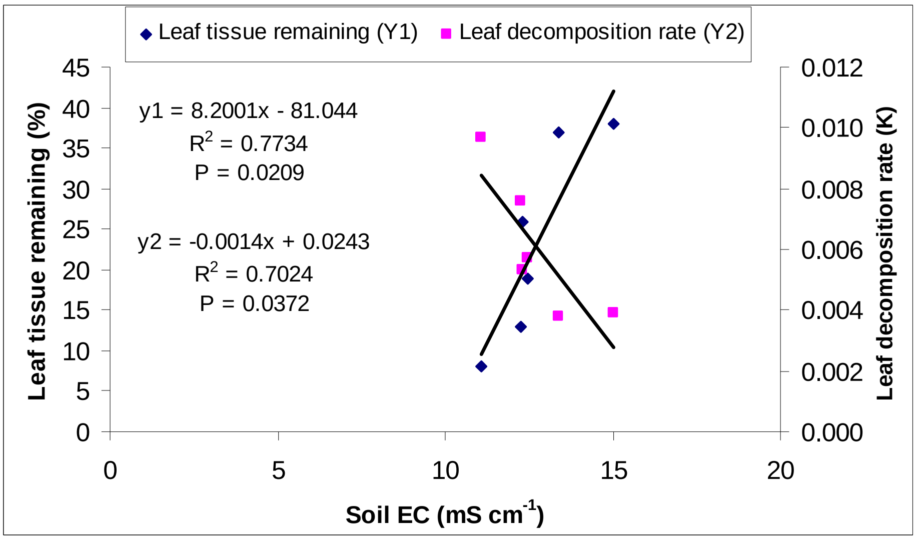

Figure 7.18: The relationship between soil EC and leaf tissue remaining and leaf decomposition rate for *Ceriops decandra* after eight months in the subsoil at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve.

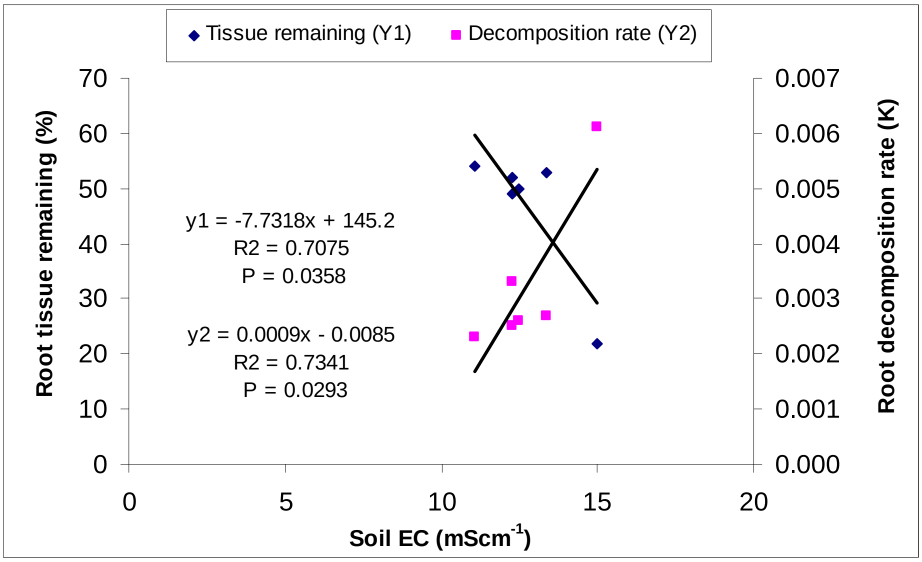

Figure 7.19: The relationship between soil EC and root tissue remaining and root decomposition rate of *Ceriops decandra* after eight months in the subsoil at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve.

7.3.2.4. Discussion

The results of the eight month decomposition study indicated that the decomposition process for both leaves and roots was affected by many biotic and abiotic factors such as the physical and chemical structure of the species tissue, the soil elevation, the flooding frequency, the EC of groundwater, and the EC of soil as discussed by Benner and Hodson (1985) and many others (Twilley et al.1986, Steinke and Ward 1987, Robertson 1988, Mackey and Smail 1996, Nga 2004).

I found that for this eight month decomposition study, which used both the percentage of tissue remaining and the decomposition rate of leaves and roots to assess decomposition, the main effects of zone and depth, and the interactive effect of zone by depth were statistically significant (Table 7.4). These effects differed, however, depending on differences in the structure of each species' tissues, the depth of incubation, and zone. Differences in elevation and flooding frequency also led to differences in the decomposition process, especially during the first stage (i.e. the fragmentation stage). Being native to a specific zone also highly affected the percentage of tissue remaining and the decomposition rate of both the leaves and the roots of species (Table 7.4). As mentioned, the difference in the percentage of tissue remaining and the decomposition rate also depended on the species' structural tissue (Mitsch and Gosselink 2000). Regardless of the differences in tissue structure among species, *Avicennia alba* in zone 1 and zone 2 at the KV site had the lowest percentage of tissue remaining and the highest decomposition rate for both leaves and roots because of this species thin leaves and soft roots. Species (e.g. *Ceriops decandra*, *Rhizophora apiculata* and *Phoenix paludosa*) with strong physical structure, such as thick leaves and hard root tissues, had a lower decomposition rate and a higher percentage of tissue remaining.

In comparing the decomposition process among zones, species with similar tissue structure could have a difference in the percentage of tissue remaining due to differences

among zones. For example, *Rhizophora alba* in zone 2 at the KV site [Rhi (KV2)] and *Ceriops decandra* in zone 2 at the KV site [Ceriops (KV2)] had significantly lower leaf tissue remaining than *Rhizophora alba* in zone 3 at the MO site [Rhi (MO3)] and *Ceriops decandra* in zone 2 at the MO site [Ceriops (MO2)] respectively (Figure 7.7). Similarly, *Rhizophora apiculata* in zone 2 at the KV site [Rhi (KV2)] had a lower root tissue remaining than *Rhizophora apiculata* in zone 3 at both the KV [Rhi (KV3)] and the MO sites [Rhi (MO3)] (Figure 7.10).

The main effect of depth on the leaf decomposition rate indicated that the decomposition rate in the topsoil was higher than in the subsoil (Figure 7.9). Due to their soft tissue structure, leaves can take up more water and therefore had a higher decomposition rate in the topsoil where a high amount of oxygen was available. In contrast, high moisture and a lack of oxygen may have prevented microbial decomposition activities in the subsoil and thus the lower the leaves' decomposition rate. However, the two-way interactive effect of zone by depth on the percentage of root tissue remaining showed no difference between the topsoil and the subsoil. Roots had thick and hard tissue structures and therefore were difficult to decompose possibly explaining the same percentage of root tissue remaining whether they were on the topsoil or in the subsoil. The exception was with the roots of *Ceriops decandra* which had harder tissue structure than other species, but its decomposition process was nevertheless affected by depth. Overall, species with harder tissues require a high level of moisture in the subsoil to support the fragmentation phase and to provide a better environment for the microbial community belowground to consume the leaf and root tissues, while species with softer tissues require a high level of oxygen in the topsoil to support the decomposition process, something that it is not available in the subsoil.

The correlation analyses also indicated a dependency between the tissue structure of each species and its location on decomposition. Elevation affected the decomposition process

through soil moisture, especially in the topsoil. Moisture is a factor necessary for the decomposition of most species, particularly species that have thick and hard tissues. For example, *Avicennia alba* in zone 1 and zone 2 at the KV site had a low percentage of root tissue remaining but a high leaf decomposition rate due to its location in low elevation zones (Figure 7.13). Similarly, root tissue remaining of *Avicennia alba* was also low in zones with high flooding frequency (Figure 7.14). For zones that had low soil drainage, the root decomposition rate of the topsoil was high, as it was in the case of *Rhizophora apiculata* (Figure 7.15).

In this study, groundwater EC was found to have an effect on decomposition. However, the effect differed based on the tissue structure of the species and the soil depth. An increase in the groundwater EC led to a decrease in the percentage of leaf tissue remaining and an increase in the leaf decomposition rate of *Rhizophora apiculata* in the subsoil (Figure 7.16). In addition, as groundwater EC increased, *Ceriops decandra* experienced a decrease in the percentage of leaf and root tissue remaining in the topsoil. The leaf tissue remaining of *Ceriops decandra* in the subsoil decreased with an increase in groundwater EC, and the leaf decomposition rate of the topsoil increased with an increase in groundwater EC (Figure 7.17). High sodium levels in the groundwater may have helped to increase the water absorbability of the tissues and to breakdown the tissue structure during the early stages of the decomposition process.

