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Survey of soil variability and consequences for land use in coconut fields in Sri Lanka

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Kartering van bodemvariabiliteit en consequenties voor landgebruik in kokosvelden te Sri Lanka

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Samenvatting


Een studiegebied (20 ha) gelegen in de belangrijkste zone voor kokos-cultivatie van Sri Lanka was opgemeten met een elektromagnetische-inductiesensor. On-the-go (schijsbare) elektrische bodemgeleidbaarheid, bewees de variabiliteit van de meest limiterende bodemeigenschappen voor kokos-cultivatie te karakteriseren: bodemtextuur/structuur (% gravel, % klei en zand) en nutriëntstatus (som van Basische kationen).

Gebaseerd op deze observaties kunnen continue schattingen gemaakt worden gebaseerd op de sensormetingen. Lineaire regressiemodellen tonen aan tot een accurate schatting te komen van de verschillende bodemeigenschappen ($R^2_{gravel} = 0.520$; $R^2_{SBC} = 0.722$; $R^2_{klei} = 0.672$ en $R^2_{zand} = 0.603$). Deze continue schattingen van bodemeigenschappen laten dan op hun beurt toe de bodem te vergelijken met de specifieke gewasvereisten wat resulteert in een geschiktheidscore. Door de verschillende (opbrengstlimiterende) bodemeigenschappen te combineren, kan een algemene geschiktheid van het land bepaald worden. Deze drukt dan de potentie van het land uit om kokos-cultivatie te ondersteunen.

Deze werkwijze vormt een verbetering tegenover de traditionele methoden waar intensieve bodemstalen en veldobservaties aan de basis liggen van een landevaluatie. Werken met continue beschikbare data geeft de mogelijkheid om tot een (ruimtelijk) gedetailleerde geschiktheidkaart te komen. Stalen zijn nog wel nodig om de variabiliteit in sensormetingen uit te leggen, maar niet meer in die hoeveelheid die een gedetailleerde landevaluatie vereist.
Summary

The gradual price increase of coconut due to the growing gap between coconut production and demand illustrates the need of means to increase productivity. Coconut plantations typically have very variable yield depending on climatic but certainly also on soil conditions. These soil conditions themselves are very variable on small scale. Therefore precision agriculture could offer release in coconut cultivation.

A study area (20 ha) situated in the main coconut growing area of Sri Lanka was surveyed using a proximal soil sensor (Electromagnetic induction). On-the-go soil electrical conductivity, proved to characterize within-field variability of the most limiting soil properties for coconut cultivation: soil texture/structure (% coarse fragments, % clay and % sand) and soil fertility status (Sum of Basic Cations).

Based on these observations, continuous estimates of reflected soil properties are made based on sensor measurements. Linear regression models show to predict the different soil properties quite accurately ($R^2_{\text{gravel}} = 0.520; R^2_{\text{SBC}} = 0.722; R^2_{\text{clay}} = 0.672$ and $R^2_{\text{sand}} = 0.603$). As continuous predictions of soil properties are available, they can be compared to the specific crop requirements resulting in suitability scores. By combining different (yield-limiting) soil properties, an overall suitability score (index) is obtained which expresses the capability of the land to support coconut growth.

This method is taught to be an improvement to the traditional methods where soil samples and field observations form the basis of land evaluation. Working with continuous available data offers the possibility to obtain a (spatially) detailed suitability map. Samples are still needed to explain observed sensor variability, but not in that amount that a detailed land-evaluation requires.
1. Introduction

1.1. Problem statement
Coconut is a very important crop for many developing countries as a food crop and as a raw material for fiber products. Due to diversity of value added products of coconut, this crop is considered as a high value commercial crop. The actual coconut production in many countries including Sri Lanka cannot keep up with the demand (Central Bank report of Sri Lanka, 2010). This has led to a gradual price increase of coconuts in the last decades. The Coconut Research Institute is one of the leading agricultural institutes in Sri Lanka. Its major focus is to conduct basic and applied research addressing to potential means of increasing the domestic production of coconut.

Coconut-plantations have a common problem of yield variability (25 000 nuts/ha/year to 2000 nuts/ha/year). Not only the large scale climatic conditions, but more importantly the small scale soil conditions play their role in this phenomenon. Producers typically manage commercial coconut plantations without paying attention to within-field variation of soil conditions. There is an emerging need for an increased efficiency in crop production and profitability. Proper land evaluation is needed to improve soil management and land diversification. This requires detailed information on the underlying factors responsible for the variation in yield. Variation in soil physical, chemical and biological properties are considered to be the most important factors responsible for the yield variability (Ping et al., 2005). In addition, the characteristics of the plantations, such as the variety, vacant patches and age of plantation can also play a role in the variation of coconut yields. Hence, understanding the variation of intrinsic soil properties is the key factor for site-specific management of coconut estates.

Site specific soil management based on these characteristics possibly is one of the most viable means to increase the productivity of existing arable lands and hereby minimizing environmental impact. Also simply choosing the most suited land for coconut cultivation can increase yield. Through efficient use of land, specific management can be a big step forward in the developing country’s agriculture. The intrinsic soil characteristics can be determined by carefully planned soil sampling, but this method is expensive and time consuming (Brouder et al., 2005; Khosla and Alley, 1999).

1.2. Research question and objectives
In this study, the applicability of using bulk electrical conductivity (termed apparent soil electrical conductivity EC_a) to characterize soil variability and delineate suitability zones will be examined. Both the use of sensor-measurements to characterize soil properties as well as the utilization of soil properties to develop suitability classes has been done numerously before. Our goal now is to investigate if it is possible to directly develop suitability classes based on sensor measurements, thereby eliminating intensive soil sampling.
To examine the applicability of bulk electrical soil conductivity in land suitability classification, following research objectives were put forward:

(1) *Characterize soil electrical conductivity variability by identification of reflected variable soil properties.*

Different soil properties prove to affect the measured soil EC₅. After characterizing the spatial variation of the study field using both EC₅ measurements and soil samples, a method to characterize relevant soil characteristics (for coconut production) using these EC₅ measurements will be investigated.

