Spatial patterns of stand structure and soil properties of an *Avicennia marina* (Forsk.) Vierh. dominated mangrove forest in the Mekong Delta, Vietnam

MSc-Thesis

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Abstract

Despite the ecological and economic relevance of mangrove forest ecosystems, its areal extent has declined significantly within the past 50 years (Duke 2007, Alongi 2002, Lewis 2005). Although reforestation or restoration efforts have been undertaken throughout the world, there is still a lack of scientifically based information on site requirements of different mangrove species (Saenger 2010). In order to gain more detailed information about the site requirements of the mangrove *Avicennia marina* (Forsk.) Vierh., the objective of this study was to analyze and identify spatial patterns of stand structure and soil properties along a gradient of depth and frequency of tidal inundation of an *A. marina* dominated mangrove forest.

The stand parameters addressed in this study were basal area (BA), quadratic mean diameter (d_g), above-ground biomass (AGB), stand height (H_g, H_o) and stem density (N). The soil parameters addressed in this study were soil texture, salinity as measured by the electrical conductivity of the saturation extract (EC_e), total dissolved salts (TDS) and osmotic potential (ψ_π) as well as soil water content (%) and organic carbon and nitrogen stocks and concentrations.

Based on the results, a seaward-, transitional-, meso-, and landward zone could be distinguished. *A. marina* showed a stunted growth form in the seaward zone, which was assumed to be due to frequent tidal inundation and hence frequent anoxic soil conditions (see Lara & Cohen 2006). In the transitional- to meso-zone, stands appeared rather well developed with above-ground biomass of about 100 Mg ha^{-1}, basal areas of about 20 m^2 ha^{-1} and a dominant height of about 9 m. In the landward zone, basal area, stand height and above-ground biomass were relatively lower, which was assumed to be due to higher salinities, soil texture and human impact.

Successional dynamics and growth were assumed to be the underlying cause of spatial patterns of stand structure, whereby accretion processes, depth and frequency of tidal inundation and the mutual interaction of stand and soil were assumed to be the underlying causes of spatial patterns of soil properties. Regarding site-species matching, the results are in line with what Hutchings & Saenger (1987) and Imbert et al. (2000) found, supporting the evidence that *A. marina* can tolerate a wide range of salinity. Furthermore, the present study adds information on soil texture, the degree of waterlogging as well as carbon and nitrogen concentrations of soils where *A. marina* occurs naturally.

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1. Introduction

1.1. Background

Mangrove forest ecosystems occur on tropical and subtropical shorelines throughout the world, where they constitute one of the dominant ecosystem types in marine or brackish coastal regions (Tomlinson 1986, Saenger 2010). Being typically inundated by tidal action, these ecosystems have been described as 'coastal woodlands', 'mangals' or 'mangrove forest' as the can form extensive and productive forests where conditions are optimal. Shrubby or dwarfed growth forms might occur, where conditions are less optimal (Saenger 2010). The term 'mangrove' itself is commonly used in two ways. On the one hand it refers to an individual plant species. On the other hand it is used to describe an assemblage of plants or a plant community.

Mangrove forest ecosystems provide various environmental services and functions. Due to their entangled above-ground root system, mangrove forests can support the protection of shorelines from erosion by reducing wave energy and water velocity (Mazda et al 1997, Saenger 2010). The reduction of water velocity can furthermore lead to sediment deposition in the root system (Saenger 2010). According to Oliver (1982), mangroves can offer windbreak and storm protection due to a higher frictional drag over the canopy than over surface water, which causes a decrease in wind speed land inwards.

Besides these functions, mangrove ecosystems are of importance as a source of various natural resources. Being a habitat for a variety of animal and plant species, mangrove ecosystems are of ecological as well as economic relevance for fisheries, timber and fuelwood production, agricultural resources and forage, pharmaceutical and energy resources (Saenger 2010, Mudiryarso 2009, Ellison 2000).

Despite their ecological and economic relevance, deforestation has led to a significant decline in the area covered by mangroves. The areal extent of mangroves is estimated to have declined by 30 - 50 % over the past 50 years (Duke et al 2007, Alongi 2002). Lewis (2005) argues that the areal extent of mangroves has declined by 2 % per year between 1980 and 1990 and 1 % per year between 1990 and 2000, based on a total extent of 146,530 km² in 1980.

Land-use change, especially the conversion of mangrove forest to aquaculture, urbanization, coastal development and over-harvesting and thus degradation are seen to be the main drivers of mangrove deforestation (Duke et al 2007, Donato et al 2011).

Restoration of degraded or deforested mangrove sites has only recently received increasing attention, although mangrove restoration projects have been implemented for decades (Lewis 2005, Stubbs & Saenger 2002). Ellison (2000) states that mangrove restoration projects have been implemented throughout the world, notwithstanding success or failure.

The main objectives of mangrove restoration have often been or are timber production, shoreline and storm protection, fisheries and wildlife enhancement as well as social enrichment and ecological restoration (Saenger 2010, Lewis 2005, Field 1996).

Ellison (2000) has raised the question: "Mangrove Restoration: Do we know enough?" In his review of mangrove restoration projects he came to the conclusion that existing data is sufficient to undergird restoration efforts. This view is supported by Field (1998), stating that there are a vast number of scientific papers on mangrove biology and ecology, though he argues that there is "little attempt to extrapolate ecological findings from normally functioning mangrove ecosystems to those existing under stressed conditions". As this view is generally supported by the author, there are - on the other hand – only a few studies that analyze mangrove forest ecosystems while taking growth limiting factors and soil properties according to quantifiable and defined criteria into account (see Imbert et al. 2000, Hutchings & Saenger 1987). Mangrove site characteristics and corresponding mangrove forest structures have often been and still are classified by qualitative criteria, e.g. zonation concepts (see Watson 1928, Tomlinson 1986), where sites are classified by the presence of mono-specific zones parallel to the shoreline. According to Saenger (2010), there is a lack of information on the relationship of mangrove forest and soil properties.

Stubbs & Saenger (2002) promoted the "application of forestry principles to the design, execution and evaluation of mangrove restoration projects" and highlighted the concept of "Site-Species Matching". In order to select suitable species for any site, it is necessary to assess the soil properties and the factors that determine the site conditions. Furthermore, the selection of suitable species for a given site requires knowledge about the ecological characteristics and site requirements of a certain species and its capability to cope with growth limiting factors. Stubbs & Saenger (2002) pointed out that the most important site factors of mangrove sites are probably.

- Depth and frequency of tidal inundation
- Degree of waterlogging (redox-potential of the soil (Eh), soil water content (%))
- Salinity of pore water

Hence, it seems appropriate to analyze mangrove forest ecosystems taking the above mentioned factors into account. Conclusions about site requirements of a species can be made by analyzing the environment where a species occurs naturally. Saenger (2010) supports the view that examining the soil conditions in an area of a specific species natural occurrence allows insights under which conditions this specific species performs optimally. He furthermore argues that there is a lack of detailed information on the soil-mangrove relationship, whereby especially the tolerance of mangroves to various salinity levels is still under-studied.

1.2. Objectives

The main objective of this study is to analyze and identify gradual changes in stand structure and soil properties of a mangrove forest with increasing distance from the seaward edge. This approach is based on the hypotheses that depth and frequency of tidal inundation decrease with increasing distance from the seaward edge, which is having an impact on stand structure and soil properties. The output of this study shall help to improve and broaden existing knowledge about mangrove ecology by linking structural characteristics of the forest to soil properties and site conditions.

The focus of this study is a mangrove forest at the coastline of the Mekong Delta, Vietnam, which has evolved from natural succession and is dominated by the mangrove *Avicennia marina* (Forssk.) Vierh.. Besides the assessment and analysis of forest structural parameters, including stem density, basal area, above-ground biomass, mean diameter and diameter distributions, stand height, the assessment and analysis of soil properties is focused on the salinity of pore water and soil water content. The assessment of depth and frequency of tidal inundation exceeded the possibilities of this project, as it needs to be monitored over a full year. Furthermore, soil texture, carbon and nitrogen concentrations and stocks as well as soil bulk density are analyzed in order to provide a wider context for interpretation and comparison with other studies. Sherman (1998) found that spatial patterning of vegetation is significantly correlated to total nitrogen and dissolved organic carbon concentrations.

Based on the results it shall be discussed whether there are spatial patterns in stand structure and soil properties and how these can be explained. The questions addressed in this study are:

- How do stand structure and soil properties change with increasing distance from the seaward edge? Are spatial patterns of stand structure and soil properties identifiable?
- How can changes in structural characteristics and soil properties be explained?
- Is there a direct correlation between stand structure and soil properties?
- What conclusions can be made regarding site-species-matching?

In the following, an introduction is given to climate, soil forming processes in the Mekong Delta and mangrove ecology, whereby special attention is paid to the ecology of *Avicennia marina*. As this species is in the focus of this study, existing knowledge about its ecology is reviewed.

The data collection has been conducted within the frame of an internship in the mangrove restoration project "Sustainable Management of Coastal Forest Ecosystems in Bac Lieu Province, Vietnam", which is implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH on behalf of the German Federal Ministry of Environment, Nature Conservation and Nuclear Safety (BMU).

1.3. Description, ecology and distribution of *Avicennia marina* (Forsk.) Vierh.

As mentioned in the previous chapter, the term mangrove is commonly referred to specific plant species on the one hand, and to specific plant communities on the other hand. According to Saenger (2010) the mangrove flora consists of about 39 genera in 26 families. However, Duke (1998) distinguished between 28 genera, out of which 17 species are growing exclusively in a mangrove environment.

As the mangrove environment is characterized by periodically or permanently water logged and hence anoxic soils as well as saline soil water, plants show numerous morphological, reproductive and physiological adaptations to these conditions. A detailed review of several adaptation mechanisms is given in Saenger (2010) and Tomlinson (1986), as only some of these mechanisms shall be discussed here with special reference to *Avicennia marina*.

Within the genus *Avicennia* L., six species can be distinguished within the Indo-Pacific and East-African region (Moldenke 1960, 1967 as cited by Tomlinson 1986). Among those, *A. marina* has the broadest longitudinal and latitudinal distribution (Tomlinson 1986). The genus

Avicennia L. is widely distributed and can be found in mangrove forests of Africa, South America, Asia, Australia and throughout South East Asia (Giessen et al. 2007).

A. marina (Forsk.) Vierh. appears as a tree of up to 10 m height where conditions are suitable (occasionally up to 30 m). Where conditions are less optimal this species also appears as a shrub. *A. marina* can be identified by its smooth, green-grey mottled and commonly peeling off bark and its elliptic-oblong or oblong-obovate leaves (Giessen et al. 2007). The fruit is round to heart-shaped, greyish green and measures about 2 cm across. The flowers are commonly orange, small (5 -8 mm) and waxy. They are identifiable by the odour of a rotten fruit (Tomlinson 1986).

Species of the genus *Avicennia* L. develop aerial roots. Pneumatophores arise from the horizontal cable root system and extend upward above the soil surface (Saenger 2010). According to Tomlinson (1986), the height of these roots is limited and pneumatophores of more than 30 cm in height are rarely found. The underlying, physiological cause for the development of such a root system can be explained by the anaerobic soil conditions and the need for atmospheric oxygenation (Tomlinson 1986).

Seeds from this crypto-viviparous species germinate while they are still attached to the mother tree. Once the precociously developed seedling (propagule) falls from the tree, it might be dispersed by seawater and establishes when conditions are suitable (Saenger 2010, Tomlinson 1986).

A. marina is a pioneer species and is often found on sheltered shores (Giesen et al. 2007). According to Clarke & Myerscough (1993), the intertidal distribution ranges between mean high water and mean sea level in esturaries in South-Eastern Australia. Dahdouh-Guebas et al. (2004) describe a disjunct zonation pattern in landward and seaward zones along the coast of Kenya. A. marina is commonly described as a highly salt tolerant species, due to its salt secreting glands (Clough 1984, Hutchings & Saenger 1987). Clough (1984) found that *A. marina* seedlings grew poorly in the absence of sodium chlorides, though growth was stimulated in 25 % seawater.

1.4. Climate

Table 1 shows the daily mean minimum and maximum temperatures as well total mean precipitation of Ho-Chi-Minh-City from 1906-1990 (WMO, 2012). Ho-Chi-Minh-City is in about 200 km distance to the study site. According to the Köppen-Geiger Climate Classification, the climate can be classified as a Tropical Monsoon Climate. The climate is characterized by a 4-5 month dry season from December to March/April with mean monthly precipitation below 50 mm. The mean annual precipitation is about 1931 mm. The mean annual daily minimum and maximum are 23.7 mm and 32.3, respectively.