Additionally, soil EC was also found to affect decomposition. An increase in soil EC led to an increase in root decomposition rate as well as the root tissue remaining of *Ceriops decandra* in the subsoil (Figure 7.18). In contrast, an increase in soil EC caused a decrease in the leaf decomposition rate and an increase in the amount of leaf tissue remaining of *Ceriops decandra* in the subsoil (Figure 7.19).

7.4. Conclusions

In this study, the decomposition process was affected by various biotic and abiotic factors (Benner and Hodson 1985, Twilley et al.1986, Robertson 1989, Mackey and Smail 1996, Nga 2004). The decomposition process was dependent on the origin of each species and their location. Different species have different tissue structure and therefore had different percentages of leaf tissue remaining and different decomposition rates (Robertson et al. 1992) for the two month and eight month incubation periods during both the dry and the wet seasons. Species with thin and soft tissue decomposed faster than species with thick and hard tissue. The decomposition of roots was slower than that of leaves in the same zone conditions.

Thin and soft tissue structures decomposed at a rapid rate on the topsoil and had a low percentage of tissue remaining in high elevation zones that had a low flooding frequency Roijackers and Nga 2002, Nga 2004). Contrary to this, thick and hard tissue structures needed a high level of moisture in the subsoil to decompose.

Soil moisture was found to affect the decomposition process as well (Mitsch and Gosselink 2000, Nga 2004). Leaf and root tissues were incubated in the subsoil, as well as those that were located in zones that had high soil moisture, decomposed at a faster rate. Tissues that were located in zones with high elevation and low flooding frequency lacked the moisture necessary for decomposition and thus, a high percentage of tissue remained in these zones.

The decomposition process of the two-month incubation period occurred faster in the subsoil than in the topsoil due to the high soil moisture level (Nga 2004). In contrast, the decomposition process for the eight month incubation period occurred faster in the topsoil than in the subsoil due to highly reduced conditions in the subsoil. No difference in the decomposition process was found between the dry and the wet seasons due to similar

flooding conditions during both seasons. With the exception of the root tissues of *Avicenia alba*, the leaf tissues of all species in the study decomposed at a faster rate than the root tissues.

Depending on the species structural tissue and their location, the percentage of tissue remaining and the decomposition rate correlated differently with elevation, flooding frequency, soil drainage, groundwater EC, and soil EC. Results from the two-month incubation period indicated that the percentage of leaf tissue remaining of *Avicennia alba* during the dry season was correlated with elevation (Figure 7.4) and flooding frequency (Figure 7.5) while the percentage of leaf tissue remaining of *Rhizophora apiculata* was positively correlated with soil drainage (Figure 7.6). Results from the eight-month incubation period indicate that the percentage of leaf tissue remaining of *Avicennia alba* was correlated with elevation (Figure 7.13) and flooding frequency (Figure 7.14). *Rhizophora apiculata*'s percentage of leaf tissue remaining was also correlated with soil drainage (Figure 7.15) and EC of groundwater (Figure 7.16). *Ceriops decandra* was found to be correlated with both groundwater EC (Figure 7.17 and 7.18) and soil EC (Figure 7.19). Finally, soil drainage also had an effect on the decomposition process in that low soil drainage allows for a higher level of soil moisture and thus tends to increase the decomposition rate. Groundwater EC and soil EC can, in addition, enhance the decomposition process by increasing the absorbability of water during the first stages of the decomposition process.

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CHAPTER 8

EFFECT OF HYDROLOGY ON PRIMARY PRODUCTION AND SPECIES DISTRIBUTION

8.1 Introduction

Mangrove forests are found along tropical and subtropical coastlines throughout the world. They occur between 32^{o} N and 28^{o}S latitude, but are most developed between 25^{o} N and 25^{o}S latitude due to warmer air and water temperate (Mendelssohn and McKee 2000, Mitsch and Gosselink 2000). Mangrove communities, which are one of the most important types of coastal wetlands, are distributed in the intertidal zones of tropical and subtropical regions of the world and are dominated by trees and shrubs (Tomlinson 1986, Duke 1992, Mendelssohn and McKee 2000, Satyanarayana et al. 2002). Most mangroves are directly connected to the sea, and water exchange ranges from daily tides to seasonal flushing (**Lara** et al. 2005). However, mangrove forest development is dependent upon three important scales: coastal range, location within an estuary, and position along the intertidal profile (Duke 1992).

Mangrove ecosystems are highly productive (Boto 1992). However, primary productivity of mangrove forests is highly dependent on mangrove type (Day et al. 1987, Brow and Lugo et al. 1982) and the environmental conditions, for example tidal regime and salinity, that dominate in the different mangrove types.

Mangroves trees develop in the saline and anaerobic soil conditions. However, mangrove production can still be limited by elevated salinities and highly reduced soils (Nickerson and Thibodeau 1985). In addition, soil nutrient status also directly controls mangrove primary productivity (Boto and Wellington 1984, Boto 1992, Alongi et al. 1992, Mendelssohn and McKee 2000). For example, nutrient enrichment had resulted in a

significant enhancement of growth in *Rhizophora mangle* (Onuf et al. 1977) and *Avicennia marina* (Naidoo 1987).

Flooding frequency is another factor that affects soil nutrient status and thus mangrove productivity. Daily tides reduce litter accumulation on the soil surface, thus tending to limit the nutrient potential of the mangrove ecosystem. Tam and Wong (1997) suggested that mangrove productivity is higher in landward zones than seaward zones because the soil in landward zones contains relatively high organic matter, total and extractable nitrogen, phosphorus and potassium. Fine silts and clays contain an abundant supply of exchangeable ions that fertilize and enhance the productivity of the plants (Chapman 1976).

Mangrove leaf litter can be used to predict mangrove production. For example, the net primary production values of North American mangrove forests were estimated from litter fall data (Lugo et al. 1975). However, differences in the amount of mangrove leaf litter depend mainly on the degree and frequency of tidal inundation (Twilley 1985, Twilley et al. 1986, Robertson 1989). Mangrove production was estimated by four methods: amount of litter fall, gas exchange rates, changes in tree diameter, and the harvest of trees of known age (Lugo et al. 1975).

The objective of this research chapter was to describe the effects of hydrology and mangrove zonation on the primary productivity of the mangrove forest by measuring litter fall in the Can Gio Biosphere Reserve.

8.2 Materials and Method

One square meter wide and 60 cm deep litter fall traps formed by bamboo sticks and nylon nets were used to catch litter fall (Figure 8.1). Each study site (KV and MO) had three transects and each transect was divided into three zones. Each zone in the three transects was divided further into three plots of 10 by 20 meters. In each plot, three litter fall traps were

installed 1.5 meters above the soil surface in different areas. The procedure was repeated for each plot on each zone along transects for both the KV and the MO sites. The litter fall of all species in the plots was collected every month for a total of three months during the dry season and again for three months during the wet season. Litter samples were oven dried at 65^{o} C until they reached a stable weight. The total dry weight of the litter was calculated as grams dry weight per square meter per day.

Litter fall samples were compared between sites and among zones, but not among species. The distribution of each species was calculated by counting the type of species that were native to each plot. The succession and dominance of each species were evaluated by counting the actual number of trees of each species that were growing in each plot. A total of nine species (Table 8.1) were observed for distribution and dominance analyses.

Figure 8.1 Litter fall trap at the KV site in the Can Gio Mangrove Biosphere Reserve.

Table 8.1 The distribution of mangrove species among zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

Site	Zone	Species
KheVinh (KV)	Z 1	*Avicennia alba*
	Z 2	*Avicennia alba, Avicennia officinalis, Ceriops decandra, Rhizophora apiculata*
	Z 3	*Rhizophora apiculata, Avicennia alba, Avicennia officinalis*
Mui O (MO)	Z 1	*Phoenix paludosa, Ceriops decandra, Hibiscus* sp, *Lumnitzera racemosa, Acrostichum* sp
	Z 2	*Rhizophora apiculata, Ceriops decandra, Avicennia officinalis, Exceocaria algallocha, Acrostichum* sp
	Z 3	*Rhizophora apiculata, Exceocaria algallocha, Ceriops decandra, Acrostichum* sp

8.3 Results and Discussions

8.3.1 Litter Fall

The amount of litter fall was affected by the main effects of site, season, and zone and the two two-way interactions of site x season and season x zone. No effect was found for the two-way interaction of site x zone, and the three-way interaction of site x season x zone (Table 8.2).