(2) *Perform land evaluation based on knowledge of within field variability and requirements for growth of coconut.*

Suitability zones express the fitness of a given piece of land for a well specified land use, in this case for growing coconut. After relating sensor measurements to soil properties, these (sensor-related) soil properties can be translated into suitability terms.
2. Literature review

In order to obtain a better understanding in the research topic and to clearly situate the need for proper land evaluation in Sri Lankan agriculture, this literature review primarily gives a global picture of the situation in Sri Lanka and the importance of coconut-cultivation. Further, the use of EC₃ measurements in agriculture will be discussed as well as the possibility to delineate management units using variable soil characteristics. Here the possible use of EC₃-measurements in this delineation will also be handled. Finally an introduction to land evaluation techniques will be made, especially with an eye on coconut cultivation. A more detailed overview of the basic theories and principles of EC₃-measurements is given in the materials and methods.

2.1. Sri Lanka

The Democratic Socialist Republic of Sri Lanka, is an island situated off the southern coast of the Indian subcontinent in South Asia. The island contains tropical forests, and diverse landscapes with high biodiversity. The country is famous for the production and export of tea, coffee, gemstones, coconuts, rubber and cinnamon. Sri Lanka boasts a diverse range of cultures, languages and religions. The majority of the population is Sinhalese.

Sri Lanka is a republic and a unitary state which is governed by a semi-presidential system. The island has a rich history with different colonial regimes. The first Europeans to visit Sri Lanka in the modern times were the Portuguese in 1505, after this the Dutch controlled the whole island except the kingdom of Kandy. In 1803 the British invaded the Kingdom of Kandy followed by the end of independence in 1815. Sri Lanka remained a British crown colony until 1948.

Sri Lanka has a total area of 65,610 km² (about two times the size of Belgium). Natural resources include limestone, graphite, mineral sands, gems, phosphates, clay, hydropower.

**Topography**

Sri Lankan terrain is mostly low, flat to rolling plain, with mountains in the south-central interior. The central part of this southern half of the island reaches altitudes exceeding 2500 m. The core regions of the central highlands contain many complex topographical features such as ridges, peaks, plateaus, basins, valleys and escarpments. The remainder of the island is practically flat except for several small hills that rise abruptly in the lowlands.

**Climate**

The pattern of life in Sri Lanka depends directly on the availability of rainwater. Topographical features strongly affect the spatial patterns of winds, seasonal rainfall, temperature, relative humidity and other climatic elements, particularly during the monsoon season. The mountains and the southwestern part of the country, known as the "wet zone," receive about an annual average of rainfall over 2500 mm. Most of the southeast, east, and northern parts of the country comprise the
"dry zone”, which receives annually mean rainfall of less than 1750 mm. Much of the rain in these areas falls from October to January; during the rest of the year there is very little precipitation. The very arid northwest and southeast coasts receive the least amount of rain, 600 to 1200 mm per year, concentrated within the short period of the winter monsoon. In between both zones is an intermediate zone, which receives about 2000 mm of rain per year. The annual rainfall patterns are shown in Figure 1.

![Figure 1: Annual rainfall distribution (mm) within Sri Lanka (Department of Meteorology, Sri Lanka)](image)

Regional differences observed in air temperature across Sri Lanka are mainly due to altitude, rather than to latitude. The mean monthly temperatures differ slightly depending on the seasonal movement of the sun, with some modified influence caused by rainfall. The mean annual temperature in Sri Lanka remains constant in the low lands and decreases with altitude. In the lowlands, up to an altitude of 100 m to 150 m, the mean annual temperature varies between 26.5°C and 28.5°C. In the highlands, the temperature falls quickly as the altitude increases. The mean annual temperature of Nuwara Eliya, at 1800 m altitude, is 15.9°C. The coldest month with respect to mean monthly temperature is generally January, and the warmest months are April and August.

**Vegetation**

The natural vegetation of the dry zone is adapted to the annual variations in rainfall. Typical ground cover is scrub forest, interspersed with though bushes and cactuses in the driest areas. Plants grow
very fast in periods with heavy rainfall, but stop growing during the hot season going from March to August. Various adaptations to the dry conditions have been developed (thick bark, tiny leaves, ...). In the wet zone, the dominant vegetation of the lowlands is a tropical evergreen forest, with tall trees, broad foliage, and a dense undergrowth of vines and creepers. Subtropical evergreen forests resembling those of temperate climates flourish at the higher altitudes. Montane vegetation at the highest altitudes tends to be stunted and windswept.

**Soil**

The soils of Sri Lanka have been classified at Great Group level for the whole country. In 1961, Moormann and Panabokke presented the classification into great soil groups and sub-groups. This classification, with some modifications in the light of subsequent surveys, is the one still used today.

Variations of soil within Sri Lanka reflect the effects of climate, lithology and terrain on the soil-forming processes. The climatic influences are reflected in the dominance of red-yellow podzolic soils (leached lateritic soils) in the Wet Zone and of reddish brown earths (nonlateritic loamy soils) in the Dry Zone. These are the two most dominant soils in the country (annex 1).

**Economy**

With an economy worth $64 billion ($170 billion PPP estimate), and a per capita GDP of about $7900 (PPP) (2012 IMF estimate), Sri Lanka has mostly had strong growth rates in recent years. In GDP per capita terms, it is ahead of other countries in the South Asian region. The main economic sectors of the country are tourism, tea export, apparel, textile, rice production and other agricultural products (such as coconut). Also overseas employment contributes highly in foreign exchange.