Table 1: Daily mean minimum and maximum temperature (°C) and total mean precipitation (mm) of Ho-Chi-Minh City from 1906-1990 according to World Meteorological Organization (2012)

Month	**Mean temperature (°C)**		**Mean total precipitation (mm)**
	daily minimum	**daily maximum**	
Jan	21.1	31.6	13.8
Feb	22.5	32.9	4.1
Mar	24.4	33.9	10.5
Apr	25.8	34.6	50.4
May	25.2	34.0	218.4
Jun	24.6	32.4	311.7
Jul	24.3	32.0	293.7
Aug	24.3	31.8	269.8
Sep	24.4	31.3	327.1
Oct	23.9	31.2	266.7
Nov	22.8	31.0	116.5
Dec	21.4	30.8	48.3
Mean/Total	**23.7**	**32.3**	**1931**

1.5. Soil

According to Chiem (1993), most landforms occurring in the Mekong Delta have been shaped by transgression and regression during the Holocene. With a few exceptions, the Delta is made up of unconsolidated sediments. Chiem (1993) distinguished five landforms within the Mekong Delta, out of which the coastal complex – as defined by Chiem (1993) – can be subdivided into sand ridges parallel to coastline, coastal flats with an elevation of 1 to 1.5 m above sea level, inter-ridges below or at mean sea level and mangrove swamps, which are dominant along the coast. This view is in line with Ta et al. (2002) that the lower delta plain is characterized by a well-developed ridge system and mainly influenced by marine processes. Chiem (1993) points out that the processes that have shaped the Delta still continue, whereby silt deposits extend the shoreline. According to Ta et al. (2002) these deposits result from sediments discharged by the Mekong River, which have been transported southwestwards by north-eastern monsoon winds. This situation is particularly the case for the examined location. However, beside these accretion processes, erosion of the shoreline is taking place simultaneously at other locations close to the examined study site.

With reference to the FAO World Reference Base for Soil Resources (2006), soils along the shoreline can be classified as Fluvisol. Fluvisols are defined as genetically young, azonal soils in alluvial, lacustrine or marine deposits. They are characterized by a weak horizon differentiation, though a topsoil horizon may occur. In general, Fluvisols are a characteristic soil type of alluvial plains, river fans and tidal marshes, where they are flooded periodically. These characteristics are in line with the soils encountered at the study site.

2. Methods

2.1. Study site

The study site is located at the coastline of the Mekong Delta in southern Vietnam (Bac Lieu Province) between 9°08'48.69'' N and 105°36'51.45'' E as south-western and 9°09'57.40'' N and 105°38'35.46'' E as north-eastern corner point. Figure 1 illustrates the location of the study site.

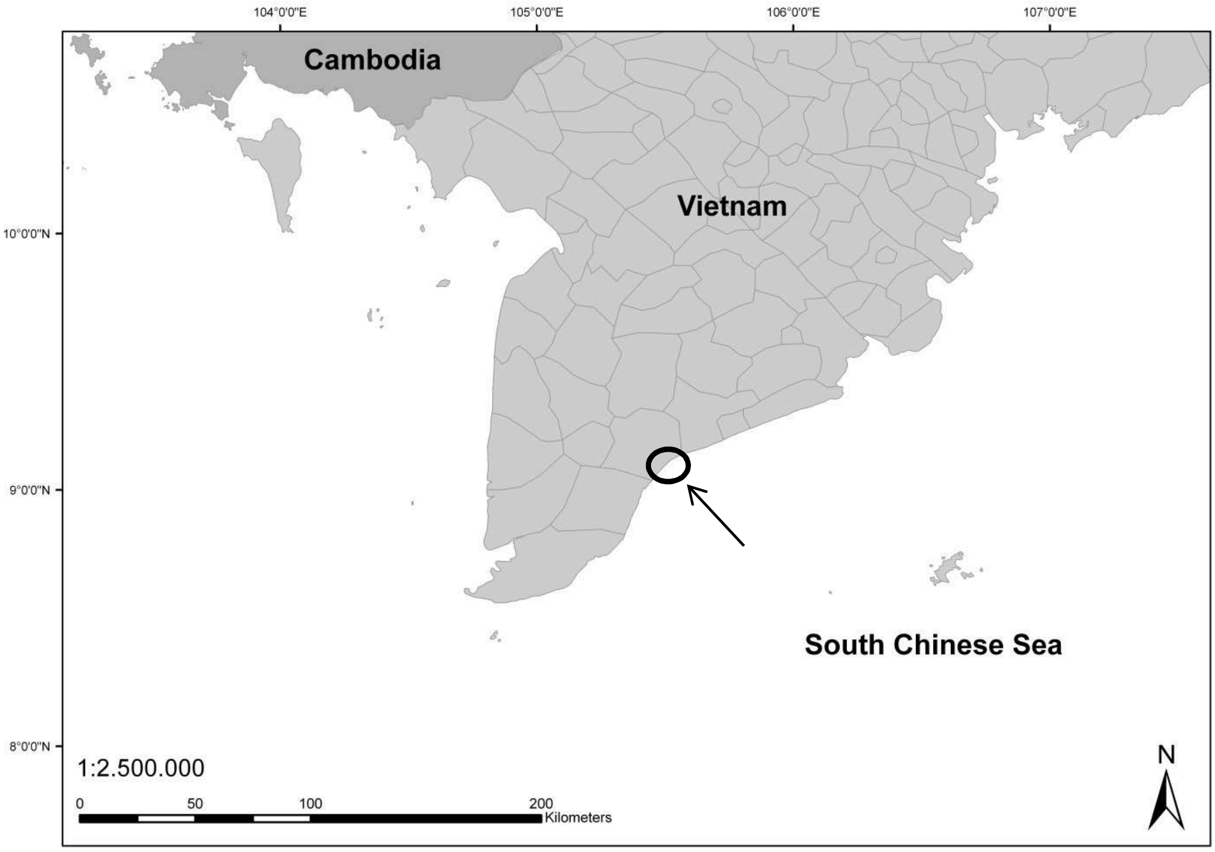

Figure 1: Location of the study site

The study site is bordered by the open sea (South Chinese Sea) to the seaward side; to the landward side it is bordered by aquaculture ponds and plantations of mainly *Rhizophora spp*. The closest Mekong river mouth is located about 75 km in east-northeastern direction in Soc Trang Province; the examined forest does not receive any fresh water input from a river. Tides at the coastline of Bac Lieu are diurnal. With reference to Clough (2011), the examined forest is situated in an accretion area. The site has recently developed during the past 40 years as marine sediments were deposited that extended the shoreline. The accreted land was then successively colonized by the mangrove *Avicennia marina*. The course of the shoreline since 1965 can be found in Annex A. According to Nam (pers. communication 2011), within Vietnam, *A. marina* is most abundant in Bac Lieu Province.

2.2. Sampling & plot design

Within the study site, two spatially divided sub sites were selected. Figure 2 shows the sampling design.

Figure 2: Sampling design

The criteria for selecting the sites were at first that the forest is at least of 700 m in width from the coastline land inwards, in order to allow the sampling of stand structure and soil characteristics over a wider range. Though the forest is of natural origin, the forest is disturbed to a certain degree. Therefore, sites were selected, where anthropogenic disturbance is minimal. Within both sites, sampling plots were laid out along five straight transect lines perpendicular to the coastline; resulting in a total of 10 transect lines (n=10). The location of each transect line was selected randomly for each sub site. Along each transect line, sample plots were laid out in 50 m, 150 m, 300 m, 500 m and 700 m distance from the seaward edge. As transect lines were selected randomly, each plot in a certain distance from the seaward edge represents an independent sample. In total 49 sample plots were assessed, as one sample plot (in 700 m distance from the seaward edge) was not accessible.

At each sample point, all trees with a DBH ≥ 3 cm were recorded in circular sampling plots of five meter radius for species and DBH. The height of the two to three largest, medium and smallest trees were measured, respectively, resulting in 6 to 9 height measurements per plot.

Furthermore, one soil sample was taken at each sample point, using a 1 m open-face soil auger in order to minimize sample disturbance and compaction. Each soil sample consisted of four sub-samples of six centimeter in length, taken in 0-15 cm, 15-30 cm, 30-60 cm and 60-100 cm soil depth. The samples were taken in the mid of the depth interval, respectively. As the volume of the auger was known and each sample taken was of approximately the same volume, bulk density could be calculated.

The data collection has been conducted from May to June 2011. None of the sample plots was inundated by tidal water during data collection.

2.3. Data analysis

In order to allow an analysis of stand structure and soil properties in different distances from the seaward edge, all calculations were made separately for each distance. This was possible as all sample plots and soil samples in a certain distance were independent of each other. A one-way analysis of variance (ANOVA) was conducted in order to check if means in different distances from the seaward edge were significantly different. A Tukey HSD Post-Hoc Test was conducted to check which means were significantly different from each other. All statistical analyses have been conducted by using the software STATISTICA 10.

2.3.1. Stand structure

In order to analyze structural characteristics of the forest, values per plot of number of stems per hectare (N ha^{-1}), basal area per hectare BA (m^2 ha^{-1}), quadratic mean diameter d_g (cm) and above-ground biomass AGB (Mg ha^{-1}) were scaled up to per hectare values (except quadratic mean diameter d_g) and arithmetic mean, standard deviation, standard error and relative standard error were calculated for each distance from the seaward edge respectively. Dominant height (H_o, *Weise`sche* Oberhöhe) and height of mean basal area tree (H_g) were derived from regression analysis. Dominant height (H_o) is defined as the height of the mean basal area tree of the 20% thickest stems (Nagel, 2001). The structural parameters named above were calculated as follows.

Number of stems per hectare (N ha^{-1}):

$$N = \sum_{i=1}^{n} * EF \quad (1)$$

Basal area per hectare BA (m^2 ha^{-1}):

$$G = \sum_{i=1}^{n} g_i * EF \quad (2)$$

Quadratic mean diameter d_g (cm):

$$d_g = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \quad (3)$$

Above-ground biomass per stem (see Comley & McGuiness, 2005):

$$w_i = 0.308 * d_i^{2.11} \; (r^2 = 0.97) \quad (4)$$

Above-ground biomass per hectare AGB (Mg ha^{-1}):

$$AGB = \sum_{i=1}^{n} w_i * EF \quad (5)$$

Whereby:

$n_i = individual\ stem$

$g_i = basal\ area\ of\ an\ individual\ stem$

$d_i = diameter\ at\ breast\ height\ (DBH) of\ an\ individual\ stem$

$w_i = above - ground\ biomass\ of\ an\ individual\ stem$

$EF = expansion\ factor$

To analyze tree height (*H*) as a function of DBH, a regression analysis was conducted to estimate the parameters $(a_{0,} a_1)$ of stand height curves based on the following equation.

$$H = a_0 + a_1 * \ln(DBH) \quad (6)$$

The regression analysis was conducted separately for each distance from the seaward edge.

2.3.2. Soil properties

Sample preparation

Soil samples were oven-dried at 40 °C for 48 hours at the day of collection. Comparison with samples dried at 105 °C has shown a residual, acceptable water content of below 1 percent (see Mudiryarso et al. 2009). Each samples weight was determined before and after drying to obtain fresh and dry weight. Each sample was then ground in the laboratory for further analysis.

Soil Sample Analysis

Samples from six transect lines (n=6) were analyzed for particle size distribution, electrical conductivity (EC) as a measure of salinity, osmotic potential (ψ_{π}) as a measure of salinity, soil water content (soil water content as % of fresh/dry weight), bulk density (ρ), organic carbon concentration (C_{org}) and nitrogen (N) concentration. Different analysis procedures for these parameters are explained in the following.

For statistical analysis, mean values of each parameter were calculated for each sample by the weighted mean of sub-samples, which represented different soil depths. In order to provide a sufficient amount of soil material for the analysis of particle size distribution, samples from three transects were combined to one sample (n=1).

Analysis of particle size distribution

The analysis of particle size distribution was conducted by a combined sieving and sedimentation analysis (HFA 2005). The share of sand (>0.063 mm) was obtained by sieving. The share of silt (>0.002 mm; <0.063 mm) and clay (<0.002 mm) was obtained by sedimentation in water-filled cylinders at a constant temperature of 25 °C. This method is based on STOKE`s law, whereby the time of sedimentation is proportional to the size the particle (HFA 2005, Scheffer & Schachtschabel 2002).

Salinity of pore-water

As the salinity of pore-water constitutes a growth limiting factor in mangrove ecosystems, it is a fundamental parameter in mangrove ecology. However, salinity can be expressed in a wide range of different units, depending on the particular interest. Salinity is commonly expressed as a density based measure of salt concentrations (e.g. as parts per thousand), although this is only an approximate (Saenger, 2010). According to Rhoades (1999), soil salinity is defined and can be assessed by the electrical conductivity of the extract of a saturated soil-paste sample (EC_e), being a practically and easily measurable index of the concentration of ionized solutes in an aqueous sample. However, Saenger (2010) argues that conductivity is a similarly approximate measure and states that salt concentrations (e.g. in g L^{-1}) or osmolality (e.g. in milliosmol kg^{-1}) might be a more appropriate measure, whereby the latter can be expressed as the osmotic potential ψ_π (e.g. in MPa). The osmotic potential ψ_π is defined as the physical work required that allows the diffusion of a specific amount of water through a semi-permeable membrane. The share of the osmotic potential on the total water potential is dependent on the amount of dissolved salts in the solution (see Scheffer & Schachtschabel 2002, Slatyer & Taylor 1960). This view is in line with Mitlöhner (1997), who argues that osmolality and the corresponding osmotic potential is a more accurate measure of salinity affecting the plant, as it reflects all substances that are osmotically relevant to the plant, including salts, sugars and organic acids. In order to be able to provide a wider range of comparable data, salinity of pore water shall be expressed as the electrical conductivity of the saturated-paste extract (EC_e), as total dissolved salts (TDS) and as the osmotic potential (ψ_π). However, in the present case a direct measurement of all three parameters was not possible to do a limited amount of soil material. Results for each of the three parameters were obtained as follows.