The two-way interactive effect of site and season indicated that the effect season on the amount of litter fall was dependent on site (Figure 8.2). At the KV site, the amount of litter fall was significantly higher during the dry season than the wet season (Figure 8.2) whereas at the MO site, no significant difference between the dry and the wet seasons (Figure 8.2) were observed. Overall, the interactive effect of site and season indicated that the amount of litter fall of at the KV site was higher than that at the MO site but only during the dry season (Figure 8.2).

The two-way interactive effect of season and zone indicated that the effect of season on the amount of litter fall was dependent on zone. During the dry season, the amount of litter

fall was not significantly different among zone 1, zone 2, and zone 3 (Figure 8.3). During the wet season, zone 3 had significantly higher litter fall than that for zones 1 and 2, which did not significantly differ (Figure 8.3). There were no other significant differences in litter fall among the remaining treatment-levels (Figure 8.3).

The amount of litter fall was negatively correlated with the number of species (r = 0.7268, P = 0.0268), but only at the KV site (Figure 8.4). During the dry season, at both the KV and MO sites, the amount of litter fall was also negatively correlated with organic matter in both the topsoil (r = -0.5284, P = 0.0240) and the subsoil (r = -0.6461, P = 0.0037) (Figure 8.5 and 8.6). Similarly, the amount of litter fall was negatively correlated with total nitrogen in both the topsoil (-0.5463, P = 0.0188) and the subsoil (r = -0.7207, P = 0.0007) (Figure 8.7 and 8.8) at both the KV and MO sites, and also negatively correlated with soil Eh (r = -0.5027, P = 0.0334) during the dry season in the topsoil at both the KV and MO sites (Figure 8.9).

Table 8.2 F values and probability levels from analysis of variance of site, season, zone, and their interactions on the amount of litter fall at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. (*) denote statistical significance at alpha = 0.05.

Source	Litter Fall		
	F	F-Ratio	Prob > F
Site (Si)	1	19.8370	0.0002*
Season (Se)	1	27.7062	<0.0001*
Si * Se	1	36.2658	<0.0001*
Zone (Zo)	2	9.1860	0.0011*
Si * Zo	2	2.3038	0.1219
Se * Zo	2	3.7653	0.0379*
Si * Season * Zo	2	3.2430	0.0564

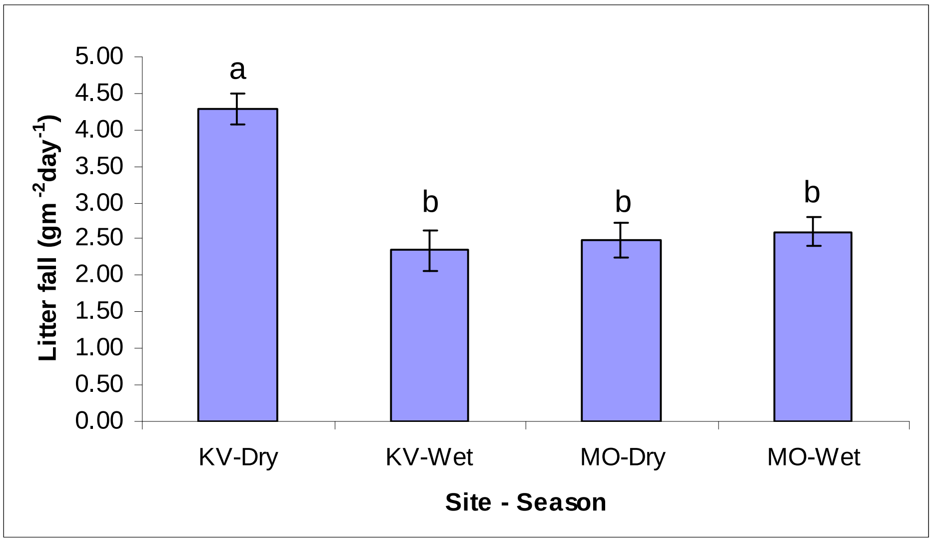

Figure 8.2 The interactive effect of site and season on litter fall (mean ± SE) at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant differences at P ≤ 0.05.

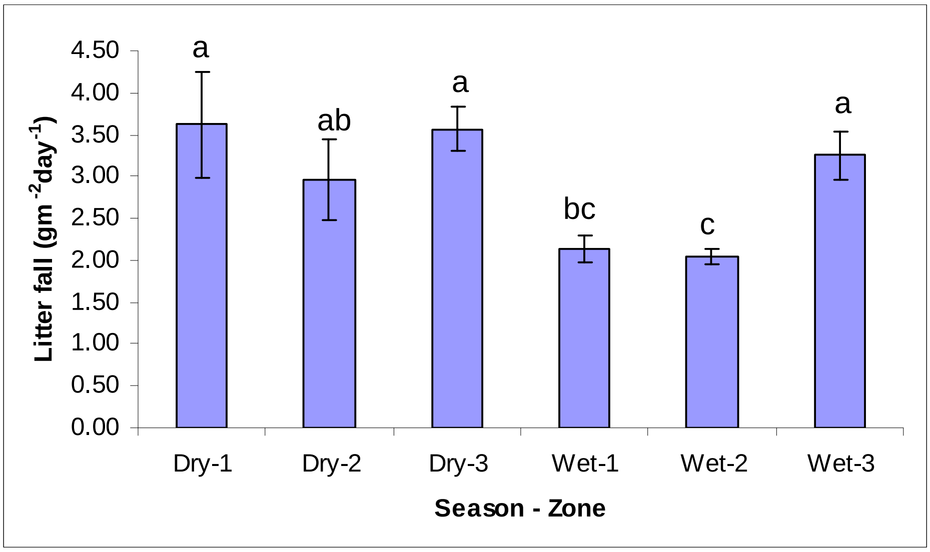

Figure 8.3 The interactive effect of season and zone on litter fall (mean ± SE) at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant difference at P ≤ 0.05.

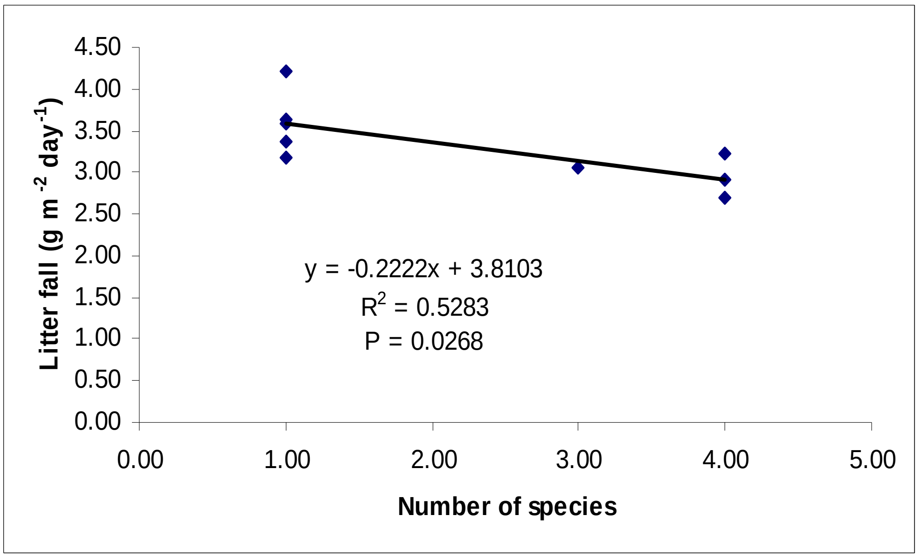

Figure 8.4 The relationship between litter fall and number of plant species during the dry and wet seasons across all zones at the KV site in the Can Gio Mangrove Biosphere Reserve.