The agricultural sector of the country produces mainly rice, coconut and grain, largely for domestic consumption and occasionally for export. The tea industry which has existed since 1867 is not regarded as part of the agricultural sector, which is mainly focused on export rather than domestic use in the country.

Poverty continues to be a growing problem despite Sri Lanka being an exceptional country with its life expectancy, literacy rate and other social indicators nearly on par with those of developed countries. Sri Lanka is only ranked in the medium category of the Human Development Index (HDI). According to the World Bank, 42% of Sri Lanka’s population live on under US$2 a day (2005). Therefore poverty remains widespread and continues to be a challenging problem in Sri Lanka.

**Coconut cultivation in Sri Lanka**

Coconut (*Cocos nucifera* L.) is a perennial tree crop that contributes significantly to the economy of Sri Lanka. Sri Lanka is the 4th largest producer of coconut in the World. Coconut cultivation spans about 402,649 ha, accounting for 21% of agricultural land in the country. It contributes 2% to Sri Lanka’s GDP, 2.5% to export earnings, and 5% to employment (Sivirajah, 2010). Although these
numbers seem modest, coconut is a very important crop in Sri Lanka since it provides about 22% of the per capita calorie intake in the diet (Fernando et al., 2007). The biggest single use (60 – 75 %) is for domestic culinary consumption, followed by desiccated coconuts (DC), coconut oil and others. GDP values and production of coconut have fluctuated between US$ 115 million in 1950; US$ 177 million in 1986, and US$ 139 million in 2002. Sixty five percent of the coconut plantations are owned by smallholders.

Coconut is grown in both the dry zone and the wet zone. On very fertile lands, a tall coconut palm tree can yield up to 75 fruits per year, but more often yields less than 30 fruits are measured due to various reasons. Variability of the yield is a typical problem in coconut production. Recently, improvements in cultivation practices and breeding has helped coconut trees to produce more. But still a lot of work is needed, especially because coconut production is scattered between small farms. From a perspective of policy making, it is useful to improve land evaluation and production. To better organize and to investigate possibilities regarding coconut production, the Coconut Research Institute of Sri Lanka was founded.

**Field crop research institutes in Sri Lanka**

Followed by the initialization of agricultural research in Sri Lanka with the establishment of an experimental station at Peradeniya in 1902 (Wickremasinghe, 2006), eight major research agricultural centers were established in different agro-ecological regions of the country. The goal of these centers is to improve agricultural practices through research in the different regions and thus contribute to the common welfare. After these important evolutions in Sri Lanka’s agricultural research, also different plantation crop research institutes were established: the Rubber Research institute (RRI, 1910), the Tea Research Institute (TRI, 1925), the Coconut Research Institute (CRI, 1929) and finally the Sugarcane Research institute (SRI, 1948).

### 2.2. Coconut research institute of Sri Lanka

The Coconut Research Institute (CRI) is a national Institute founded as the Coconut Research Scheme under the coconut Research Ordinance No.24 of 1928. The scheme established its headquarters at Bandiripuwa Estate, Lunuwila (North Western Province) and began its research activities with three Technical Divisions namely, Genetics, Chemistry and Soil Chemistry for assisting coconut growers with technical information on coconut cultivation. Following the enactment of the coconut Research Act No. 37 in 1950, it was renamed as the CRI of Ceylon. Since its establishment all scientific research on coconut in Sri Lanka was centered in the CR, and it gained national as well as international reputation for coconut research. Under the Coconut Development Act No. 46 promulgated in 1971, the Coconut Research Board was set up in 1972 to function as the Board of Management of the CRI. The CRI is a semi-autonomous research institution coming under the purview of the Ministry of Coconut Development and Janatha Estate Development.
As given in the Coconut Development Act No. 46 of 1971, statutory functions of the Coconut Research Board are (Annual Report CRI, 2002):

- Conducting and furthering of scientific research in respect of the growth and cultivation of coconut palms. The growing of other crops and engagement in animal husbandry in coconut plantations and the prevention and cure of diseases and pests;
- Establishment and maintenance of research Institutes, experimental stations and nurseries;
- The conducting and furthering of scientific research in connection with the processing and utilization of coconut products;
- Establishment and maintenance of pilot plants for the processing of coconut products and fabrication of experimental processing equipment;
- Training of advisory and extension workers to assist the coconut industry; and
- Guiding and advising of the coconut industry on all matters of technical nature.

For the implementation of all policies and programs laid down by the Board, the Coconut Research Institute consists of different Research and Service Divisions:

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<th>Research Divisions</th>
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Of course, in line of this work, the Soils and Plant Nutrition Division is the most important. This Research Division is responsible for developing cost effective technology for the maintenance of nutrient status of coconut palms by the application of inorganic and organic fertilizers. They also investigate the conservation of productive soil and improvement of sub optimal soils for coconut production as well as management of soil moisture for the sustainable production of coconut plantations in diverse soils and agro-ecological conditions. Furthermore suitability tests of non-traditional coconut lands are already part of the ongoing research.

As a public sector organization, CRI is primarily dependent on government funding (Consolidated Fund). However, reduced spending for research and extension due to severe budget cuts, increasingly affects research and maintenance activities of the Institute. Through international
collaboration via Peradeniya University however, new possibilities in the research arise, as shown by this study.

2.3. Application of apparent soil electrical conductivity in agriculture

In this study, the use of on-the-go electrical conductivity measurements to support land evaluation techniques will be examined. Because of the time and cost of obtaining soil-solution extracts, the measurement of EC shifted in the 1970s to the measurement of the soil EC of the bulk soil, commonly referred to as apparent electrical conductivity (EC<sub>a</sub>). Apparent electrical soil conductivity provides a very quick, simple and (relatively) inexpensive method all different kind of land-users can use to assess soil variability. The exact working principle of this system will be explained later, but in essence soil EC describes the ability of a soil to transmit an electrical current.