As the amount of soil material per sample was not sufficient to prepare extracts of a saturated soil-paste sample, samples were diluted by distilled water to a 1:5 soil-water ratio. Measuring the electrical conductivity of a 1:5 soil-water ratio (EC 1:5) is a widely used and well excepted method of determining salinity (Rhoades et al 1999, Slavich & Petterson 1993, Sonmez et al 2008). 15 ml of distilled water (EC = 0.5 µS cm^{-1}) were added to 3 g of soil in a screw lid container. The soil water suspensions were then shaken by hand. After 23 hours, the suspensions were shaken again automatically by a reciprocal shaker for 1 hour. Afterwards, the samples were centrifuged at 1400g for 15 minutes (see Visconti et al 2010). The EC was then measured with a WTW Electrical Conductivity Meter in the water protrusion. To convert the results of EC 1:5 (mS cm^{-1}) measurements to EC_e (dS m^{-1}), the following equation by Sonmez et al. (2008) was applied:

$$ECe = 7.36 * EC(1:5) - 0.24 \tag{7}$$

Determining the total amount of water-soluble salts required more soil material per sample than it was available. According to Simon et al. (1994), the total amount of dissolved salts TDS (g L^{-1}) can be estimated by the EC_e (dS m^{-1}) according to the following equation (r^2 = 0.99).

$$TDS = 490*EC_e \quad (r^2=0.99) \tag{8}$$

Simon et al. (1994) argue that this equation can be applied to all saturation extracts regardless of the concentration and types of ions present, although the relationship is not completely linear. This issue is discussed in detail in Simon et al. (1994).

In order to measure the osmotic potential (ψ_π) of the soil solution, 7 ml of de-mineralized water were added to 1 g of soil. The suspensions were shaken and stored at 55 °C for 24 hours and centrifuged at 1400 g for 15 minutes (see Mitlöhner 1997). 1.5 ml of the water protrusion was pipetted into plastic containers and stored in the fridge. Based on the concept of freezing point depression (see Kreeb 1990), osmolality (milliosmol kg^{-1}) was then measured with a semi-micro osmometer (Knauer, Germany). According to Kreeb (1990), the osmotic pressure π^* (= -osmotic potential ψ_π) in [atm] of a solution is correlated to the freezing point depression (Δt [°C]) of the solution and can be calculated according to the following equation.

$$\pi^* = 0.021 * (\Delta t)^2 - 12.06 * \Delta t \tag{9}$$

Mitlöhner (1997) refers to Walter & Kreeb (1970) that the osmotic pressure (π^*) obtained by equation (9) refers to a temperature of 0 °C. Hence, a correction due to the effect of temperature on the osmolality of the solution is necessary and was done by (see Mitlöhner 1997):

$$\pi^*_{t\,°C} = \pi^*_{0\,°C} * (1 + \frac{t_{°C}}{273}) \tag{10}$$

The resulting osmotic pressure was converted from [atm] to [MPa]. Due to the limited amount of soil sample material, osmolality measurements were only conducted for 52 samples. As the soil material used for osmolality measurements was from the same soil samples that have been used for electrical conductivity measurements, a regression analysis was conducted to check the relationship between electrical conductivity and osmolality. There is a linear relationship between both parameters as shown in Annex B. The regression equation obtained was:

$$\text{osmolality}\left(\frac{\text{milliosmol}}{\text{kg}}\right) = -0.028 + 12.4144 * \text{EC}(1:5) \qquad (r^2 = 0.95) \tag{11}$$

This equation was used to calculate the corresponding osmolality of electrical conductivity measurements. The values obtained were then converted to the corresponding osmotic potential, adjusted to the actual soil water content (as % of dry weight) encountered in the field.

Soil water content

The gravimetric soil water content is commonly used as an index for soil moisture and is defined as the ratio of the mass of water to the mass of dry soil. It was calculated by the following formula (Scheffer & Schachtschabel, 2002), whereby (M_w) is the fresh weight and (M_d) the dry weight of the sample.

$$\theta_g = (M_w - M_d)/M_d \qquad (12)$$

However, in some studies the soil water content is expressed as the share of mass of water on the total mass (see Hutchings & Saenger, 1987).

$$\theta_m = (M_w - M_d)/M_w \qquad (13)$$

In order to allow comparisons with other studies, soil water content was calculated by both equations, whereby results of equation (12) are given in Annex E-6e and the results of equation (13) are given in chapter 3.2.3.

Bulk density

The soil bulk density is defined as the ratio of the soils dry mass to its volume (Scheffer & Schachtschabel, 2002). The bulk density of each sample was calculated by:

$$\rho_b = \frac{M}{V} \qquad (14)$$

Organic carbon and nitrogen

Carbon and nitrogen content of soil samples was analyzed by the Elementar Vario El C-N Analyzer, whereby samples are combusted in a stream of pure oxygen at 1000 °C (see Schumacher 2002). As this method is measuring the total amount of carbon, the samples were treated prior to the analysis to remove carbonates (Schumacher, 2002). In order to remove all carbonates, 5 ml of 5% HCl solution were added to 5 g of soil. The samples were heated on a heating plate at 70 °C to volatilize the HCl solution. The treatment has shown that all samples contained carbonates. Afterwards samples were dried at 60 °C to constant mass for 24 hours and analyzed for C and N concentrations. The respective C and N percentages were multiplied by bulk density (ρ_b) and depth of layer (m) to obtain the total amount for 0 – 100 cm soil depth.

3. Results

3.1. Stand structure

3.1.1. Basal area

Figure 3 shows the mean, standard deviation and outliers of basal area (m² ha^{-1}) in different distances from the seaward edge. Standard error, relative standard error as well as sample size are shown in table 2.

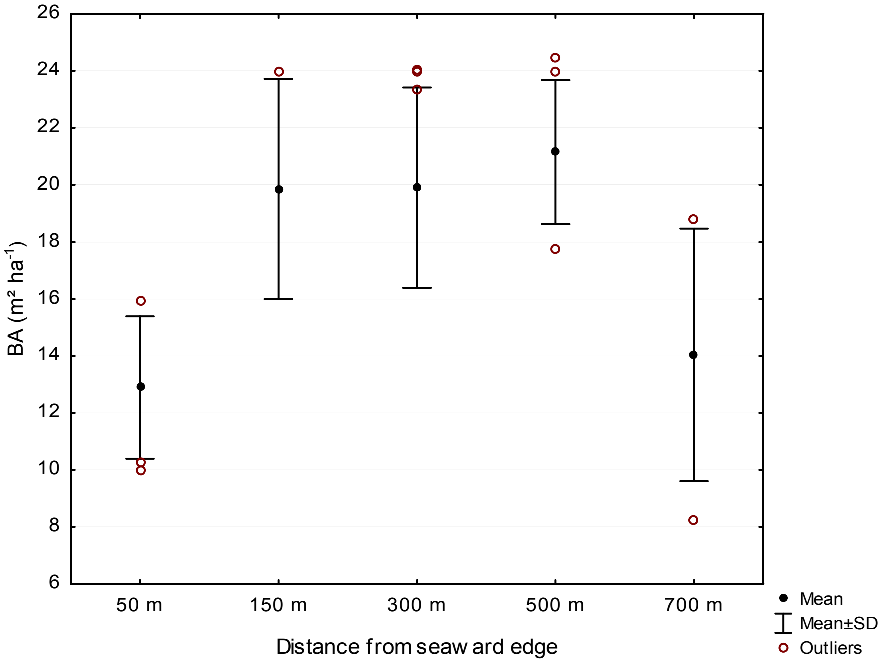

Figure 3: Mean, standard deviation and outlier values of basal area (m² ha^{-1}) in different distances from the seaward edge

Basal area first increases from 50 m (12.89 m² ha^{-1}) to 150 m (19.86 m² ha^{-1}) distance, then stays similarly between 19.86 and 21.15 m² ha^{-1} as it decreases again in 700 m distance from the seaward edge (14.03 m² ha^{-1}). The estimations of means are quite robust with a relatively low standard error. Differences between means are significant (ANOVA, $p < 0.01$). Similar mean basal areas in 50 m and 700 m distance from the seaward edge are significantly different from similar mean basal areas in 150 m, 300 m and 500 m distance (Tukey HSD Post-Hoc Test, $p < 0.01$). There are no significant differences between the latter.

Table 2: Mean, standard deviation (SD), standard error (SE), rel. standard error (SE%) & sample size (n) of basal area (m² ha^{-1}) in different distances from the seaward edge

Distance	Mean (m² ha^{-1})	SD	SE	SE%	n
50 m	12.89	2.50	0.79	6.13 %	10
150 m	19.86	3.86	1.22	6.15 %	10
300 m	19.91	3.51	1.11	5.58%	10
500 m	21.15	2.53	0.80	3.78%	10
700 m	14.03	4.43	1.48	10.52%	9

3.1.2. Stem density

Figure 4 shows mean and standard error of stem density (N ha^{-1}) in different distances from the seaward edge. Standard deviation, relative standard error as well as sample size are shown in table 3.

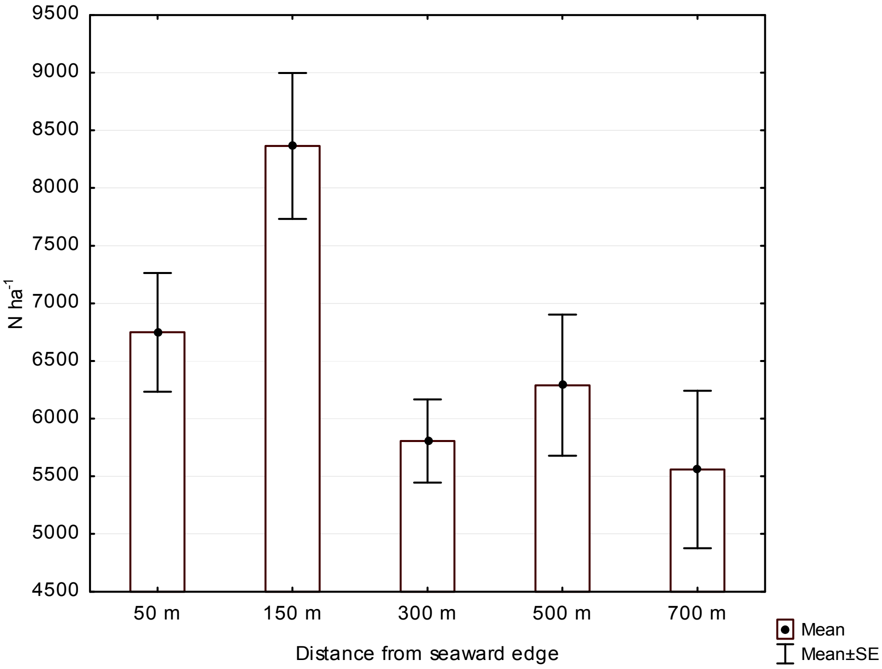

Figure 4: Mean and standard error of stem density (N ha^{-1}) in different distances from the seaward edge

Stem density (N ha^{-1}) increases from 50 m (6748 N ha^{-1}) to 150 m (8365 N ha^{-1}), showing a peak in 150 m distance. Stem densities (N ha^{-1}) in 300 m, 500 m and 700 m distance are generally lower and range between 5559 and 6289 N ha^{-1}. Differences between means are significant (ANOVA, $p < 0.01$). Differences in stem density are only significant for means (Tukey HSD Post Hoc Test, $p < 0.05$) between 150 m and 700 m distance from the seaward edge. The lack of significant differences between the other groups is due to larger variances within each group than between groups. Especially in 150 m, 500 m and 700 m distance from the seaward edge the variance of stem density is relatively large.

Table 3: Mean, standard deviation (SD), standard error, rel. standard error (SE%) and sample size (n) of stem density (N ha^{-1}) in different distances from the seaward edge

Distance	Mean (N ha^{-1})	SD	SE	SE%	n
50 m	6748.17	1623.90	513.52	7.61%	10
150 m	8365.18	1997.95	631.81	7.55 %	10
300 m	5831.44	1083.38	342.59	5.87%	10
500 m	6289.80	1931.15	610.68	9.71%	10
700 m	5559.81	2048.10	682.70	12.28%	9

3.1.3. Quadratic mean diameter

Figure 5 shows the mean, standard deviation and outlier values of quadratic mean diameter d_g (cm) in different distances from the seaward edge. Standard deviation, relative standard error as well as sample size are shown in table 4.