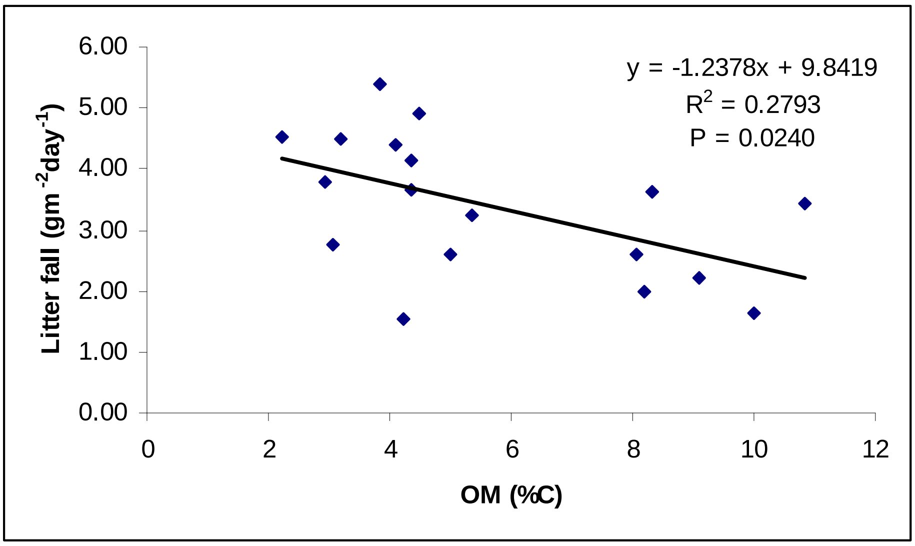

Figure 8.5 The relationship between litter fall and OM (organic matter) in the topsoil during the dry season across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

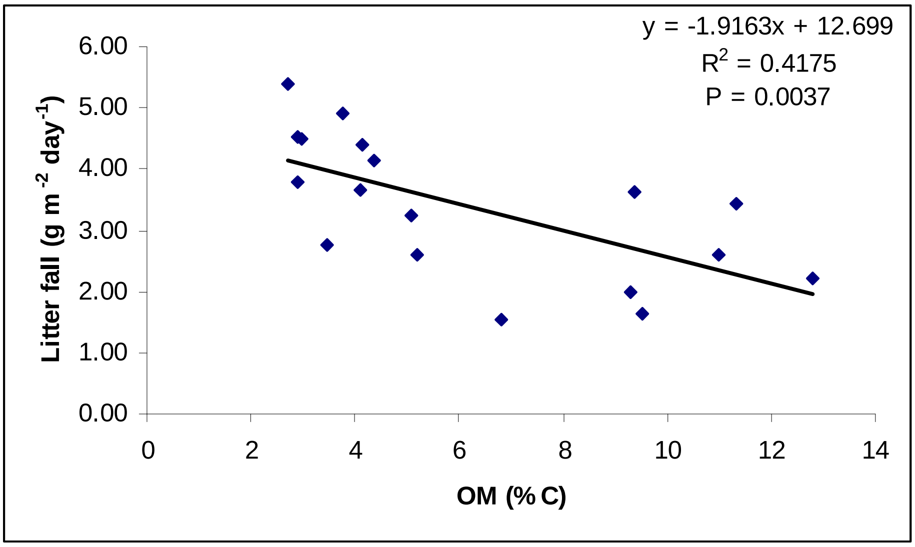

Figure 8.6 The relationship between litter fall and OM (organic matter) in the subsoil during the dry season across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

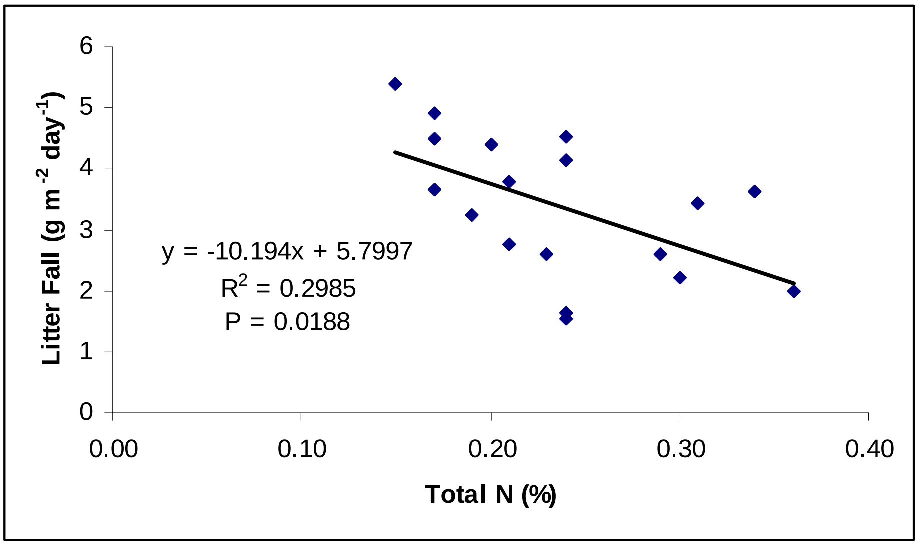

Figure 8.7 The relationship between litter fall and total nitrogen in the topsoil during the dry season across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

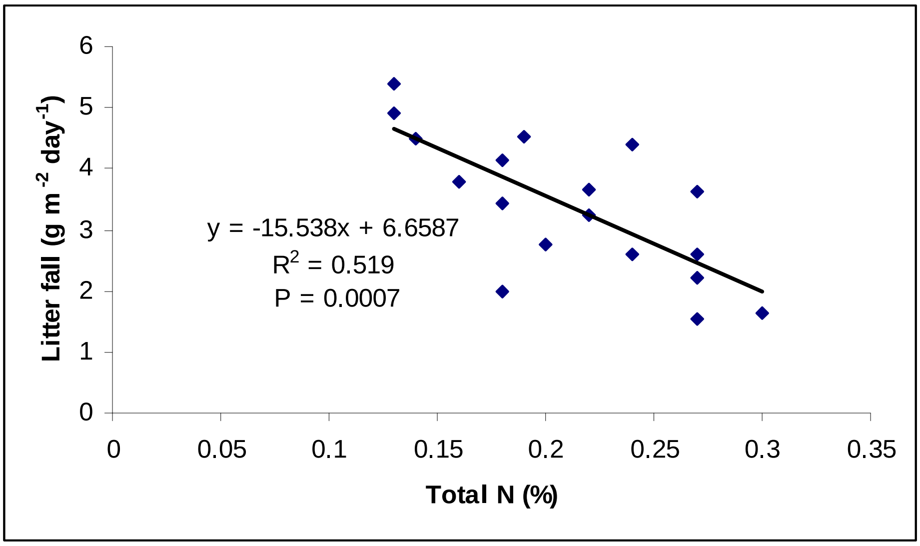

Figure 8.8 The relationship between litter fall and total nitrogen in the subsoil during the dry season across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

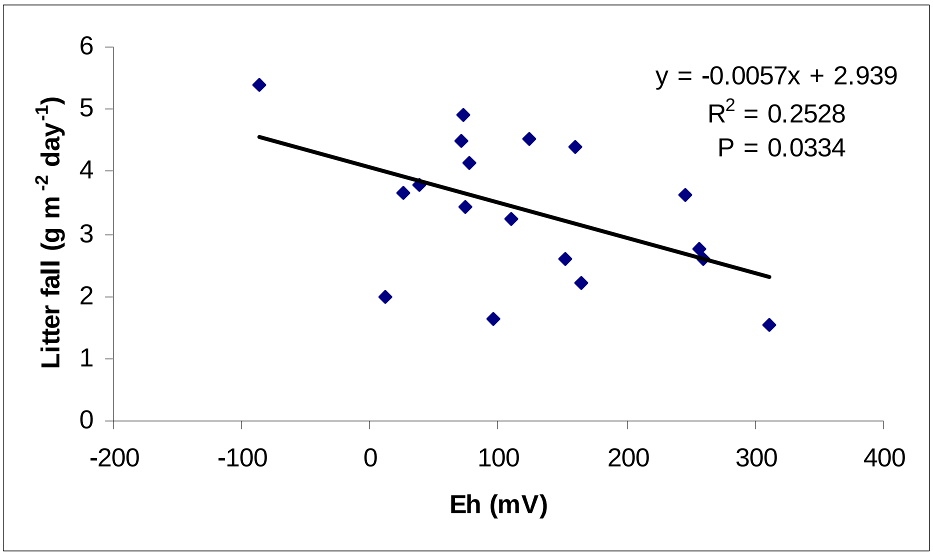

Figure 8.9 The relationship between litter fall and Eh (redox potential) in the topsoil during the dry season across all zones at the KV and MO sites in the Can Gio Mangrove Biosphere Reserve.