A first logical application of EC<sub>a</sub> in agriculture was for the measurement of soil salinity. Research in this area was primarily conducted by Rhoades and colleagues in the 1970’s at the USDA-ARS Salinity Laboratory in Riverside, CA. As described by Rhoades et al. (1989), the electrical conductivity of a soil containing dissolved electrolytes can be represented by conductance via the following pathways acting in parallel: (1) a liquid phase pathway via salts contained in the soil water occupying the large pores, (2) a solid pathway via soil particles that are in direct and continuous contact with each other, and (3) a solid-liquid pathway primarily via exchangeable cations associated with clay minerals (Rhoades et al., 1999a). To measure soil salinity only the first pathway is required; consequently, EC<sub>a</sub> measures more than just soil salinity. In fact, EC<sub>a</sub> is a measure of anything conductive within the volume of measurement. Therefore the agricultural application of EC<sub>a</sub> has evolved into a widely accepted means. However, EC<sub>a</sub> is a complex measurement that has been misinterpreted by users in the past due to the fact that it is a measure of the bulk soil, not just a measure of the conductance of the soil solution.

In a non-saline soil, the measured EC<sub>a</sub> is the product of both static (e.g. soil texture) and dynamic factors (e.g. moisture). Mostly, the observed conductivity is dominated by one or two different factors, which will vary from one field to another making the interpretation of an EC<sub>a</sub> signal very site specific. In fact even within a field, different influencing factors can determine the sensor’s output. It should also be stated that because EC<sub>a</sub> measurements can be dominated by those static and dynamic factors, as described by Johnson et al. (2003), interpretation of the data is not always straightforward.

Numerous EC<sub>a</sub> field studies have been conducted revealing site specific spatial EC<sub>a</sub> measurements with respect to the particular property influencing the EC<sub>a</sub> measurement at that study site. Corwin and Lesch (2005) made a compilation of all the physico-chemical and soil-related properties either directly or indirectly measured by EC<sub>a</sub> in literature. They concluded that the following properties are possibly reflected in an EC<sub>a</sub>-measurement:
• Directly measured soil properties
  o Salinity (+nutrients);
  o Water content;
  o Texture related properties (e.g. sand, clay, depth to claypans);
  o Bulk density related (e.g. compaction);
• Indirectly measured soil properties
  o Organic matter related (including soil organic carbon, and organic chemical plumes);
  o Cation Exchange capacity;
  o Leaching;
  o Groundwater recharge;
  o Herbicide partitioning coefficients;
  o Soil map unit boundaries;
  o Soil drainage class.

As is clear from this list, $EC_a$ measurements have the potential to reflect all kinds of soil related properties. Mostly, these soil properties relate with yield as well, so $EC_a$ can be an indirect measure of yield. Therefore these measurements have a great potential in agriculture, especially at low salinity, a property that dominates $EC_a$ measurements when present. Application of a proximal soil sensor in a developing country however is not very realistic since expertise knowledge is required as well as budget to obtain such a tool. Only through international collaboration and the help of crop research institutes, precision agriculture is a possibility in Sri Lanka and other developing countries.

2.4. Applications of $EC_a$ measurements in precision agriculture

In the search of ways to maximize returns in agriculture, Remote Sensing, Geographic Information Systems (GIS) and Global Positioning Systems (GPS) open up new possibilities. Precision farming is a management concept based on observing and responding to intra-field variability. The significance of within-field spatial variability has already been scientifically acknowledged and documented by Nielsen et al. (1973).

Conventional farming treats a field uniformly, ignoring the naturally inherent variability of soil conditions within fields. At present, the use of site-specific management zones, rather than the traditional whole field approach, is a popular concept to cope with field variability. Management zones (MZ) are delineated as sub regions, these sub-regions of a field are characterized by a relatively homogeneous combination of yield limiting factors. To achieve maximum overall efficiency specific management practices can then be defined for each of the defined sub-units (Doerge, 1999; Vrindts et al., 2005).

Site specific management or precision agriculture has the potential to change the way fields are managed through variable-rate application of inputs and/or amendments (Larson and Robert, 1991). The task of determining within-field zones is difficult due to the complex combination of factors that
affect crop yields. Basically, four possible approaches have been used to delineate soil management zones for site-specific management (Robert, 1989). The first uses traditional soil surveys (at a certain scale) that give a general understanding of the effect of soil mapping units on crop productivity, but they were not intended for making small-scale recommendations (Mausbach et al., 1993). A second approach is to use geostatistical interpolation techniques to estimate the spatial distribution of soil properties from a network of sample locations (Mulla, 1991; Corwin et al., 2003). But as mentioned before, this method is very expensive and time-consuming as a lot of soil samples are needed (Wollenhaupt et al., 1997). In a third method, yield maps are used to delineate management units (Eliason et al., 1995, Stafford et al., 1999). Long (1998) indicated that yield maps alone do not provide information about the inputs/amendments necessary needed to manage the observed differences in yield.

A fourth way is the use of temporally-stable data, such as bulk soil electrical conductivity (EC$_a$) or other remote/proximal sensing approaches. As stated before, EC$_a$ can be used to investigate and characterize yield variability. Soil EC$_a$ is, as explained above, an integrated measure of many soil properties, the most important of those are: salinity (Lesch et al., 1995), texture (Williams and Hoey, 1987), organic matter content (Banton et al., 1997), clay content, water content, and depths of conductive soil materials (Doolittle et al., 1994; Kitchen et al., 2005).