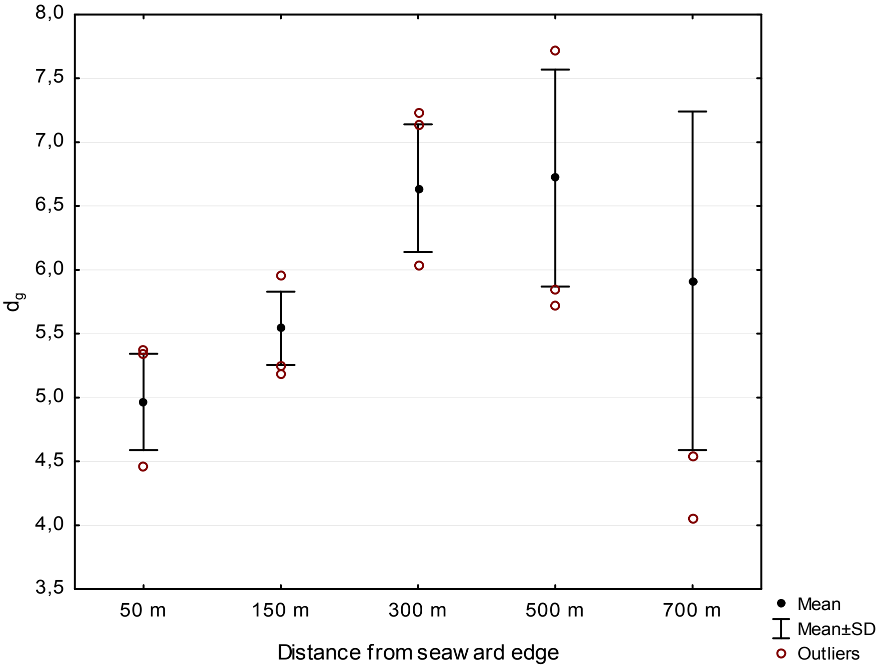

Figure 5: Mean, standard deviation and outlier values of quadratic mean diameter (d_g) different distances from the seaward edge

The quadratic mean diameter (d_g) increases constantly with increasing distance from the seaward edge, showing a peak in 300 m (6.64 cm) to 500 m (6.72 cm) distance, while it decreases again in 700 m (5.91 cm) distance. The latter is also showing the highest variance in quadratic mean diameter. In this case an analysis of variance (ANOVA) was not conducted due inhomogeneity of variances (Levene Test, $p < 0.01$). Variance homogeneity is a necessity for this test statistic. However, due to a relatively low standard error, the estimations of means can be seen as quite robust. Diameter distributions for each distance can be found in Annex D.

Table 4: Mean, standard deviation (SD), standard error (SD), rel. standard error (SE%) and sample size (n) of quadratic mean diameter d_g (cm) in different distances from the seaward edge

Distance	Mean (cm)	SD	SE	SE%	n
50 m	4.97	0.38	0.12	2.40%	10
150 m	5.54	0.29	0.09	1.64%	10
300 m	6.64	0.50	0.16	2.38%	10
500 m	6.72	0.85	0.27	4.00%	10
700 m	5.91	1.33	0.44	7.47%	9

3.1.4. Above-ground biomass

Figure 6 shows mean and standard error of above-ground biomass (Mg ha^{-1}) in different distances from the seaward edge. Standard deviation, relative standard error as well as sample size are shown in table 5.

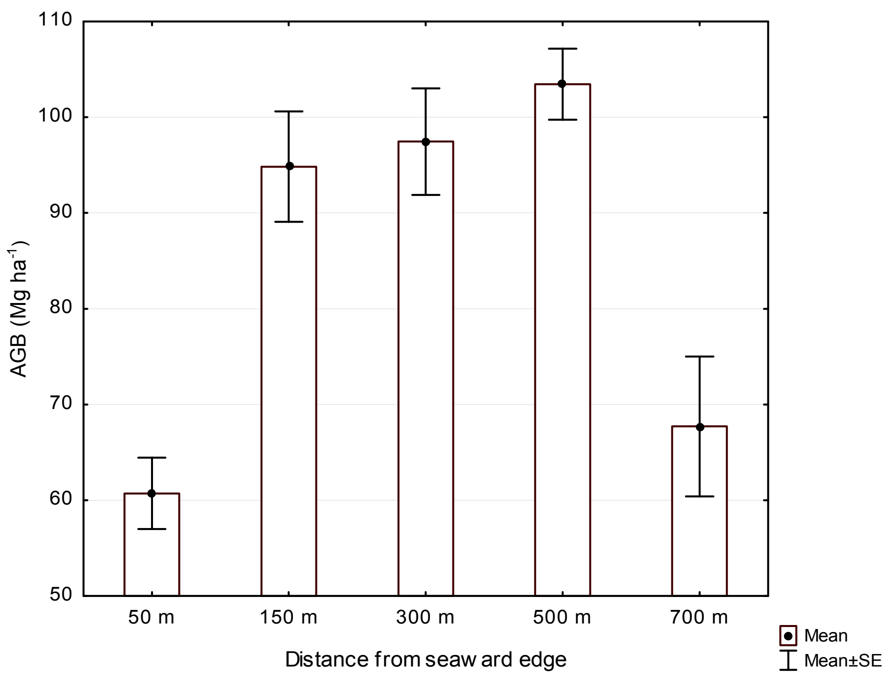

Figure 6: Mean and standard error of above-ground biomass (Mg ha^{-1}) in different distances from the seaward edge

Mean above-ground biomass increases from 50 m (60.72 Mg ha^{-1}) to 150 m (94.83 Mg ha^{-1}) distance from the seaward edge, while it stays similar from 150 m to 500 m distance from the seaward edge between 94.83 and 103.44 Mg ha^{-1}. It decreases significantly in 700 m distance

(67.71 Mg ha^{-1}). The estimations of means are quite robust due a relatively low standard error, although the variances can be relatively high. There are significant differences between means of above-ground biomass in different distances from the seaward edge (ANOVA, $p < 0.01$). Mean above-ground biomass (Mg ha^{-1}) is similar in 50 m and 700 m distance and significantly different from similar means in 150 m, 300 m and 500 m distance (Tukey HSD Post Hoc Test, $p < 0.01$).

Table 5: Mean, standard deviation (SD), standard error (SD), rel. standard error (SE%) & sample size (n) of above-ground biomass (Mg ha^{-1}) in different distances from the seaward edge

Distance	Mean [Mg ha^{-1}]	SD	SE	SE%	n
50 m	60.72	11.83	3.74	6.16%	10
150 m	94.83	18.25	5.77	6.09%	10
300 m	97.45	17.64	5.58	5.72%	10
500 m	103.44	11.72	3.71	3.58%	10
700 m	67.71	21.90	7.30	10.78%	9

3.1.5. Stand height

Figure 7 shows tree height as a function of DBH in different distances from the seaward edge. Dominant height and height of mean basal area tree are shown in table 6.

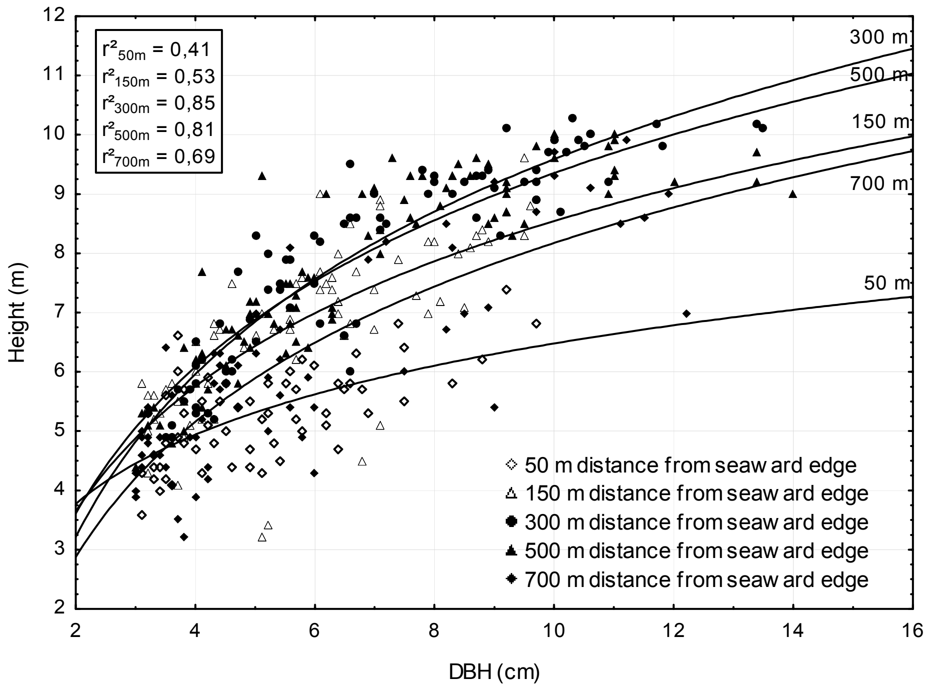

Figure 7: Tree height as a function of DBH in different distances from the seaward edge

Parameter estimates for all five functions are significant ($p < 0.05$). Exceptions are the intercepts of the function for 300 m and 700 m distance from the seaward edge. Differences in slopes of these functions indicate different h/d ratios of trees in different distances.

Both, dominant height (H_o) and height of mean basal area tree (H_g) increase with increasing distance from the seaward edge, showing a peak in 500 m (9,27 m) and 300 m (7.97 m), respectively. In 700 m distance stand height decreases again.

Table 6: Dominant height (H_o) and height of mean basal area tree (H_g) with distance from seaward edge

	Distance from seaward edge				
	50 m	**150 m**	**300 m**	**500 m**	**700 m**
H_o [m]	5.82	7.73	8.51	9.27	7.76
H_g [m]	5.30	6.75	7.97	7.94	6.44

3.2. Soil properties

3.2.1. Soil texture

Table 7 shows the particle size distribution for 0 - 60 cm soil depth in different distances from the seaward edge. As the analysis of particle size distribution required larger amounts of soil material per sample (at least 300 g), samples from different plots in a certain distance were put together in order to allow a representative analysis. Hence, variance and standard errors cannot be given here (n=1).

However, the results clearly indicate a decrease of the share silt and an increase of the share of clay with increasing distance from the seaward edge. While soil texture is made up by more than 80% of silt in 50 m distance, the share of silt decreases to about 50% in 700 m distance. On the other hand the share of clay increases from 17.7% in 50 m distance to about 50 % in 700 m distance. Sand is almost entirely absent in the examined soils. During data collection it was noticed that sandy textures appear in depth of 0.8 to 1 m, though this was only the case for two plots in 50 m distance from the seaward edge.

Based on the FAO Guidelines for Soil Description (2006), the soil can be classified as a silt loam in 50 m distance, a silt clay loam in 150 and 300 m distance and as clay in 500 m and 700 m distance.

Table 7: Particle size distribution (0 - 60 cm soil depth) in different distances from the seaward edge

Distance	Sand	Silt	Clay	n
50 m	0%	82.3%	17.7%	1
150 m	0.1%	70.6%	29.3%	1
300 m	0%	62.9%	37.1%	1
500 m	0.1%	51.9%	48.0%	1
700 m	0%	50.1%	49.9%	1

3.2.2. Salinity of pore water

Figure 8 shows mean, standard deviation as well as outlier values of the calculated electrical conductivity of the saturation extract EC_e (dS m^{-1}) in different distances from the seaward edge.

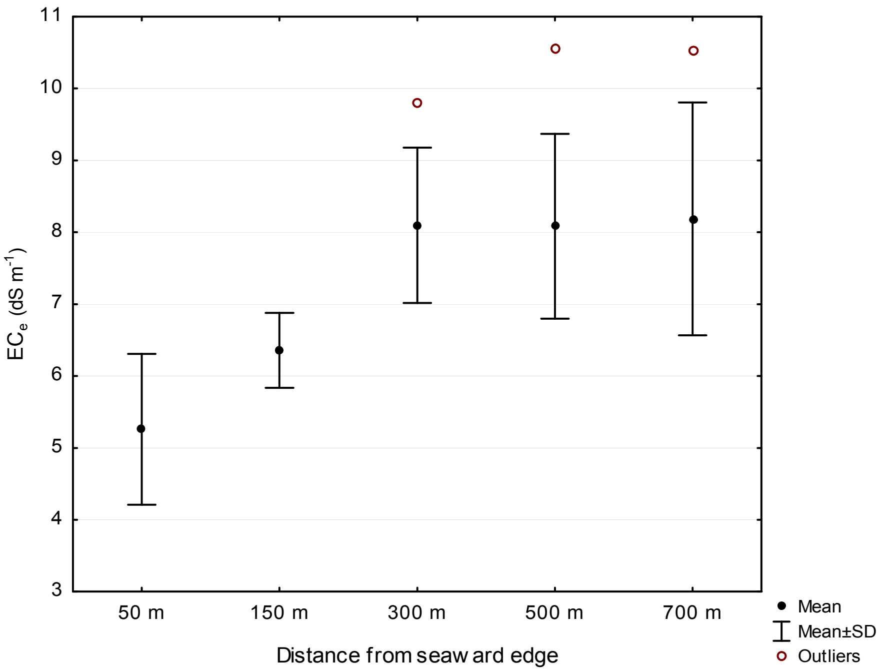

Figure 8: Mean, standard deviation and outlier values of calculated electrical conductivity of the saturation extract ECe (dS m^{-1}) for 0-100 cm soil depth in different distances from the seaward edge

The EC_e (dS m^{-1}) increases from 50 m to 300 m distance from the seaward edge from 5.26 dS m^{-1} to 8.1 dS m^{-1} and stays similar from 300 m to 700 m distance at around 8.1 dS m^{-1}. Estimations of means are acceptably robust with relatively low standard errors below 9 %.