The amount of litter fall in each zone was calculated from the total litter fall which included both the leaves and the reproductive organs of species that are native to the zone. The total collected litter fall in the experiment was composed mainly of leaves (e.g. 80 – 81 % at the KV site and 77 - 79 % at the MO site) because the experiment was carried out during the non-reproductive season. The results indicated that the greatest amount of litter fall was found at the KV site in the dry season. Higher stress experienced by mangroves during the dry season may explain the amount of the litter fall.

During the dry season, the amount of litter fall at the KV site was higher than the MO site (Figure 8.1). This is because zone 1 and zone 3 of the KV site were dominated by a single older species with a large canopy (e.g. *Rhizophora apiculata* in zone 3 and *Avicennia alba* in zone 1). Zone 2 of the KV site also had a high density of *Avicennia alba* and *Ceriops decandra,* which contributed a high amount of litter fall. In contrast, only zone 3 of the MO site had older species with large canopies (e.g. *Rhizophora apiculata*). Zone 2 and 1 had younger species with smaller canopies that were less dense. Zone 2 was occupied by *Rhizophora apiculata* and zone 1 was occupied by *Phoenix paludosa, Ceriops decandra, Exceocaria algallocha, Hibiscus* sp, and *Lumnitzera racemos*.

The interactive effect of season by zone showed that during the dry season zone 1 and zone 3 had the highest amount of litter fall and during the wet season, zone 3 had the highest the amount of litter fall. The high amount of liter fall found can be accounted for by the older species that resided in these zones. Their large canopies coupled with the high stress experienced during the dry season yielded the large amount of litter fall.

In general, most species have to cope with a variety of stressors during the dry season more so than during the wet season. Several types of physical stressors are related to the high amount of litter fall in the dry season. First, high temperature and high evaporation lead to an increase in soil salinity, which may cause stress for the trees. Leaves also lack excess water in

the dry season as compared to the wet season and hence, fall at a faster rate. High activities of insects during the dry season, as observed from field survey and hot winds during March were additional factors that caused high amounts of leaves to die. These factors also contributed to a higher litter fall rate during the dry season than in the wet season.

Observed relationships between the amount of litter fall and the number of species (Figure 8.4) demonstrated that the amount of litter fall depends on species structure and age. High amounts of litter fall were consistently found in zones with a single species type that was older and had large canopies. During the dry season, organic matter (OM) and total N were also found to be related to the amount of litter fall. Low OM and low total N in soil contributed to the early maturation of leaves, thus increasing the amount of litter fall (Figure 8.5, 8.6, 8.7 and 8.8). In addition, low soil Eh during the dry season also caused stress for the trees and contributed to the high amounts of litter fall (Figure 8.9).

In general, the amount of litter fall in the KV and MO sites at the Can Gio Mangrove Biosphere Reserve was similar to that of earlier studies on litter fall. For example, the amount of litter fall of *Rhizophora apiculata* in zone 3 at both the KV and the MO sites varied from 3.17 gm^{-2} day^{-1} to 3.92 gm^{-2} day^{-1}, which was similar to litter fall of *Rhizophora* spp in Mexico at 3.40 gm^{-2} day^{-1} (Day et al. 1987), litter fall of *Rhizophora apiculata* in Australia at 3.10 gm^{-2} day^{-1} (Bunt 1982), litter fall of *Rhizophora apiculata* in Mekong Delta of Vietnam from 2.58 to 5.16 gm^{-2} day^{-1} (Clough et al. 2000) and from 2.43 to 3.89 gm^{-2} day^{-1} (Nga 2004).

8.3.2 Number of Species

The number of species that grow in each plot of the study site was used as a measure of species distribution. Number of species was highly affected by the main effects of site and zone and the two-way interaction of site by zone (Table 8.3).

Although the number of species at the MO site was significantly higher than at the KV site, this effect was dependent on zone. At the KV site, the number of species peaked in zone 2, having significantly higher species number than in zones 1 and 3, which did not significantly differ (Figure 8.10). At the MO site, the number of species peaked in zone 1 and tended to decrease into the mangrove swamp from zone 1 to zone 3 (Figure 8.10).

The number of species was affected by soil bulk density. We found that the number of species at the MO site was positively correlated with soil bulk density ($r = 0.777$, $P = 0.0137$) (Figure 8.11). The highest number of species was found in zones that had high soil bulk density (Figure 8.11) such as zone 1 and 2 at the MO site. Species native in these zones belong to group of plant association that adapted well to soil with high elevation, low soil moisture and high soil bulk density.

8.3.3 Tree Species Frequency

The frequency of each species of tree also provides an indication of species distribution. Species frequency was highly affected by the main effect of species and the two-way interaction of site by species, zone by species, and the three-way interaction of site by zone by species (Table 8.3). The main effects of zone and site, and the two-way interaction of zone by site had no effect on species frequency.

The interactive effect of zone by site by species showed that the effect of site and zone on species frequency was dependent on the particular tree species. At the KV site, the frequency of *Avicenia alba* in zone 1 was significantly higher than in zone 2, while the frequency of *Rhizophora apiculata* in zone 2 was significantly lower than in zone 3. The species frequencies of *Ceriops decandra* and *Avicenia officinalis* in zone 2 were the lowest, and no significant difference was found between the two species (Figure 8.17). At the MO site, the frequency of *Rhizophora apiculata* in zone 3 was significantly higher compared to *Phoenix paludosa* in zone 1. No differences in frequencies were found between *Rhizophora*

apiculata in zone 2 and zone 3 and between *Rhizophora apiculata* in zone 2 and *Phoenix paludosa* in zone 1 at the MO site (Figure 8.13). However, the frequency of all species of *Rhizophora apiculata* in zone 2 and zone 3 and *Phoenix paludosa* in zone 1 were significantly different from other remaining species (Figure 8.13).

Overall, there were no significant differences in frequency of *Rhizophora apiculata* among the zones it occupied (i.e., zone 3 at KV and zone 2 and zone 3 at MO). Concurrently, no significant difference was found in frequency of *Ceriops decandra* among the zones that it was found to dominate (i.e. zone 2 at KV and zone 1 and zone 2 at MO) (Figure 8.13).

The distribution of each species reflects the different environmental conditions in which species can adapt. Most species can occur in different environmental conditions. However, not all species can survive and successfully reproduce in new environments, especially in new environments with extreme conditions.

In this study, a difference in the number and frequency of species was found between sites and among zones. A total of nine species (Table 8.1) were observed from the KV and MO sites, but only four species (*Rhizophora apiculata, Avicennia alba, Phoenix paludosa,* and *Ceriops decandra*) dominated the study sites. Each of the four species was distributed and developed in specific areas with different elevations and tidal regimes. Their distributions were indicative of their ability to adapt to particular zones. For example, *Phoenix paludosa* was found only in zone 1 whereas *Avicennia alba, Rhizophora apiculata* and *Ceriops decandra* were found in several zones (Figure 8.13). The remaining five species were present, but their frequencies were low, possibly due to these species' inability to adapt to their environment.

The highest number of species was found in zones with high elevation and low flooding frequency. These zones (e.g., zone 1 and 2 of MO) are characterized by dry and compacted soil conditions. Species such as *Pheonix paludosa, Exceocaria algallocha,*

Lumnitzera racemosa, *Avicennia officinalis* and *Hibiscus* sp. thrive in these zones possibly due to their ability to adapt to the dry and compacted soil environment that occur there. A low number of species was found in zones with low elevation and high flooding frequency. These zones (zone 1 at the KV site and zone 3 at the KV and MO sites) are usually inundated with water and have less compacted soil. Therefore, species that can adapt to these conditions, such as *Avicennia alba* and *Rhizophora apiculata*, can be found in these zones. However, there are some species that can survive at both high and low elevations as well as in dry soil and inundated soil. These species include *Rhizophora apiculata*, *Ceriops decandra*, and *Avicennia officinalis* (Hong 1993, Tuan et Al. 2002).