Soil EC$_a$ has become one of the most reliable and frequently used measurements to characterize field variability for application to precision agriculture due to its ease of measurement and reliability (Rhoades et al., 1999a, 1999b; Corwin and Lesch, 2003). Since the variability in soil EC reflects the cumulative variability of multiple soil properties, it is also a possible criterion to define management zones (Sudduth et al., 1995). For some soils, EC mapping appears to integrate soil parameters related to productivity to produce a template of potential yield (Kitchen et al., 1999, 2005). Johnson et al. (2001) found that management zones based on EC mapping provided a useful framework for soil sampling to reflect spatial heterogeneity and could potentially be applied to assess temporal impacts of management on soil conditions. Ferguson et al. (2003) concluded that management zones based on easily obtained soil EC measurement gave a better result than using slope and surface soil texture data. Islam et al. (2011) as well as Vitharana et al. (2008a) identified top soil EC$_a$, pH and elevation as key properties to delineate management zones, indicating the potential use of proximal soil sensing in land evaluation. Vitharana et al. (2008b) even used those key properties to improve existing soil-maps.

Integrating soil information with yield data to delineate subfield management zones can offer improvements on the techniques explained before. Franzen and Kitchen (1999) utilized a combination of different information layers such as topography, soil EC, soil survey data together with crop yield maps to construct management zones for N fertilizer management. Based on these zones, they proposed zone sampling to reduce the sampling costs.
It should be stated however, that precision agriculture studies relating crop yield directly to ECa frequently provide inconsistent results due to the complex interaction of the soil properties that influence the ECa measurement and the complex interaction of biological, anthropogenic, and meteorological factors that influence yield beyond soil-related factors, thereby confounding results (Corwin and Lesch, 2003). Nevertheless with the possibility of characterizing intra-field variability quickly using sensors offers great potential in developing site specific management or to assess the suitability of land more detailed.

2.5. **Land suitability assessment**

The concept of land in land suitability assessment and classification is wider than that of either soil or terrain. Land compromises the physical environment including climate, relief, soils, hydrology and vegetation to that extent that these influence potential for land use. The variation of each of the above factors influences the coconut productivity in varying degrees. However, within a region of fairly uniform climate, relief and hydrology, soil is the main cause of differences in the productivity of a particular crop.

**Land evaluation Framework**

A proper land evaluation can help agriculture to work more efficiently as the most suitable lands will be selected for a certain crop production. In 1976 the Food and Agriculture Organization of the United Nations (FAO) published *A Framework for Land Evaluation*.

The original Framework formulated principles of land evaluation and set out concepts, methods and procedures for a systematic biophysical and socio-economic assessment of the potentials for specific land uses likely to be relevant to the area. It provides detail on which factors or land qualities should be considered in the evaluation for different kinds of land uses and how to evaluate these qualities. For purposes of supra-national classification of potential productivity, climate and land resources were combined into agro-ecological zones (FAO 1978a, 1978b, 1980, 1981). Socio-economic aspects were also dealt with in subsequent guidelines on land evaluation for rainfed agriculture, forestry, irrigated agriculture and extensive grazing (FAO 1983, 1984a, 1985 and 1991 respectively), and for the special conditions of steep lands (Siderius, 1986). The modern methods of land suitability assessment that have been evolved in a systematic and scientific manner over the last decades, today constitute a powerful tool that could be used for several different requirements.

**Delineation of land units**

Land evaluation compares and matches each potential land use with the properties of individual parcels of land or land units (FAO, 2007). Although any parcel of land can be considered as a land unit, a land unit should represent an area that is, in terms of predetermined properties, different from surrounding land and can be assumed to have homogeneous land properties (FAO, 1984b). Depending on the type and objective of evaluation, small or large map scales are required (Samranpong et al., 2009; Ziadat, 2007).
In the context of precision agriculture, the size of land units should be kept as small as possible to limit generalization. However too many units can become unmanageable as each individual unit is considered individually regarding its land properties and requirements. Fortunately, thanks to technological advancements in the context of GIS often the decision about the size, number and delineation of land units is determined by data availability. Apart from the four typical approaches in delineating soil management zones in precision agriculture (explained above), some more land-evaluation based methods exist to delineate land units.

While soil type boundaries would probably be the most suitable delineation of land units for agricultural land uses, soil information is often not available at the required scales. Furthermore, variability of soil properties within mapped soil types often is substantial. Of course, land unit delineation can be the result of intensive soil sampling, but as mentioned before, this is an expensive and time-consuming technique. Another possibility is the use of land components instead of soil maps (Minár and Evans, 2008). Boundaries of land components as cliffs, valley floors and channels, often coincide with transitions in environmental land properties such as soil, climate and biology (Speight, 1977; MacMillan et al., 2004). However, the interpretation and mapping of land components have a strong subjective nature (Speight, 1977) and is extremely time and money consuming (Adediran et al., 2004). In the last decade the use of GIS and DEM provided a solution to this subjectivity and some procedures were developed for land surface segmentation based on these technologies (Dikau et al., 1991; Irvin et al., 1997; Romstad, 2001; Adediran et al., 2004).

As for topographical homogeneous or flat land however, other soil formation factors than topography will play an important role in resulting soil variability. The delineation of land units has been investigated using several other techniques. They include among others a mechanistic simulation model based on detailed soil inventory and climate records (van Alphen and Stoorvogel, 1998), multi-year yield estimates for cotton derived from Landsat Thematic Mapper imagery (Boydell and McBratney, 1999), multivariate K-means clustering utilizing temporal yield data (Cupitt and Whelan, 2001), morphological and spectral filtering of elevation data and soil EC combined in binary form (Zhang and Taylor, 2001) and the classification of remotely sensed imagery using supervised and unsupervised methods (Yang and Anderson, 1996; Stewart and McBratney, 2001).