Differences between means are significant (ANOVA, $p < 0.01$). Mean EC_e in 50 m and 150 m distance are similar and different from the mean EC_e in 300 m to 700 m distance from the seaward edge (Tukey HSD Post-Hoc Test, $p < 0.01$). There are no significant differences between the latter.

Table 8 shows mean, standard deviation and relative standard error as well as sample size of EC 1:5 (mS cm^{-1}), ECe (dS m^{-1}) and TDS (g L^{-1}).

Table 8: Mean, standard deviation (SD), rel. standard error (SE%) and sample size (n) of EC 1:5 (mS cm^{-1}), calculated electrical conductivity ECe (dS m^{-1}) and TDS (g L^{-1}) for 0 – 100 cm soil depth in different distances from the seaward edge

	EC 1:5 (mS cm^{-1})		ECe (dS m^{-1})		TDS (g L^{-1})		SE %	n
Distance	Mean	SD	Mean	SD	Mean	SD		
50 m	7.18	1.42	5.26	1.05	25.77	5.14	8.92%	5
150 m	8.67	0.71	6.36	0.52	31.14	2.56	3.67%	5
300 m	11.03	1.47	8.10	1.08	44.78	11.72	5.44%	6
500 m	11.01	1.75	8.08	1.29	44.75	12.42	6.50%	6
700 m	11.16	2.20	8.19	1.62	47.99	25.54	8.07%	6

Table 9 shows mean, standard deviation and standard error of the osmotic potential of soil water

Table 9: Mean, standard deviation, standard error, relative standard error and sample size of the osmotic potential of the soil solution for 0 - 100 cm soil depth in different distances from the seaward edge

Distance	Mean (MPa)	SD	SE	SE %	n
50 m	-2.95	0.56	0.25	8.48%	5
150 m	-3.14	0.47	0.21	6.77%	5
300 m	-3.09	1.03	0.42	13.68%	6
500 m	-3.35	0.45	0.19	5.54%	6
700 m	-4.03	0.37	0.15	3.79%	6

The osmotic potential of soil water gets more negative from 50 m (-2.95 MPa) to 700 m (-4.03 MPa) distance, though it is similar between 150 m and 500 m distance. It needs to be taken into account that these values refer to the actual soil water content encountered in the field, whereby the results given in table 8 refer to the standardized soil water content of a saturated soil.

3.2.3. Soil water content

Figure 9 shows mean, standard deviation as well as outlier values of soil water content as percentage of fresh weight in different distances to the seaward edge. Standard error, relative standard error and sample size are shown in table 10.

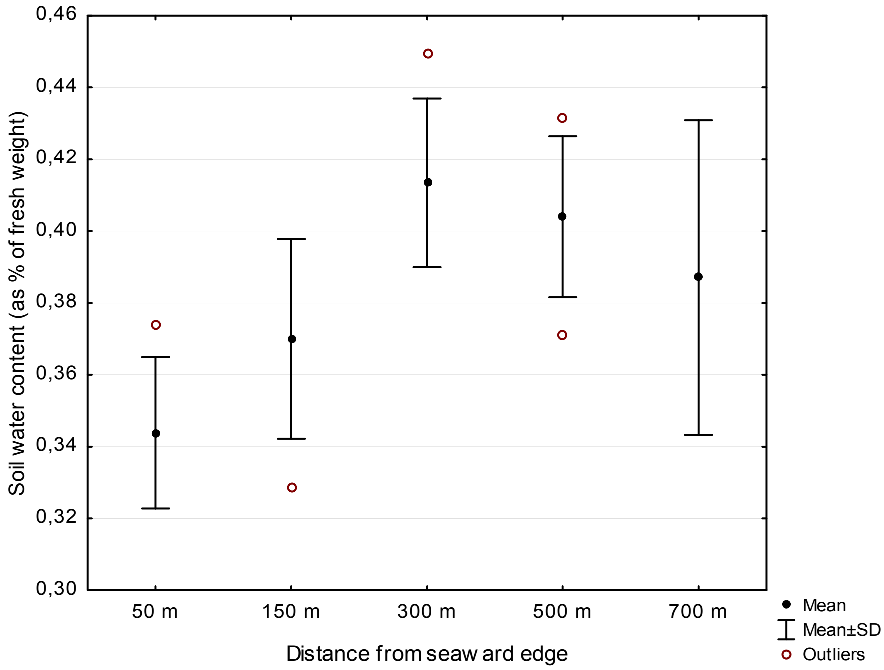

Figure 9: Mean, standard deviation & outlier values soil water content as percentage of fresh weight for 0-100 cm soil depth in different distances from the seaward edge

The soil water content increases from 50 m (34.4%) to 300 m (41.3%) distance. It then decreases slightly from 300 m to 700 m (38.7%) distance. Due to variance inhomogeneity (Levene Test, $p < 0.01$) an ANOVA and a subsequent Post-Hoc Test were not conducted. However, due to relatively low standard errors the estimations of mean soil water contents are quite robust and allow conclusions to a certain extent. Nevertheless, especially the soil water content can be highly dynamic, depending on varying flooding depths and frequencies as well as precipitation patterns, soil texture, canopy openness and the resulting varying evaporation. This issue is needs to be taken into account as a limitation of this study. The soil water content as percent of dry weight can be found in Annex E-6e.

Table 10: Mean, standard deviation (SD), standard error (SE), rel. standard error (SE%) and sample size (n) of soil water content as percentage of fresh weight for 0 – 100 cm soil depth in different distances from the seaward edge

Distance	Mean (%)	SD	SE	SE%	n
50 m	34.4	2.1	0.9	2.5 %	6
150 m	37.0	2.8	1.1	3.1 %	6
300 m	41.3	2.3	1.0	2.3 %	6
500 m	40.4	2.2	0.9	2.3 %	6
700 m	38.7	4.4	1.8	4.6 %	6

3.2.4. Organic carbon and nitrogen

Figure 10 shows mean and standard error of organic carbon per hectare (Mg ha^{-1}) for 0 – 100 cm soil depth. Standard deviation, relative standard error and sample size are shown in table 11.

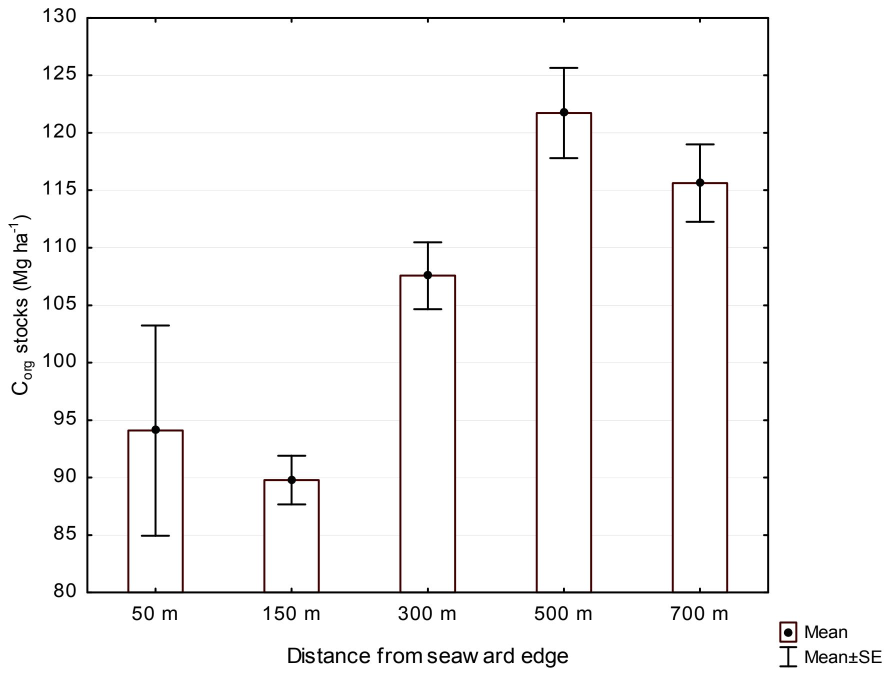

Figure 10: Mean and standard error of Corg stocks (Mg ha-1) for 0 – 100 cm soil depth in different distance from the seaward edge

Mean organic carbon stocks (Mg ha^{-1}) increase with increasing distance from the seaward edge, showing a maximum in 500 m (121.72 Mg ha^{-1}) distance and a minimum in 150 m distance (89.78 Mg ha^{-1}). However, as the amount of C_{org} shows a high variance in 50 m distance compared to the other groups, a minimum can be expected here as well. Due to variance inhomogeneity (Levene Test, $p<0.05$) an an ANOVA and a subsequent Post-Hoc Test were not conducted.

Figure 11 shows mean and standard error of nitrogen stocks per hectare (Mg ha^{-1}) in different distances from the seaward edge. Standard deviation, relative standard error and sample size are shown in table 12.

Mean nitrogen stocks per hectare (N Mg ha^{-1}) increase constantly with increasing distance from the seaward edge, showing a maximum in 500 m distance (12.75 Mg ha^{-1}) and a minimum in 50 m (9.2 Mg ha^{-1}).

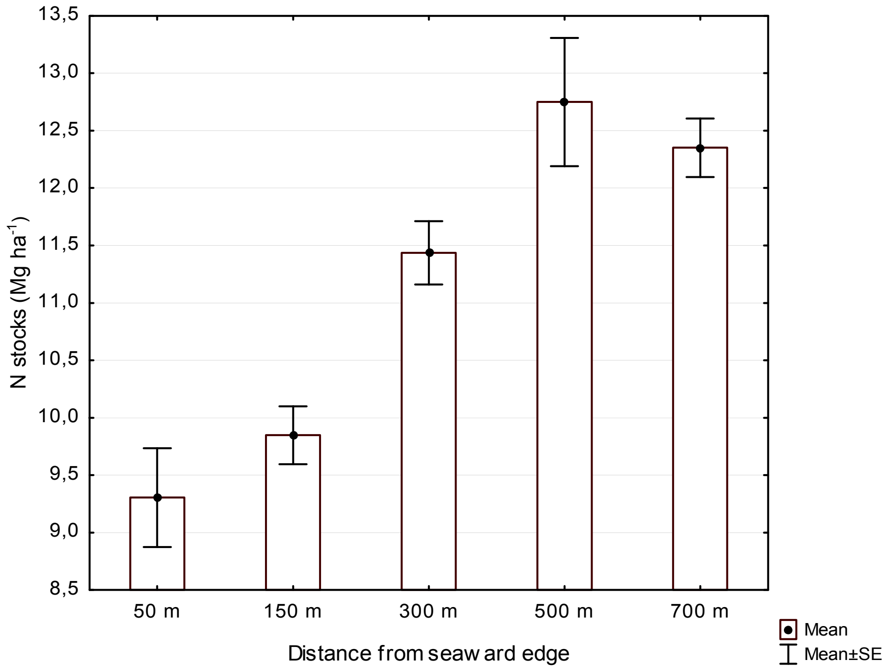

Figure 11: Mean and standard error of N stocks (Mg ha-1) for 0 – 100 cm soil depth in different distances from the seaward edge

A decrease can be observed in 700 m distance compared to the maximum in 500 m distance. Differences between group means are significant (ANOVA, $p < 0.01$). Mean values in 50 and 150 m distance are similar and significantly different from similar means in 300 to 700 m distance (Tukey HSD Post-Hoc Test). Mean stocks, standard error and concentration of organic carbon and nitrogen as well as C/N ratio and bulk density are shown in table 11.

Table 11: Mean stocks (Mg ha-1), standard error (SE) and concentrations of soil organic carbon and nitrogen as well as mean soil bulk density and standard error for 0 – 100 cm soil depth in different distances from the seaward edge

	C_{org} stocks & concentration			N stocks & concentration				Bulk density		
Distance	**Mean ($Mg\ ha^{-1}$)**	**SE**	**C%**	**Mean ($Mg\ ha^{-1}$)**	**SE**	**N%**	**C/N**	**Mean ($g\ cm^{-3}$)**	**SE**	**n**
50 m	94.09	9.16	0.791%	9.30	0.43	0.078%	10.11	1.19	0.03	6
150 m	89.78	2.11	0.839%	9.85	0.25	0.092%	9.12	1.07	0.03	6
300 m	107.56	2.92	1.120%	11.44	0.28	0.119%	9.41	0.96	0.02	6
500 m	121.72	3.92	1.230%	12.75	0.56	0.129%	9.55	0.99	0.02	6
700 m	115.62	3.38	1.134%	12.35	0.26	0.121%	9.36	1.02	0.05	6

4. Discussion

4.1. Spatial patterns of stand structure and soil properties

The first question raised in the introduction was how stand structure and soil properties change with increasing distance from the seaward edge and if spatial patterns - or in other words – if a zonation of stand structure and soil properties can be identified.