The highest tree frequency was found for *Avicennia alba* in zone 1 of the KV site, a zone with inundated water conditions. However, this species' frequency decreased with increased elevation. The frequency of *Avicenia alba* was 100% in zone 1, 24 % in zone 2, and 2 % in zone 3. These frequencies may be explained by *Avicennia alba's* preference for areas with low elevation, brackish water, and newly formed mudflats such as occurred in zone 1 at the KV site (Hop and Giao 2001). Zone 2, a transition zone with high interspecific species competition, had a higher elevation and lower water inundation than zone 1. Zone 3 had the highest elevation among all zones and the lowest water inundation. Coupled with a higher soil salinity level, zone 3 was not optimal for the growth of *Avicennia alba*.

Individuals of *Rhizophora apiculata* were found in zone 2 and zone 3 of both the KV and MO sites (Figure 8.13). With the exception of zone 2 at the KV site, which had a lower frequency of 46 %, *Rhizophora apiculata* formed extensive stands with a high frequency of occurrence in zone 3 at the KV site (96 %), in zone 3 at the MO site (94 %), and in zone 2 at the MO site (84 %). *Rhizophora apiculata* adapts well to areas with high elevation (2 to 2.25 m above mean sea level) and well-developed soils, which were characteristics of zone 3 at the

KV and MO sites. In addition, *Rhizophora apiculata* can also survive in areas of high salinity (Hop and Giao 2001).

Tuan et al (2002) suggested that *Ceriops decandra* belongs to a plant association that is distributed in areas with a high elevation and with relatively developed, compacted soil and is adapted to medium and low elevation conditions. However, in this study *Ceriops decandra* was found in zone 2 of the KV site, and all of the zones at the MO site, but was not abundant enough to dominate these areas. Even though zone 2 at the KV site and zone 1 at the MO site had a low to medium flooding frequency that would have been optimal for *Ceriops decandra* to develop, both of these zones also had a high percentage of clay. Additionally, interspecific competition might have played a critical role in *Ceriops decandra* development in these areas. *Ceriops decandra* frequency was highest at 22 % in zone 2 of the KV site and at the MO site, 20 % in zone 2 % in zone 2 and a low 4 % in zone 3.

The distribution of *Phoenix paludosa* was found only in zone 1 of the MO site with a high frequency (Figure 8.13). *Phoenix paludosa* belongs to group of species that can adapt to high saline conditions and grow in areas with high elevation (3.5 to 4 m above mean of sea level) (Tuan et al. 2002). It is usually distributed in areas with low flooding frequency and very hard compacted soil (Hop and Giao, 2001). In this study, *Phoenix paludosa* extensively occurred in zone 1 of the MO site, a zone that is located near the riverside. This area has very good soil drainage and low flooding frequency, which results a very dry and compacted soil optimal for *Phoenix paludosa*'s growth and development.

Other species such as *Avicennia officinalis*, *Exceocaria algallocha, Lumnitzera racemosa*, *Acrostichum* sp and *Hibiscus* sp. were found in most zones at both study sites except for zone 1 of KV site. However, these species had frequencies below 7 % (Figure 8.13). According to Tuan et al. (2002), these species can adapt to soils that are unstable and very hard. They can also adapt to a wide range of salinity condition including

saline to brackish water condition (Hop and Giao 2001). Because of their ability to adapt to a wide range of environmental conditions, species the preceding species can grow in most areas, but their growth does not result in extensive development.

Table 8.3 F values and probability levels from analysis of variance of the main effects of zone, site and species and their interactions on number of species and tree frequency at the study sites in the Can Gio Mangrove Biosphere Reserve, (*) denotes statistical significance at alpha = 0.05. The number of species was analyzed for the main effects of zone and site only.

Source		Number of species type		Tree frequency	
	DF	F-Ratio	Prob > F	F-Ratio	Prob > F
Site (Si)	1	34.5714	<0.0001*	0.0048	0.9450
Zone (Zo)	2	18.0000	<0.0001*	0.0040	0.9961
Si * Zo	2	31.1429	<0.0001*	0.0022	0.9978
Species (Sp)	8			233.5915	<0.0001*
Si * Sp	8			60.9192	<0.0001*
Zo * Sp	16			113.9142	<0.0001*
Si * Zo * Sp	16			41.9307	<0.0001*

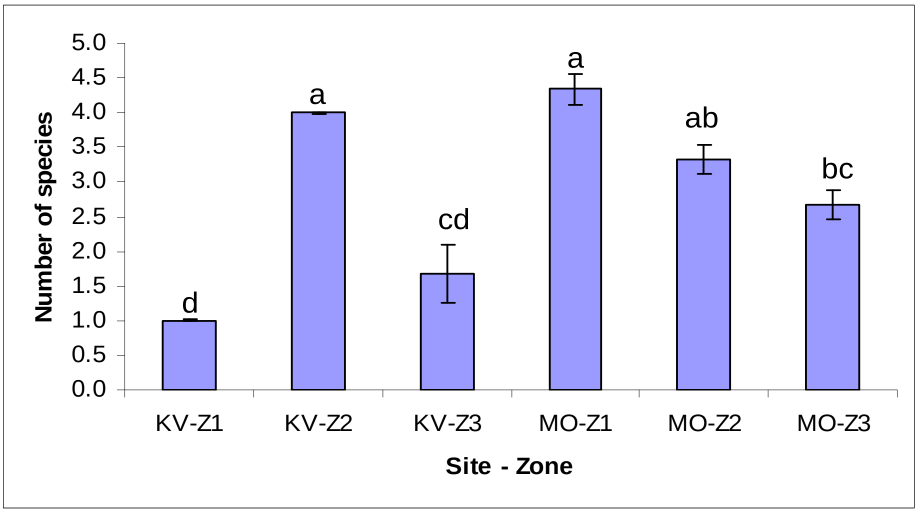

Figure 8.10 The effect of site and zone on number of species (mean ± SE) at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant difference at $P \leq 0.05$.

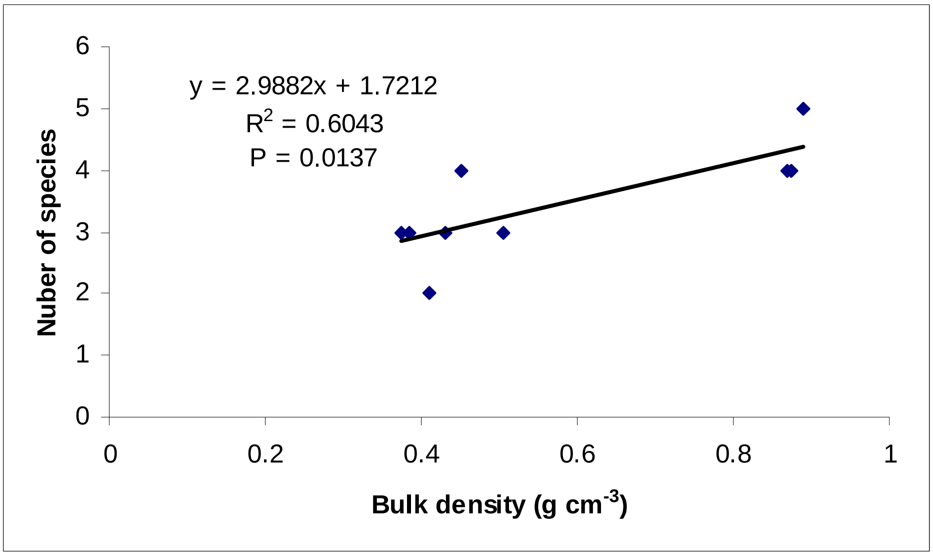

Figure 8.11 The relationship between the number of species and soil bulk density across all zones at the MO site in the Can Gio Mangrove Biosphere Reserve.