Also continuous soil electrical conductivity (EC) measurements have been used directly to delineate either land units (Nehmdahl and Greve, 2001) or productivity zones (Kitchen et al., 2005), both based on textural differences. Other applications of EC₄ measurements in delineation of management zones have been described before (Applications in precision agriculture). As apparent soil electrical conductivity (EC₄) can be used to spatially characterize soil properties, an indirect application of EC₄ in delineating land units, or better land suitability units can be an alternative.
**Land suitability index**

The suitability of a given piece of land is its natural ability to support a specific purpose. A land suitability index has been computed for homogeneous land units using various methodologies. In most of the cases, first a given field or area is divided in different land units. For each land unit then there is the possibility to determine the suitability for a specific purpose based on the land characteristics and qualities of each unit. However, because in precision agriculture the ability arises to characterize soil variability continuously, suitability indices could be determined continuously in GIS. Because of the continuous nature of soil and landscape variation and uncertainties in measurements which can result in the misclassification of sites that just fail to match strictly defined requirements, the continuous determination of suitability is a logical step.

Several procedures to estimate the impact of land qualities on crop production exist. Some of these determine suitability by mathematical combinations. A well-known, simple method attributes a factor to each land quality that reduces the expected yield by a certain fraction. Example of this approach is "The parametric method" as defined by Sys et al. (1991). Parametric systems find their origin in field trials and fertility tests, where good correlations were found between crop productivity and land factors.

In the parametric approach all factors with a relevant impact on the land use potential /crop productivity get a numerical value (rating) ranging between 100 (for the best potential/productivity) and 0 (for the lowest potential/productivity). If a certain soil property forms a limitation for the intended land use, it gets a rating assigned proportional to its magnitude of limitation. A final index can be obtained by either multiplying or adding individual rating values.

**Parametric method for index calculation : the Sys System**

The first and best known parametric system for rating the quality of the land is the Storie index. In its original version, three factors: soil profile, texture of surface soil and a miscellaneous land factor including drainage, slope and alkalinity are included. In subsequent versions, slope got a separate score resulting in four factors. Each factor is scored as a percentage and multiplied. Adaptations of this system as the Sys parametric approach is an example of, may differ in the factors they include and in their mathematical manipulation (Verheye, 2008).

Because the land suitability class will be determined using arithmetic procedures (e.g. multiplication) combining all individual ratings, the number of land characteristics taken into account needs to be restricted to an absolute minimum of the most relevant properties. The recommended set of land characteristics in the Sys parametric approach always comprises following 5 land characteristics:

1. climate (one single rating)
2. slope
3. flooding
4. drainage
As our study area is found in the humid tropics, soil fertility-based characteristics are added:

6. cation exchange capacity
7. sum of base cations
8. organic carbon content

The land evaluation rating is realized by comparing the land characteristics (or qualities) with the requirements of the land utilization type. Ratings can be assigned to each of the selected land characteristics by consulting the requirement table set up by Sys et al. in 1993 (annex 3). In this study, no information is available on all the land evaluation-parameters. As they will be left out in calculating a final rating, possibly specific limiting factors will be excluded resulting in a biased result.

**Land suitability assessment for Coconut**

Land evaluation lends itself well to crops with distinctive physical requirements and a range of suitable conditions while being characterized by varying yields. Coconut (*Cocos nucifera* L.) grows on a wide variety of soils, tolerates salinity and pHs from 5 to 8, but thrives best on well-drained soils of at least 2 m depth with no hardpans. Similarly, a considerable climatic range is possible, but high humidities, mean annual temperature of 27°C, 1300-2300 mm mean annual rainfall and a small diurnal variation in temperature are ideal. In essence the performance of coconut depends on (Chan and Craig, 2006):

(a) **Rooting depth in the soil.**
   A thick quartz or gravel layer within a depth of 120 cm from the surface may inhibit the root penetration of coconut resulting in limited availability of moisture and nutrients.

(b) **Fertility status of the soil.**
   The nutrient availability in soils and the ability of soils to retain the applied fertilize nutrients in an available form to plants mainly depends on the nature of the clay mineralogy which in turn may depend on the soil parent material and the degree of weathering. Generally sandy soils are poor in soil fertility while loamy and clayey soils have better fertility.

(c) **Aeration and soil drainage.**
   Aeration or oxygen availability is very important for the performance of coconut. The aeration of a soil highly depends on the texture. In sandy textured soils (more than 70% sand), the particle size is larger, less cohesive, and less compact compared to loamy or clayey soils. In such soils, aeration or oxygen availability is high.

(d) **Moisture availability in the soil.**
   Moisture availability is mainly determined by climate, hydrology and drainage. Moisture stress is experienced by coconut palm depending on the duration of a dry period and the hydrological conditions of the landscape. In some soils no significant moisture stress is experienced by coconut palm because of the ideal rainfall distribution or hydrological conditions of the landscape.
These performance influencing factors are also incorporated in the landscape and soil requirements for coconut set by Sys et al. (1993). The limitation set by climatic conditions for coconut are described in detail by Peiris et al. (1995). The climatic requirements for coconut described by Sys et al. (1993) translate these climatic conditions into suitability terms. The ideal conditions for growing coconut set by Sys et al. (1993) corresponds to the climatic condition set by Peiris et al. (1995).

At soil and plant nutrient department of CRI itself, land suitability assessment was also performed already for coconut at Bandirippuwa estate (A coconut estate were the CRI is located). The resulting map from this research showed the land suitability for coconut on a 1:8500 scale (annex 2). The Great Soil groups defined under the National Soil Survey (De Alwis and Panabokke, 1972) were considered inadequate for the purpose of land evaluation. Each Great Soil Group was therefore subdivided into soil series. A soil series is defined as soils which are developed from the same parent material under similar conditions and having soil horizons similar in differentiating characteristics and arrangement within the soil profile.

As the variation in soil characteristics and qualities within a soil series is taught to be minimal, and correspondingly the performance of coconut, the soil series is considered as the appropriate mapping unit that could provide the necessary information on soils for the purpose of land suitability mapping for coconut. Based on the soil requirements of coconut, the coconut growing soil series of Bandiripuwwa estate were divided into five suitability classes (annex 2). A major limitation was found to be soil depth, as a petroplintite (hard laterite) layer in a part of the Red Yellow Podzolic soils (Boralu soil series) limit rooting conditions. Furthermore very high sand concentrations in the Latosols and Regolos (Sudu soil series) implies low moisture availability and low nutrient holding capacity forming another important limitation.