Based on significant differences or similarities between parameters of stand structure and soil properties (ANOVA, Tukey HSD Post-Hoc-Test), a seaward-, transitional-, meso- and landward zone can be distinguished. As stand structure and soil properties change gradually, it is not possible to identify sharp boundaries for each zone, but rather distinct characteristics or properties. These are summarized in the following table 12.

Table 12: Summary of stand structure and soil properties in a seaward-, transitional-, meso- and landward-zone

	Seaward zone	**Transitional zone**	**Meso-zone**	**Landward zone**
N ha^{-1}	6748	8365	6061	5560
BA (m² ha^{-1})	12.89	19.86	20.53	14.03
d_g (cm)	4.97	5.54	6.68	6.72
H_o (m)	5.82	7.73	8.89	7.76
AGB (Mg ha^{-1})	60.72	94.83	100.45	67.71
Soil texture	silt loam	silt clay loam	silt clay loam - clay	clay
EC_e (dS m^{-1})	5.26	6.36	8.1	8.19
TDS (g L^{-1})	25.77	31.14	44.77	47.99
Ψ_π (MPa)	-2.95	-3.14	-3.22	-4.03
Soil water content (%)	34.4	37	40.85	38.7
C_{org} (Mg ha^{-1})	94.09	89.78	114.64	115.62
N (Mg ha^{-1})	9.3	9.85	12.06	12.35
C/N	10.12	9.11	9.48	9.36

However, in some cases there were no significant differences between parameter values of the transitional and seaward zone or the meso-zone, i.e. in some cases stand structure in the transitional zone is similar to the seaward zone or to the meso-zone. Nevertheless, this categorization seemed appropriate, as a gradual transition from the seaward zone to the meso-zone was clearly obvious in the field.

Parameter values of respective zones are based on the means of plots in different distances from the seaward edge, whereby values of the meso-zone represent the average of respective means of plots in 300 m and 500 m distance from the seaward edge.

Basal area, quadratic mean diameter, dominant height as well as above-ground biomass tend to increase from a seaward zone to a meso-zone, while they decrease again in a landward zone. Stem density shows a decrease despite a peak in the transitional zone.

Salinity of pore-water, soil water content as well as stocks of organic carbon and nitrogen tend to increase from a seaward to a landward zone. Changes in soil texture from silt loam to silt clay loam to clay are obvious.

4.2. Correlation of stand structure and site conditions and causes of spatial patterns

The second and third question raised in the introduction was if there is a correlation between stand structure and soil properties and how a spatial pattern or zonation can be explained? This issue is discussed in the following, focusing at first on stand structure and at second on soil properties.

While no significant correlations between stand structural parameters and parameters of soil properties were found, stand structure cannot be explained by soil properties directly, at least not by the parameters examined. However, these parameters of course have a mutual influence on each other, but this does not seem to be the underlying cause for the pattern or zonation found here.

In order to be able to explain these spatial pattern or zonation, ecosystem dynamics in space and time must be taken into account. It is rather likely that changes in stand structure can be explained by growth or successional dynamics (see Tomlinson 1986, Snedaker 1982), whereby changes in soil properties can be explained by accretion processes. Both, stand and soil, have been and are influenced by the depth and frequency of tidal inundation and its changes over space and time as well as their mutual interaction. This view is supported by Semeniuk (1980, 1983 as cited by Tomlinson 1986) who argues that any zonation is modified by topography, which is determining tidal and freshwater run-off as well as sediment composition and stability.

In order to explain the underlying causes of gradual changes, it must be taken into account that the examined mangrove forest has evolved from natural succession. As newly accreted land extended the shoreline within the past 45 years, it has been successively colonized by *Avicennia marina*. This means as a consequence that forest and soil "age" increase with increasing distance from the seaward edge. Hence, distance dependent changes in stand structural parameters are likely to be a function of forest growth or stand dynamics rather than being directly linked to soil properties. However, different slopes of distance specific DBH-Height curves imply different h/d ratios of trees (see figure 7) related to the distance from the seaward edge. These differences are also visually obvious in the field, as trees in the seaward zone and partially in the landward zone show a stunted growth form. This stunted growth form might be explainable by the site conditions that prevail in these respective sites. The seaward zone is more frequently and more deeply inundated by the tides than sites further inland. As a result, trees experience anoxic soil conditions more frequently than trees further inland. This constitutes a growth limiting factor as below-ground roots must rely on internal gas transport to fulfill their oxygen requirements (Clough 1992, see Stubbs & Saenger 2002). Furthermore, strongly anoxic conditions can lead to the formation of hydrogen sulfide and other compounds that might be toxic to plants (Clough 1992). The landward zone in turn is less frequently and deeply inundated, but shows highest salinities and it seems more influenced by human impact than stands further seawards. High salinities constitute a growth limiting factor as well, as water can only be taken up against an osmotic gradient, which in turn results in higher metabolic costs (Saenger 2010, Tomlinson 1986). The view that the stunted growth forms of trees in the seaward zone is due to more frequent anoxic soil conditions, whereby it is due to higher salinity in the landward zone is supported by Lara & Cohen (2006), who found a significant correlation of vegetation height with inundation frequency and pore water salinity in a mangrove forest in Brazil. However, as no significant correlation of tree h/d ratios and salinity was found in this study ($r < 0.14$), it must be assumed that salinity is not the only influencing factor in the case of the landward zone. As the analysis of particle size distribution has shown that clay content is highest in the landward zone (about 50 %), the availability of soil water to plants is further limited. This constitutes a potential for water stress in dry periods. The reason why stands in the landward-zone are furthermore characterized by a relatively lower basal area, stand height and above-ground biomass might be explainable by more intensive human impact compared to stands further seaward.

In contrast to the outer zones, stands in the meso-zone do not show a stunted growth and appear as rather well developed forest with a dominant height of about 9 m, a basal area of about 20 m^2 ha^{-1} and an above-ground biomass of about 100 Mg ha^{-1}. All these parameter values are highest compared to the other zones in this study site. Table 13 shows above-ground biomass and height of a primary and a secondary *Avicennia marina* pure stand in Australia.

Table 13: Above-ground biomass (Mg ha^{-1}) and Height (m) of a primary and a secondary *Avicennia marina* pure stand in Australia as given in Komiyama et al. 2008

Condition	Species	AGB (Mg ha^{-1})	H (m)	Reference
Primary forest	*A. marina*	112	7	Briggs 1977
Secondary forest	*A. marina*	341	16	Mackey 1993

A comparison shows that above-ground biomass and height of stands in the meso-zone is more or less similar to what Briggs (1977) found in a primary *A. marina* forest in Australia, although canopy height is lower and above-ground biomass slightly higher. However, Mackey (1993) found a much higher above-ground biomass and a higher canopy height in a secondary forest in Australia. The causes might be questionable. On the one hand the exemplary secondary forest might have had a higher productivity due to more suitable site conditions compared to the examined forest in this study. On the other hand the lower above-ground biomass and height might be explainable as the examined forest is simply younger in age. Furthermore, anthropogenic impacts in the past and present might be responsible.

The increase of soil water salinity from the seaward to the landward zone is a function of several factors. Saenger (2010) names "tidal inundation, soil type, topography, amount and seasonality of precipitation, freshwater discharge of rivers and evaporation" as major factors in the regulation of soil salinity. He furthermore states than an intertidal gradient in salinity "is directly related to the salinity of tidal water, time interval between inundations, rainfall (…) and evaporation rate". As the climate at the study site is characterized by seasonality with a distinct dry season with a relatively high evaporation, salinity at a certain site is higher, the less frequently the site is inundated; as soil water evaporates, salts remain in the soil and tend to accumulate (Saenger 2010). This can be seen as the underlying cause of increase of salinity related to the distance from the seaward edge. It needs to be taken into account that the shown salinity levels measured by the EC_e and TDS refer to a soil under water saturation. When the soil water content decreases the salinity of pore water increases and vice versa. In contrast, the osmotic potential of soil water refers to the actual soil water content. They are hence not directly comparable. The changes in soil water content with increasing distance from the seaward edge are dependent on several factors. Relief and run-off, texture, frequency of tidal inundation, precipitation patterns, canopy openness as well as evaporation influence the soil water content. Being influenced by a variety of factors, the soil water content can be quite dynamic during the course of a year or month.

Organic carbon and nitrogen stocks increase from the seaward to the landward zone, whereby OC stocks show a high variability in the seaward- zone and slight decrease in the landward zone compared to the meso-zone. Donato et al. (2011) argue that forest structure and soil depth are major determinants of C-storage in a mangrove ecosystem rather than environmental gradients. Although Donato et al. (2011) claim that mangrove forests are "among most carbon-rich forests in the tropics", with a mean soil carbon storage of 1,093 Mg ha^{-1} within the Indo-Pacific region, soil carbon stocks at the study site are relatively low compared to what Donato et al. (2011) and also Mudiyarso (2009) found. The highest soil carbon stocks found in the study site are 116 Mg ha^{-1}. However, Khan et al. (2007) reported even lower soil carbon stocks of 57.3 Mg ha^{-1} in a *Kandelia obovata* stand. In order to be able to explain why OC stocks in the present study are relatively low compared to an average in the Indo-Pacific region, two issues need to be taken into account. On the one hand the studies by Donato et al. (2011) and Mudiryarso (2009) included mangrove forests on peat soils with up to three meters soil depth, which can have a quite high concentration of organic carbon in the soil. On the other hand the soil examined here has only recently developed as sediments have been deposited within the past 45 years. Hence, the timespan in which soil organic matter has accumulated is relatively short. This might partially explain the increase with increasing distance from the seaward edge, as sediments more far away from the seaward edge have received input of organic matter over a longer period compared to sediments further seawards. This view is supported by Alongi et al. (2004), who argue, as the primary productivity increases with stand age, the efficiency of carbon burial in sediments increases. According to Kristensen et al. (2008), mangrove litter and benthic algae are the major input of organic matter to the soil. They furthermore state that phytoplankton and seagrass detritus brought in by tides can make up a significant C input. As the seaward zone is most frequently inundated by tides, it might be a possible explanation for the high variance of OC stocks within this zone. It remains questionable whether the underlying causes for the increase of total nitrogen with increasing distance from the seaward edge are the same as for carbon.

4.3. Site-species matching

The fourth question raised was what conclusions regarding site-species matching can be made. As mentioned in the introduction, depth and frequency of tidal inundation, the degree of waterlogging as well as pore water salinity are probably the most important site factors determining species suitability (Stubbs & Saenger 2002). Figure 12 shows the distribution of mangrove genera against salinity and soil water content or redox-potential as a measure of the degree of waterlogging (Stubbs & Saenger 2002).

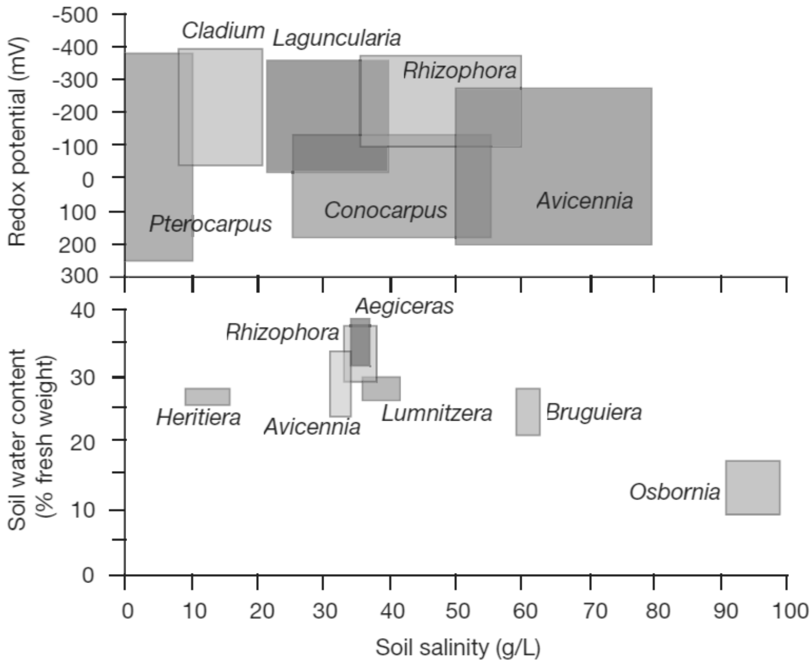

Figure 12: Distribution of different mangrove genera against soil water content (as % of fresh weight), redoxpotential (mV) and soil salinity (g L^{-1}) (Stubbs & Saenger 2002)

The upper graph is based on data from Guadeloupe by Imbert et al. (2000), whereby the lower graph is based on data from Queensland, Australia by Hutchings & Saenger (1987). The latter found *Avicennia spp*. to occur on sites with a soil water content (as percent of fresh weight) between 23 % and 34 % and a salinity of 31 g L^{-1} and 35 g L^{-1} (both parameters have been monitored over 1.5 year period). Comparing this distribution to the results in the present case shows that *A. marina* can further tolerate a higher soil water content (34 % - 41 %) and higher salinity (25 g L^{-1} and 49 g L^{-1}). The results from Imbert et al. (2000) imply that *Avicennia spp.* can even occur on sites with salinity from 50 to 80 g L^{-1}.