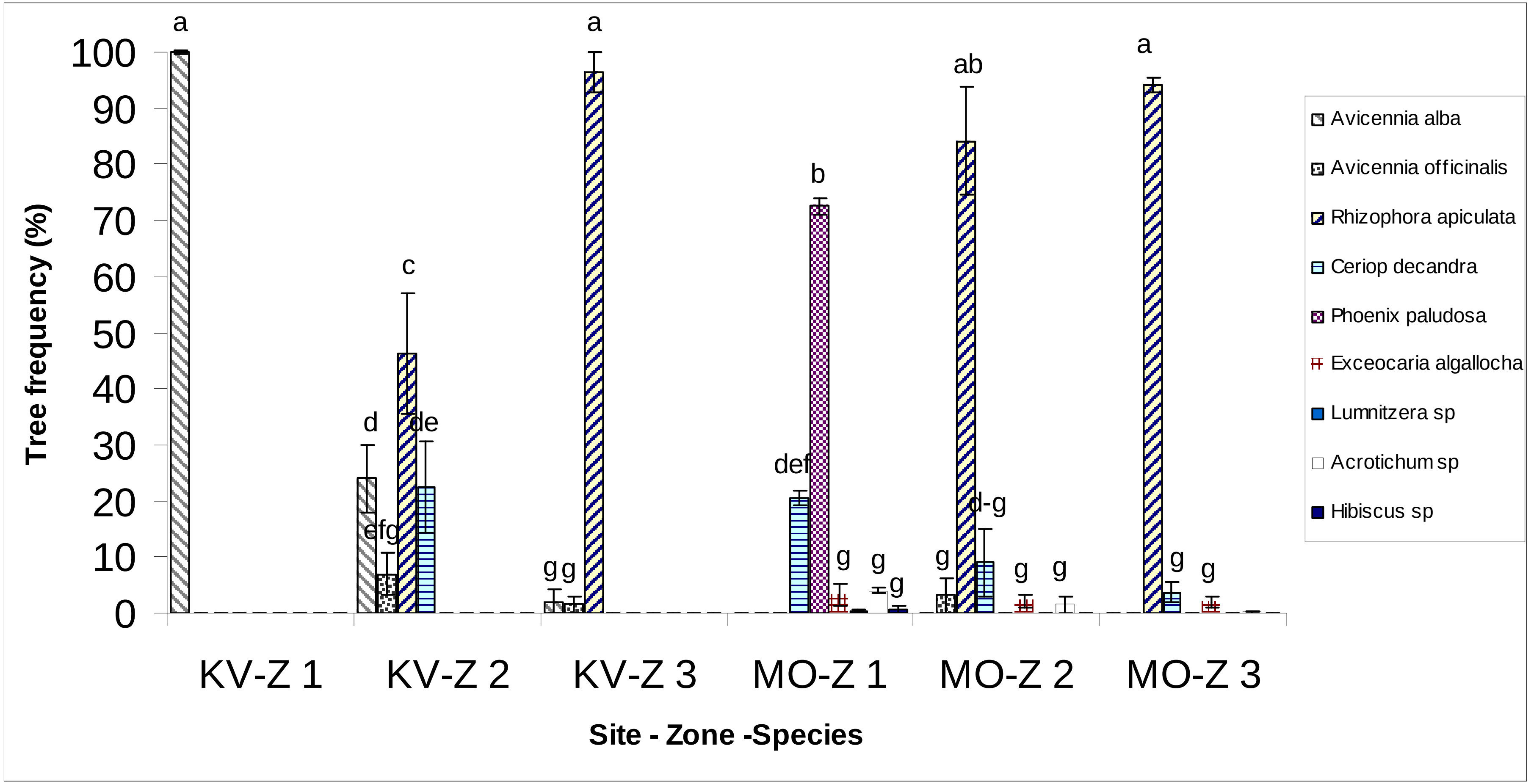

Figure 8.12 Comparison of tree species frequencies (mean ± SE) as a function of zone and species at the KV and MO study sites in the Can Gio Mangrove Biosphere Reserve. Means with different letters denote significant difference at $P \leq 0.05$.

8.4. Conclusion

The litter fall at the study site in the Can Gio mangrove forest was affected by two, two-way interactions: site by season and season by zone. Differences in the litter fall between the dry and the wet seasons were found at the KV site, but not at the MO site. The litter fall in the dry season at the KV site was significantly higher than in both the wet and dry seasons at the MO site as well as in the wet season at KV site, where no differences were found. During the wet season, zone 3 had significantly higher litter fall than zone 1 and zone 2. However, no difference was found between zone 3 at both sites in the wet season and all zones in the dry season. Overall, litter fall was determined by the species that grows in each zone. In this study, litter fall was high in zones with only a single species as in the case of *Rhizophora apiculata* in zone 3 at the KV and MO sites and *Avicenia alba* in zone 1 of the KV site.

Generally, primary production can be estimated from the amount of litter fall (Lugo et al. 1975). However, differences in mangrove litter fall depend mainly on the degree and frequency of tidal inundation (Twilley 1985, Twilley et al. 1986, Robertson 1989). In this study, the total calculated primary production at the KV site was higher than at the MO. The KV site had higher litter fall in all of its zones compared to the MO site, and hence, higher production.

The distribution of species depended on the number of species and the tree frequency. Mangrove distribution is affected by differences in geographical and hydrological conditions. In this study, the highest number of species was found in the transition zones such as zones 2 at the KV and MO sties and in high elevation zones that have low soil moisture such as zone 1 at the MO site. Only four of the nine species (*Avicennia alba, Rhizophora apiculata, Ceriops decandra* and *Phoenix paludosa*) were prosperously and successfully developed. The remaining five species (*Avicennia officinalis, Exceocaria algallocha, Lumnitzera racemosa, Acrostichum* sp and

Hibiscus sp) were found ubiquitously distributed, but were not heavily populated in any zones. Species of *Avicennia alba* adapted well to low elevation areas that have high water inundation and newly formed mudflat. Contrary, species of *Rhizophora apiculata* was better adapted in areas that have medium to high elevation areas, low water inundation, and medium to high compacted soil. Meanwhile, *Ceriops decandra*'s adaptability extended to areas that have low and high elevation, medium to low water inundation, and medium to compacted soil. Finally, *Phoenix paludosa* can only adapt to areas that have high elevation, rare water inundation, and dry compacted soil.

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CHAPTER 9

GENERAL CONCLUSIONS

Results from this research indicate that the structure and function of mangrove forests at the Khe Vinh (KV) and Mui O (MO) sites in the Can Gio Mangrove Biosphere Reserve are affected by various biotic and abiotic factors (Mendelssohn and McKee 2000). Analyses from chapter 4 to chapter 8 show that the hydrological regime plays an important role in the structure and function of the Can Gio mangrove ecosystem.

In chapter 4 it was found that the tidal regime at the Can Gio study was were mainly affected by the tidal regime of the South China Sea and also influenced by the Sai Gon and Dong Nai rivers via the main branch of the Dong Tranh River (Tuan et al. 2002). Tidal levels were different throughout the year at the study sites. The highest tidal levels during the spring tide occurred from November to January and the lowest tidal levels during the ebb tide occurred from June to July. There were two monthly peaks in tidal levels. The first occurred around the middle of the month and the second occurred around the end of the month. Because of the effect of the China Sea tidal regime, during a month, there were two tides per day except some days had only one tide a day due to the effect of the China Sea tidal regime.

The water level at the study sites during the dry season was higher than during the wet season due to the influx of water released from the Tri An Hydroelectric Dam (Loon 2005). The EC of water at the study sites was highest at the end of the dry season and remained relatively stable at a lower rate during the other times of the year. The EC of water in the Dong Tranh River was higher than the EC in the mangrove creek because of water runoff into the creek from areas higher in elevation.

Zone 1 at the KV site had a significantly lower elevation than the other zones, including the zones at the MO site. Other than that, the KV and MO sites had approximately the same elevation in all of their zones. Differences in elevation coupled with differences in flooding frequency affected the soil biogeochemistry as well as the structure and function of the mangrove forests (Mendelssohn and McKee 2000, Mitsch and Gosselink 2000). Flooding frequency was affected by elevation and season. Due to its low elevation at zone 1, the KV site had a higher flooding frequency than the MO site. Flooding was more prevalent in the dry season than in the wet season. The release of water from the Tri An Hydroelectric Dam increased the water level downstream. When combined, elevation and flooding frequency were found to affect soil drainage. Zone 2 at the KV site had the least soil drainage while zone 1 at the MO site drained of water the most. The groundwater EC at the KV site was higher than at the MO site with the highest groundwater EC found in zone 3 at the KV site and the lowest in zones 2 and 3 at the MO site.