The FAO procedure for land evaluation is also demonstrated for farming systems which include coconut in the coastal belt of Tanzania by Nogwi J. and Stocking M. (1989). Also a case study in the Aceh Barat District (Indonesia) uses the same FAO guidelines to make a land use recommendation map (Ritung et al., 2007).

2.6. Summary

The traditional agricultural practices in Sri Lanka fail to respond to the observed yield variability in coconut-cultivation. The local institute tries to solve this problem and has made considerable efforts in this matter. Though partly because the local institute does not have the resources, still a lot of work is needed. Through international collaboration, new possibilities in the research arise which can help Sri Lankan agriculture and economy. A possible approach to cope with the yield variability of coconut would be the use of precision agriculture. By characterizing spatial variability of soil
properties through the use of soil-sensors, site specific management could offer an important mean to improve productivity.

Apparent electrical soil conductivity measurements appear to have numerous applications in agriculture in general and more specifically in precision agriculture. Their possibility of a quick and reliable survey, thereby exposing all kind of relevant soil properties regarding crop yield has made it the number one technique in precision agriculture. Introducing precision agriculture in the country might maybe not improve productivity per coconut tree, but it could improve overall productivity as small scale soil variability could be characterized and thereby suitability classes could be introduced.

Suitability classes are characterized by very specific soil properties, if a relation between these properties and the measured ECₐ can be established, ECₐ measurements, together with few soil samples, can be used to delineate suitability classes/land units. In this way, the typically intensive data-collection in land evaluation can be reduced thereby saving time and budget.
3. Materials and methods

First a suited location was chosen for the survey, after this an EC-survey of the study area was performed. Based on this survey soil sampling was performed to be able to give an interpretation to the variability observed in the EC₄-signal.

3.1. Selection and location of the study area

This study was conducted in collaboration with the Coconut Research Institute (CRI) of Sri Lanka. Therefore a coconut estate where the CRI was located (Bandirippuwa estate) was selected (Figure 2). The estate is located in the centre of the main coconut growing area of Sri Lanka: the coconut triangle. Within this region, coconut is grown across three main agro-climatic zones, the Dry zone, the Intermediate zone and the Wet zone. This land is found in the intermediate agro-ecological region of the country. With an average annual precipitation of about 2400 mm of rainfall (which has a good distribution throughout the year) and an average temperature of 28°C, the climate is highly suitable for the production of coconut (Sys et al., 1993). The Intermediate zone has the best combination of rainfall and solar radiation for the performance of coconut.

Figure 2: Location of the study area (Bandirippuwa estate) in Sri Lanka
3.2. **Description of the study area**

The selected field for the soil survey was managed by the CRI itself. For the whole estate a map of coconut growing soil series has been made at a scale of 1:8500 shown in annex 2. The isolated land parcel at the southern corner on this soil map, shown on the soil map in Figure 3, contains all 6 coconut growing soil series of the estate as defined by the CRI. The variability in this 20 ha land parcel is basically due to joint impact of erosion and marine sedimentation. This 20 ha will be the focus of this study.

![Soil Map of Bandirippuwa Estate](image)

**Figure 3: Boundary of the study area overlain on map with coconut growing soil series of Bandirippuwa estate (1:8500), CRI**

Based on the soil map of Sri Lanka (annex 1), soils found in this region are Red Yellow Podzolic soils with soft or hard plinthite, Latosols and Regosols on old and yellow sands and finally Alluvial soils. The Red-Yellow Podzolic soil is strongly mottled and consists of soft plinthite that hardens on exposure or has already hardened either massively or as gravel. The main limitations of these soils are depth and infiltration. Latosols and Regosols are reddish to yellowish and coarse textured, these soils possibly limit yield because of their low moisture content and their low capacity to retain nutrients. Alluvial soils have highly variable texture but mostly relative high amounts of silt and clay.

Different coconut growing soil series are defined within these soil units by CRI. A brief description of coconut growing soil series, chemical and physical characteristics of each soil type is given in Table 1. Each soil type is characterized by a representative profile. All the soil series found in this area are very sandy according to those profiles, so low conductivity values are to be expected here. No large differences between top (A horizon) and sub (B horizon) soil characteristics are shown indicating homogeneous profiles. Furthermore these soils are characterized by low organic matter content which is typical for this region.
The presence of a petroplintite layer and high amounts of sand determines limitations of the soil series in these areas. However, the soil series as defined by CRI do not explain all variability within the field. Different suitability classes are defined (annex 2) based on a very homogeneous study area (following the representative soil profiles by Wijebandara, 2006). As coconut trees in the estate all have the same age (25 years) and management practices are very limited except for increasing organic matter content by leaving crop residues, a basic evaluation of coconut performance upon a field visit is possible. Doing so, clearly the central and southern part have least productivity potential (small coconut trees, low relative production per tree). However, on a very short distance (to the east) best coconut growing conditions are found based on field observations. Suitability classes by CRI (annex 2) do follow this observed variability to a certain extent, but lack to explain the reasons for varying yield. Suitability analysis by CRI was to a great extent based on field observations together with the National soil map, rather than on a soil survey.

The soil survey with the DUALEM EC-sensor proved to be quite challenging as the terrain was very rough. Not every part of the above mentioned 20 ha could be surveyed due to the presence of houses, a small lake or too much undergrowth. The borders of the surveyed area are also shown in Figure 4.