In order to be able to obtain water from the soil, plants must maintain an internal salt concentration higher than the salt concentration of the soil solution (Mitlöhner 1993). Iqbar (2008) found internal leaf osmotic potentials of *Avicennia officinalis* below -5 MPa in Indonesia, indicating that species of this genus are adapted to even higher salinities than encountered in the present study. The pronounced salinity tolerance of *A. marina* is further acknowledged by Tomlinson (1986) and Macnae (1968). The latter found that *A. marina* can tolerate salinities of up to 90 g L^{-1}. Clough (1982) and Burchett et al. (1984) even found that *A. marina* seedlings grow poorly in the absence of sodium chloride.

5. Conclusions

Summarizing it can be said that the examined forest shows a spatial pattern of stand structure and soil properties with a seaward-, transitional-, meso- and landward-zone. Forest growth or successional dynamics are assumed to be the underlying cause of forest zonation, whereby accretion processes, depth and frequency of tidal inundation and the mutual interaction of stand and soil are assumed to be the underlying causes of spatial patterns of soil properties. Site conditions have an influence on the growth form of *Avicennia marina*, which shows a stunted growth in the seaward zone. The lack of oxygen availability due to frequent inundation by the tides is assumed to be the underlying cause. Stands further inland appear as well developed forest, where depth and frequency of tidal inundation are less frequent. Stands in the landward zone show lower basal areas, above-ground biomass and stand height, which is assumed to be the result of higher salinities, limited water availability due to a high clay content and human impact.

Avicennia marina occurs on silt loam to clay soils and tolerates a wide range of salinities and degrees of waterlogging, which is in line with the view of Imbert et al. (2000) and Hutchings & Saenger (1987). Being a "one-point-in-time" study, a major limitation of this study it that it did not take the dynamics of certain parameters, including soil water content and salinity, into account, which might be quite variable as it is influenced by several other factors. Furthermore, the assessment of depth and frequency of tidal inundation exceeded the possibilities of this project.

In order to support the effectiveness and efficiency of mangrove restoration or reforestation projects, it is recommended to focus further research on mangrove species occurrence in relation to the mentioned limiting factors as proposed by Stubbs & Saenger (2002). To provide more useful information for reforestation efforts, it is necessary to further put an emphasis on the ability of specific species to cope with those factors under extreme conditions. In this context it further recommended to study the underlying causes of success or failure of reforestation efforts.

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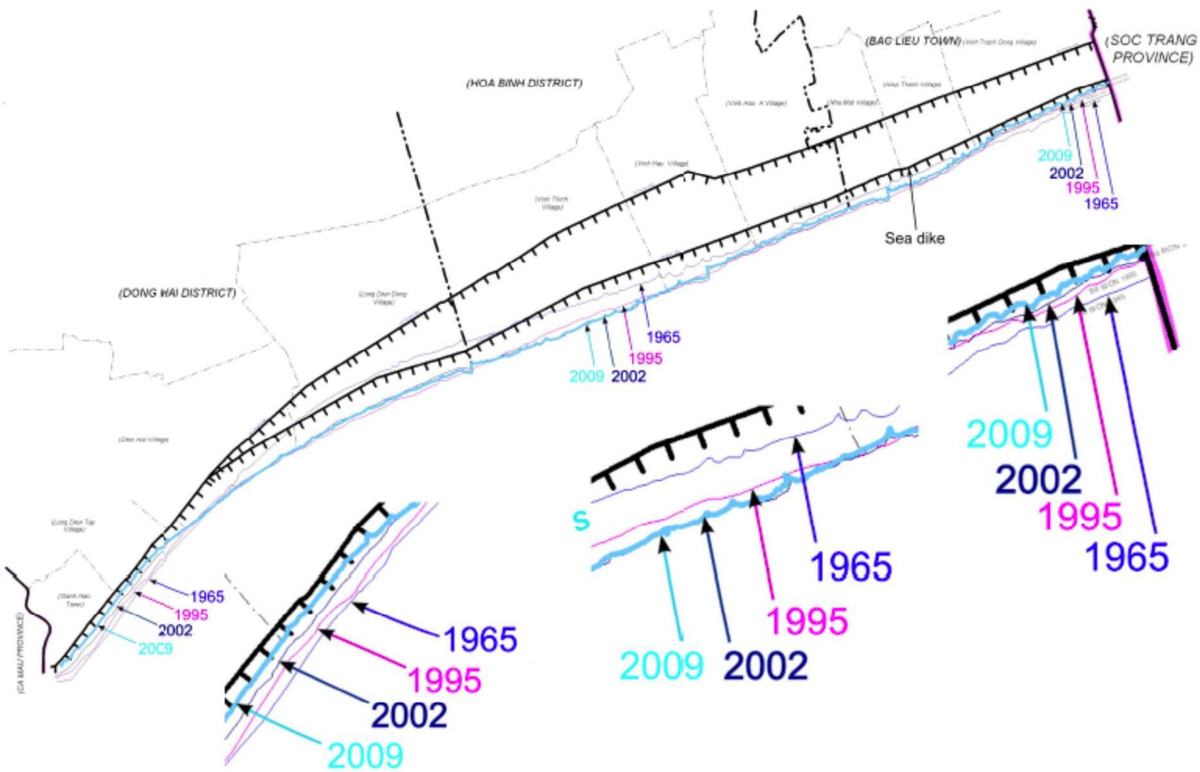
All maps have been created by the author using the software ESRI ArcMap 9.2 (Multi-Seat License, Georg-August-University of Göttingen)

All diagrams have been created by the author using STATISTICA 10

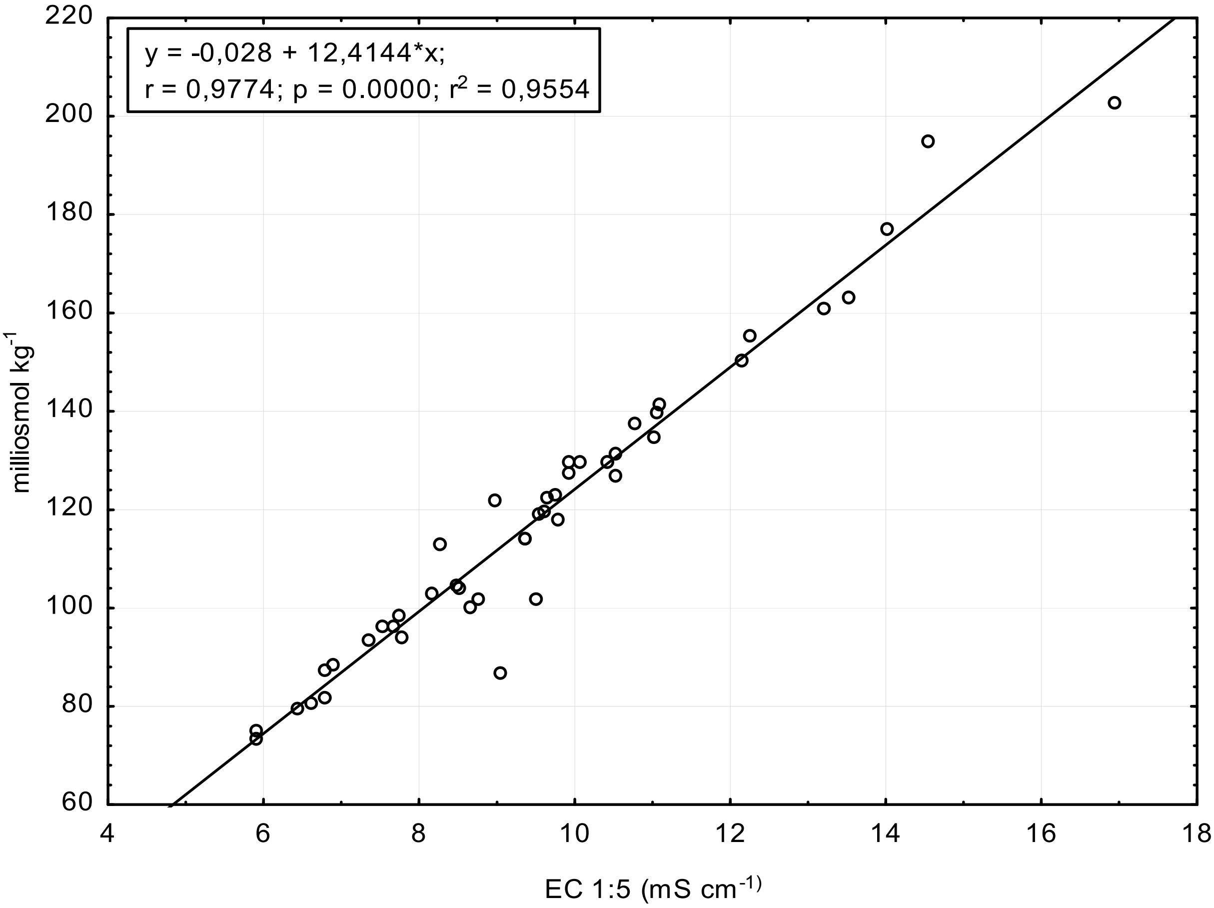
All diagrams have been created by the author using MS EXCEL 2010

ANNEX

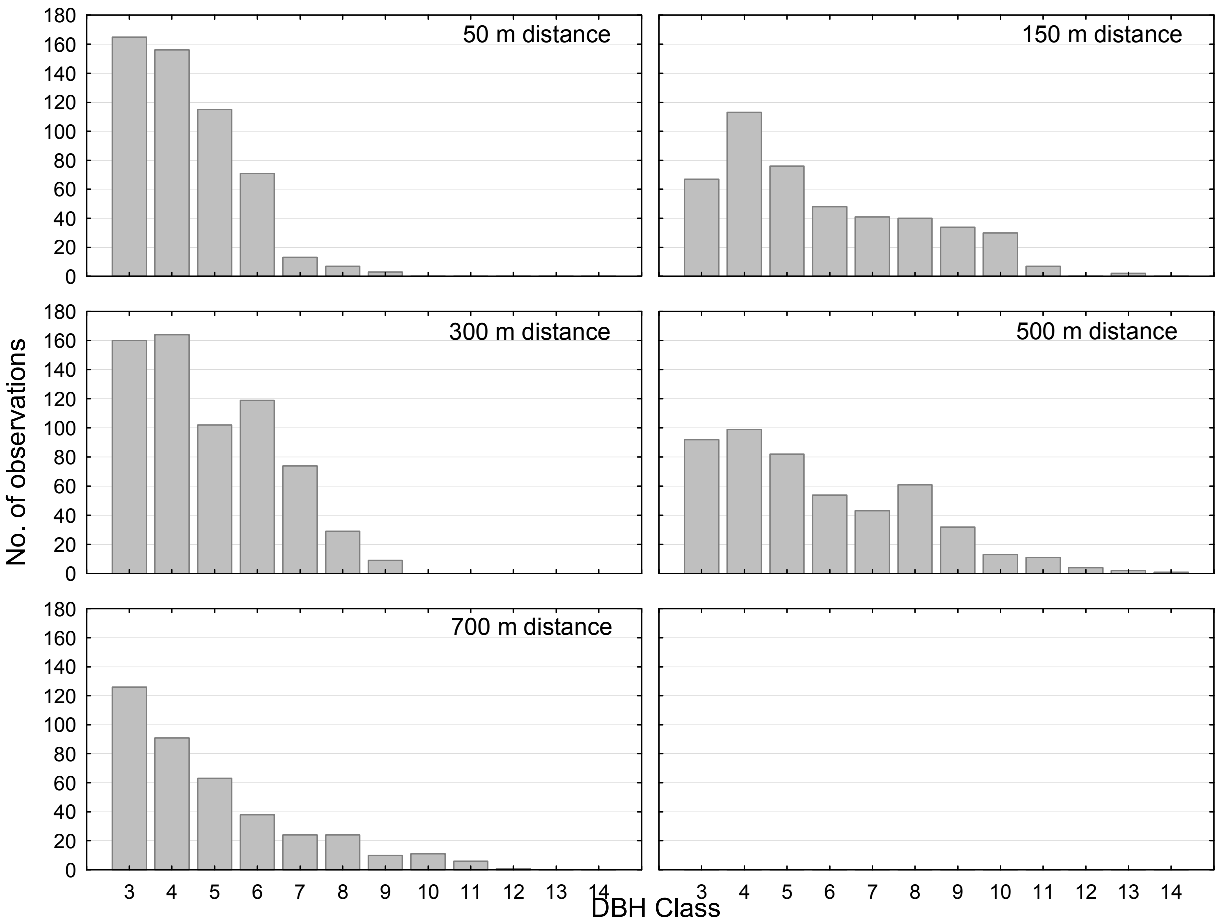
ANNEX A: Changes in the course of the Bac Lieu Coastline from 1965 to 2009 (Clough 2011)