In chapter 5, the effect of the hydrological regime on sedimentation at the KV and MO study sites in the Can Gio mangrove forest was discussed. The texture of the sediment at both sites was predominantly silt and clay, which together comprised more than 95 % of the soil by weight. Elevation was related to soil texture. Areas with a high elevation such as zone 2 and zone 3 of the MO site had greater proportion of sand than other zones and the proportion of sand was higher in the subsoil than in the topsoil. Areas with a low elevation, such as zone 1 of the KV site, had less silt and more clay in the topsoil than in the subsoil. Zones with lower organic matter (OM) during the dry season had a high soil bulk density. Soil OM was higher in the wet season and in zones that were more landward and higher in elevation.

Soil pH and Eh were also affected by the hydrological regime and elevation. High pH was found in zones with high elevation and low flooding frequency (Tam and Wong 1997). In contrast, low Eh was found at zones with low elevation and high water inundation (Gambrell 1994, Delaune and Pezeshki 1991). Soil EC was highly affected by the main effects of season and elevation. Higher EC was found in the dry season in the subsoil of zones with high elevation. High CEC occurred during the wet season in the topsoil of zones with high elevation.

In this study, I found that nitrogen had a strong relationship with elevation and OM in the soil. Total N and NH_4^+-N were high in zones with high elevation and high OM content (Tam and Wong 1997). No relationship was found for total P with regards to elevation and OM in the soil. Available P was high during the wet season in zones that had high reducing conditions and high OM content.

In chapter 6 I continued to investigate the process of sedimentation at the study sties. I found that the sedimentation process was affected by the tidal regimes from the China Sea and the Dong Tranh River. At the KV site, the sediment was composed mainly of silt and clay. The sedimentation rate was significantly greater in zone 1 than in zones 2 and 3 due to high sediment at concentrations in the water adjacent to zone 1. Season had a marginal effect (Table 6.2) on sedimentation in that differences in amount of sedimentation between the dry and wet season were found only in zone 1. Results on sedimentation for the MO site were not available because of the low sediment availability in the water adjacent to the MO study site resulted in little sedimentation on the marsh surface during the time of study.

Litter decomposition was the focus of chapter 7. I found that various biotic and abiotic factors affected the percentage of leaf tissue remaining and the decomposition rate of litter fall at KV and MO. The decomposition process was dependent on whether the species were native to

the zones and on their location. Species with thin and soft tissue decomposed faster than species with thick and hard tissue (Roijackers and Nga 2002 and Nga 2004). In this study, species that had thin tissue (e.g. leaf of *Avicennia alba*) had a faster decomposition rate in the topsoil of zones that had high elevation and low flooding frequency. In contrast, species that had thick and hard tissue had a higher decomposition rate in the subsoil of zones that had low elevation and low soil drainage. Other factors such as soil drainage, groundwater EC, and soil EC affected the decomposition process as well. Low soil drainage allowed for moisture to stay in the soil and thus increased the decomposition rate. Groundwater EC and soil EC also enhanced the decomposition process by increasing the absorbability of water by leaves and roots during the first stages of the decomposition process. The decomposition rate for the two-month experiment was faster in the subsoil than in the topsoil. In contrast, the decomposition rate for the eight-month experiment was faster in the topsoil than in the subsoil. No difference in the decomposition rate was found between the dry and the wet seasons.

Depending on the tissue structure of the species and their location, the percentage of tissue remaining and the decomposition rate correlated differently with elevation, flooding frequency, soil drainage, groundwater EC and soil EC. After two months of decomposition, the percentage of leaf tissue remaining of *Avicennia alba* during the dry season had a negative correlation with elevation and positive correlation with flooding frequency while the percentage of leaf tissue remaining of *Rhizophora apiculata* was positively correlated with soil drainage. After eight months of decomposition, the percentage of leaf tissue remaining of *Avicennia alba* was positively correlated with elevation and negatively correlated with flooding frequency. The percentage of leaf tissue remaining of *Rhizophora apiculata* was positively correlated with soil drainage and negatively correlated with groundwater EC, and the percentage of leaf tissue

remaining of *Ceriops decandra* had a negative correlation with groundwater EC and a positive correlation with soil EC.

The amount of litter fall and the distribution of species at the KV and MO study sites were discussed in chapter 8. The amount of litter fall was affected by the interactive effect of site by season and season by zone. Differences in the amount litter fall between the dry and the wet seasons were found at the KV site only. The amount of litter fall in the dry season at the KV site was significantly higher than in the wet season at the KV site and also higher than both the wet and dry seasons at the MO site. During the wet season at the MO site, zone 3 had a significantly higher amount of litter fall than zone 1 and zone 2. No difference in the amount of litter fall was found among the three zones at the KV site during the dry season. Overall, litter fall during the dry season was higher than the wet season. Litter fall was determined by the number of species that grow in each zone. In this study, litter fall was high in zones that had only a single species growing as in the case of *Rhizophora apiculata* in zones 3 at the KV and MO sites and *Avicennia alba* in zone 1 of the KV site.

Primary production of mangroves was estimated from the amount of litter fall as suggested by Lugo et al. (1975). Differences in litter fall depended mainly on the degree and frequency of tidal inundation (Twilley 1985, Twilley et al. 1986, Robertson 1989). The total calculated primary production at the KV site was higher than at the MO. The amount of litter fall was also found to be related to the number of species, soil EC, OM, total N and Eh. Zones with single species such as *Rhizophora apiculata* and *Avicennia alba* had a higher amount of litter fall. Low OM and low total N caused a low amount of litter fall while low Eh led to high amounts of litter fall.

Mangrove distribution was affected by differences in geographical and hydrological conditions (Chapman 1977, McKee 1995a, McKee 1985b and Ball 1980), in this study, the highest number of species was found in transition zones such as zones 2 at the KV and MO sites and in high elevation zones such as zone 1 at the MO site. Only four of the nine species (*Avicennia alba, Rhizophora apiculata, Ceriops decandra* and *Phoenix paludosa*) were dominant and successfully developed at the study sites. The remaining five species (*Avicennia officinalis, Exceocaria algallocha, Lumnitzera racemosa, Acrostichum* sp. and *Hibiscus* sp.) were found ubiquitously distributed, but did not heavily populate any specific zone. Species of *Avicennia alba* adapted well to low elevation areas. Therefore, they were a pioneer species and successfully developed in heavily inundated and newly formed mudflat zones. In contrast, *Rhizophora apiculata* was better adapted to areas that had medium to high elevation, low water inundation, and medium to highly compacted soil. Thus *Rhizophora apiculata* developed behind the pioneer species such as *Avicennia alba*. Meanwhile, *Ceriops decandra* was able to successfully develop due to its ability to adapt to a wide range of intertidal gradients including low to high elevation, medium to low water inundation, and medium to compacted soil. And finally, *Phoenix paludosa* could only be found in areas that had high elevation, rare water inundation, and dry compacted soil.

In conclusion, this research has provided some of the first analyses of the basic plant ecology of the Can Gio Mangrove Biosphere Reserve. As for mangroves outside of Vietnam, hydrology was the primary forcing function. Future research on these mangrove systems should be interested on the interactive effects of hydrological regime, photosynthesis and tree density on the mangrove restoration and flora-fauna biodiversity. In addition, the nutrients exchange

between mangrove ecosystem and adjacent areas need to be study in Can Gio Mangrove Biosphere Reserve.

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VITA

Loi Tan Le was born in Can Tho City, Vietnam, in May 1959 to Chieu Pham and the late Ty Le. He is married to Tuyet Nguyen and they have one daughter, Thu Le, and one granddaughter, Han Ngo. From 1975 to 1978, he was a student at Can Tho High School in Can Tho City. He entered Can Tho University in 1978 and received a Bachelor of Science degree in agronomy in 1982. After graduation he was employed as a researcher in the Agricultural College at Can Tho University and eventually became an instructor in 1984. In 1996, he entered Wageningen Agricultural University on a fellowship from the MHO-8 project on “Integrated Management of Coastal Resources in the Mekong Delta Vietnam” and earned a Master of Science degree in agronomy in 1998. Le came to the Department of Oceanography and Coastal Science at Louisiana State University in August 2001 through funding from the MHO-8 project under the direction and supervision of Professor Irving A. Mendelssohn to study the effect of hydrology on the structure and function of mangrove forests. After seven challenging years, including two years of doing research in the mangrove swamps of the Can Gio Mangrove Biosphere Reserve in Ho Chi Minh City, Vietnam, he will be receiving a Doctor of Philosophy degree in oceanography and coastal science in August 2008.