ANNEX B: Milliosmol kg^{-1} as a function of EC 1:5 (mS cm^{-1})



ANNEX D: Diameter distributions



ANNEX E: Mean values per plot, results of ANOVA, Levene Test and Tukey HSD Post-Hoc Test of stand and soil parameters

ANNEX E-1a: Basal area per hectare for each plot

Plot No.	50m	150m	300m	500m	700m
1	8.58	20.43	17.12	19.68	16.75
2	9.98	22.35	19.54	22.04	21.86
3	14.78	21.15	21.15	23.24	13.06
4	13.51	24.00	24.01	20.36	12.13
5	12.27	19.31	23.94	24.49	9.87
6	10.25	10.24	16.66	17.77	18.79
7	15.11	18.81	13.22	21.45	14.68
8	14.30	18.10	20.79	21.66	8.22
9	14.18	23.11	23.38	23.95	10.95
10	15.96	21.08	19.27	16.82	

ANNEX E-1b: Analysis of variance (ANOVA)

	SS	df	MS	SS	df	MS	F	p
G/ha	565.9902	4	141.4976	516.0994	44	11.72953	12.06336	0.000001

ANNEX E-1c: Levene Test

	SS	df	MS	SS	df	MS	F	p
G/ha	14.43314	4	3.608286	176.8963	44	4.020371	0.897501	0.473618

ANNEX E-1d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.000509	0.000471	0.000159	0.949390
150 m {2}	0.000509		1.000000	0.916341	0.005260
300 m {3}	0.000471	1.000000		0.926869	0.004796
500 m {4}	0.000159	0.916341	0.926869		0.000545
700 m {5}	0.949390	0.005260	0.004796	0.000545	

ANNEX E-2a: Quadratic mean diameter per plot

Plot No.	50 m	150 m	300 m	500 m	700 m
1	5.35	5.61	6.04	7.72	6.55
2	4.26	5.25	5.76	7.16	6.19
3	5.09	5.66	6.20	5.72	6.83
4	5.31	5.55	7.23	6.08	4.53
5	5.00	5.18	6.79	6.50	8.40
6	4.77	6.05	6.45	8.27	6.13
7	5.15	5.96	7.00	6.13	4.87
8	4.88	5.32	6.87	7.27	4.05
9	5.38	5.41	7.13	5.85	5.67
10	4.47	5.45	6.94	6.49	

ANNEX E-2b: Analysis of variance (ANOVA)

	SS	df	MS	SS	df	MS	F	p
dg	22.02005	4	5.505012	24.81677	44	0.564017	9.760357	0.000010

ANNEX E-2c: Levene Test

	SS	df	MS	SS	df	MS	F	p
dg	3.974225	4	0.993556	7.526158	44	0.171049	5.808605	0.000765

ANNEX E-2d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.434395	0.000229	0.000176	0.062616
150 m {2}	0.434395		0.017249	0.009131	0.816661
300 m {3}	0.000229	0.017249		0.999343	0.238106
500 m {4}	0.000176	0.009131	0.999343		0.154754
700 m {5}	0.062616	0.816661	0.238106	0.154754	

ANNEX E-3a: Stem density per hectare for each plot

Plot no.	**50 m**	**150 m**	**300 m**	**500 m**	**700 m**
1	3819.72	8276.06	5984.23	4201.69	4965.63
2	7002.82	10313.24	7512.11	5474.93	7257.47
3	7257.47	8403.38	7002.82	9040.00	3565.07
4	6111.55	9931.27	5856.90	7002.82	7512.11
5	6238.87	9167.32	6620.85	7384.79	1782.54
6	5729.58	3565.07	5092.96	3310.42	6366.20
7	7257.47	6748.17	3437.75	7257.47	7894.09
8	7639.44	8148.73	5602.25	5220.28	6366.20
9	6238.87	10058.59	5856.90	8912.68	4329.01
10	10185.92	9040.00	5092.96	5092.96	

ANNEX E-3b: Analysis of variance (ANOVA)

	SS	**df**	**MS**	**SS**	**df**	**MS**	**F**	**p**
N/ha	48350270	4	12087568	138492278	44	3147552	3.840308	0.009216

ANNEX E-3c: Levene Test

	SS	**df**	**MS**	**SS**	**df**	**MS**	**F**	**p**
N/ha	5286143	4	1321536	49255200	44	1119436	1.180537	0.332531

ANNEX E-3d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.265481	0.758435	0.977729	0.594632
150 m {2}	0.265481		0.019208	0.084883	0.010775
300 m {3}	0.758435	0.019208		0.972853	0.998199
500 m {4}	0.977729	0.084883	0.972853		0.897085
700 m {5}	0.594632	0.010775	0.998199	0.897085	

ANNEX E-4a: Above-ground biomass (Mg ha^{-1}) per hectare for each plot

Plot no.	50 m	150 m	300 m	500 m	700 m
1	40.85	97.72	82.71	97.88	81.95
2	46.11	106.24	93.84	108.49	106.29
3	69.92	101.36	102.79	111.92	64.30
4	64.20	114.49	118.70	98.83	56.69
5	57.89	91.72	117.69	119.40	49.56
6	47.95	49.55	81.47	88.50	91.21
7	71.35	90.47	64.71	103.97	69.13
8	67.15	85.84	102.15	107.44	37.81
9	67.66	110.25	115.47	115.63	52.44
10	74.15	100.66	94.97	82.35	

ANNEX E-4b: Analysis of variance (ANOVA)

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
AGB Mg/ha	14499.52	4	3624.879	12130.44	44	275.6918	13.14830	0.000000

ANNEX E-4c: Levene Test

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
AGB Mg/ha	393.1956	4	98.29891	4127.559	44	93.80817	1.047872	0.393570

ANNEX E-4d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.000459	0.000241	0.000135	0.889465
150 m {2}	0.000459		0.996624	0.773877	0.007884
300 m {3}	0.000241	0.996624		0.927149	0.003012
500 m {4}	0.000135	0.773877	0.927149		0.000377
700 m {5}	0.889465	0.007884	0.003012	0.000377	

ANNEX E-5a: Organic carbon stocks (Mg ha^{-1}) per hectare for each plot

Plot no.	50 m	150 m	300 m	500 m	700 m
1	65.86	90.48	108.75	117.40	128.08
2	112.38	97.57	96.93	136.06	111.91
3	90.03	88.74	110.86	107.28	107.73
4	125.46	92.90	114.40	122.39	118.40
5	74.63	86.27	100.77	120.39	120.77
6	96.17	82.72	113.67	126.81	106.84

ANNEX E-5b: Analysis of variance (ANOVA)

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Corg	4481.766	4	1120.441	3708.023	25	148.3209	7.554170	0.000391

ANNEX E-5c: Levene Test

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Corg	663.1142	4	165.7786	1084.622	25	43.38488	3.821114	0.014762

ANNEX E-5d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.971754	0.334981	0.005017	0.038019
150 m {2}	0.971754		0.115994	0.001171	0.009239
300 m {3}	0.334981	0.115994		0.288975	0.780746
500 m {4}	0.005017	0.001171	0.288975		0.906260
700 m {5}	0.038019	0.009239	0.780746	0.906260	

ANNEX E-6a: Mean soil water content as percentage of fresh weight per plot for 0-100 cm soil depth

Plot no.	50 m	150 m	300 m	500 m	700 m
1	32.36%	32.87%	38.90%	37.11%	43.66%
2	37.38%	39.66%	42.74%	43.16%	42.02%
3	32.39%	39.75%	44.93%	42.24%	35.15%
4	35.67%	36.91%	39.24%	40.64%	42.19%
5	35.58%	38.18%	40.08%	38.60%	35.59%
6	32.92%	34.63%	42.17%	40.61%	33.62%

ANNEX E-6b: Analysis of variance (ANOVA)

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Soil water	0.018482	4	0.004621	0.020952	25	0.000838	5.513337	0.002530

ANNEX E-6c: Levene Test

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Soil water	0.002015	4	0.000504	0.002870	25	0.000115	4.387672	0.007984

ANNEX E-6d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.532768	0.002859	0.011174	0.103971
150 m {2}	0.532768		0.101328	0.280914	0.843370
300 m {3}	0.002859	0.101328		0.978752	0.524889
500 m {4}	0.011174	0.280914	0.978752		0.848245
700 m {5}	0.103971	0.843370	0.524889	0.848245	

ANNEX E-6e: Mean soil water content as percentage of dry weight per plot for 0-100cm soil depth

Plot no.	50 m	150 m	300 m	500 m	700 m
1	48.59%	49.29%	63.67%	59.80%	78.41%
2	60.23%	68.64%	84.30%	77.38%	74.73%
3	48.03%	66.60%	81.89%	74.33%	54.40%
4	56.09%	58.67%	64.77%	68.68%	73.84%
5	55.55%	62.20%	67.14%	62.98%	55.77%
6	49.12%	53.37%	73.19%	69.16%	51.05%

ANNEX E-7a: Mean bulk density (g cm^{-3}) per plot for 0-100 cm soil depth

Plot no.	50 m	150 m	300 m	500 m	700 m
1	1.14	1.13	1.00	1.05	0.89
2	1.11	0.95	0.93	0.93	0.95
3	1.32	1.05	0.89	0.94	1.10
4	1.16	1.11	1.03	0.98	0.93
5	1.16	1.07	0.99	1.03	1.12
6	1.22	1.15	0.92	1.03	1.15

ANNEX E-7b: Analysis of variance (ANOVA)

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Bulk density	0.188997	4	0.047249	0.144567	25	0.005783	8.170820	0.000234

ANNEX E-7c: Levene Test

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Bulk density	0.012738	4	0.003185	0.024312	25	0.000972	3.274607	0.027352

ANNEX E-7d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.116483	0.000319	0.001680	0.009507
150 m {2}	0.116483		0.085902	0.363272	0.786033
300 m {3}	0.000319	0.085902		0.922233	0.545082
500 m {4}	0.001680	0.363272	0.922233		0.948785
700 m {5}	0.009507	0.786033	0.545082	0.948785	

ANNEX E-8a: Mean nitrogen stocks per hectare (Mg ha^{-1}) for each plot for 0-100cm soil depth

Plot no.	50 m	150 m	300 m	500 m	700 m
1	7.58	9.72	11.11	12.71	12.40
2	10.53	11.02	10.25	13.32	11.52
3	9.61	9.70	11.73	10.36	11.79
4	9.45	9.75	11.53	14.56	12.30
5	8.63	9.16	11.84	12.96	13.08
6	10.03	9.74	12.15	12.59	13.01

ANNEX E-8b: Analysis of variance (ANOVA)

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
N	55.07679	4	13.76920	21.12134	25	0.844854	16.29773	0.000001

ANNEX E-8c: Levene Test

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
N	1.058383	4	0.264596	8.978581	25	0.359143	0.736741	0.575705

ANNEX E-8d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.842361	0.004067	0.000142	0.000177
150 m {2}	0.842361		0.044415	0.000223	0.000798
300 m {3}	0.004067	0.044415		0.128913	0.438419
500 m {4}	0.000142	0.000223	0.128913		0.942083
700 m {5}	0.000177	0.000798	0.438419	0.942083	

ANNEX E-9a: Mean values per plot of calculated electrical conductivity of the saturation extract for 0-100 cm soil depth

Plot no.	50 m	150 m	300 m	500 m	700 m
1	6.59	7.03	7.31	7.35	10.52
2	5.12	5.99	7.07	10.56	8.32
3	6.00	6.56	9.80	8.16	7.75
4	3.97	6.50	7.47	7.34	9.49
5	4.63	5.69	7.93	7.06	6.26
6			9.00	8.03	6.78

ANNEX E-9b: Analysis of variance (ANOVA)

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
ECe	37.45953	4	9.364882	32.67510	23	1.420657	6.591939	0.001094

ANNEX E-9c: Levene Test

	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
ECe	1.974400	4	0.493600	10.02985	23	0.436080	1.131901	0.366143

ANNEX E-9d: Tukey HSD Post-Hoc Test

	{1}	{2}	{3}	{4}	{5}
50 m {1}		0.600684	0.005564	0.005825	0.004142
150 m {2}	0.600684		0.148117	0.153563	0.117139
300 m {3}	0.005564	0.148117		1.000000	0.999933
500 m {4}	0.005825	0.153563	1.000000		0.999881
700 m {5}	0.004142	0.117139	0.999933	0.999881	