![Figure 4](image.png)

**Figure 4**: Borders of the study area on the aerial image of Bandiripuwwa estate
Table 1: Description of each soil series, chemical and physical characteristics (after Wijebandara, 2010)

<table>
<thead>
<tr>
<th>Great soil group</th>
<th>Soil series</th>
<th>Depth</th>
<th>pH 1:5</th>
<th>EC</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
<th>O.M. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red yellow podzolic soil</td>
<td>Boralu Top soil (A-horizon)</td>
<td>4.9</td>
<td>47.7</td>
<td>77.9</td>
<td>17.1</td>
<td>3.5</td>
<td>1.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sub soil (B-horizon)</td>
<td>4.3</td>
<td>25.1</td>
<td>78.2</td>
<td>11.0</td>
<td>4.6</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>Red yellow podzolic soil</td>
<td>Pallama Top soil (A-horizon)</td>
<td>5.2</td>
<td>37.2</td>
<td>85.5</td>
<td>7.1</td>
<td>3.4</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sub soil (B-horizon)</td>
<td>4.8</td>
<td>34.1</td>
<td>87.1</td>
<td>8.5</td>
<td>3.3</td>
<td>0.63</td>
<td></td>
</tr>
<tr>
<td>Latosols and Regosols on old red and yellow sands</td>
<td>Madampe Top soil (A-horizon)</td>
<td>5.3</td>
<td>32.6</td>
<td>94.5</td>
<td>2.8</td>
<td>3.1</td>
<td>0.47</td>
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<tr>
<td></td>
<td>Sub soil (B-horizon)</td>
<td>5.2</td>
<td>25.1</td>
<td>88.4</td>
<td>3.3</td>
<td>3.9</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>Latosols and Regosols on old red and yellow sands</td>
<td>Sudu Top soil (A-horizon)</td>
<td>5.1</td>
<td>28.1</td>
<td>97.7</td>
<td>1.6</td>
<td>3.5</td>
<td>0.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sub soil (B-horizon)</td>
<td>5.0</td>
<td>26.6</td>
<td>93.6</td>
<td>2.5</td>
<td>3.0</td>
<td>0.68</td>
<td></td>
</tr>
<tr>
<td>Alluvial soils</td>
<td>Lunuwila Top soil (A-horizon)</td>
<td>5.3</td>
<td>29.6</td>
<td>94.6</td>
<td>0.9</td>
<td>2.7</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sub soil (B-horizon)</td>
<td>5.3</td>
<td>22.1</td>
<td>97.6</td>
<td>1.6</td>
<td>2.8</td>
<td>0.36</td>
<td></td>
</tr>
</tbody>
</table>
3.3. **Proximal soil sensing: electromagnetic induction**

The use of proximal soil sensing, more specifically apparent electrical conductivity, is key in this study, therefore this technique is explained in detail here.

**Principle**

Field instruments for measuring EMI-instruments contain a transmitter coil and one or more receiver coils at a fixed distance. By inducing a current in the transmitter coil, a primary magnetic field ($H_p$) is transmitted. This primary magnetic field creates eddy (alternating) currents in the electrically conductive soil. These time-varying currents induce their own magnetic field ($H_i$) (McNeill, 1980) which is superimposed over the primary field (Figure 5). A fraction of both $H_p$ and $H_i$ is intercepted by the receiver coil, where the signal is amplified and formed into an output voltage that is linearly related to $EC_a$ (Rhoades and Corwin, 1981).

![Figure 5: Basic principle of electromagnetic induction sensing](image)

**Instrument: Dualem 1S**

The DUALEM-1S is a compact, rugged ground conductivity/susceptibility sensor featuring a 1 meter transmitter-receiver separation with dual-geometry receivers. The transmitter and one of the receivers in a pair have horizontal windings, and these components form the horizontal co-planar geometry (HCP). The other receiver in a pair has vertical windings; it combines with the transmitter to form the perpendicular geometry (PRP).

DUALEM sensors can be applied to many types of shallow earth investigations as explained before. The sensor was designed for mechanized, cart or sled-borne, ultra-high-resolution soil surveys, and provides a 1.5 meter maximum depth of investigation. For the survey in Sri Lanka, a wooden sled was used as shown in Figure 6. A GPS is integrated and therefore GPS-data is collected simultaneously by a simple netbook through a serial port. Data was collected every second while walking the field, so a dense network of measurement points were collected.
Based on the different configuration of the DUALEM-1S transmitter and receiver coils, two different cumulative depth response profiles have been established. The cumulative sensitivities of PRP and HCP are plotted in Figure 7. The depth of exploration (DOE) is defined as the depth where 70 % of the response is obtained from the soil volume above this depth. This DOE has a value of 0.54 m for the PRP coil configuration and 1.55 m for the HCP. This means that EC$_a$-PRP is mostly determined by top-soil characteristics, while EC$_a$-HCP reflects deeper soil properties.
shift on the EC$_a$ measurements, this effect can be substantial especially when EC$_a$ measurements are low. All measurement need to be set to the same reference and corrected for drift during the measurements.

**Apparent Electrical conductivity**

Electrical conductivity is the ability of a material to transmit (conduct) an electrical current. EC$_a$ is an ancillary soil attribute which could be measured by either electromagnetic induction or electrical resistivity (Vitharana et al., 2008c). The conductivities of geological materials span many orders of magnitude. A convenient unit for terrain conductivity is the millisiemen per meter (mS/m) (Palacky, 1987).

The different soil properties reflected in an EC$_a$ measurement were described in the literature review. To measure EC$_a$, currently two basic types of sensors are used i.e. (i) electrical resistivity and (ii) electromagnetic induction based sensors. The noninvasive and immediate response of EMI sensors has made them very popular among others researchers, agricultural planners and farmers (Saey et al., 2009a) and this sensor will be used in this study.

3.4. **EC$_a$ survey**

The purpose of an EC$_a$ survey from a site-specific crop management perspective is to establish the within-field variation of soil properties influencing the variation in crop yield (Corwin and Lesch, 2003). Following the guidelines for an EC$_a$-survey established by Corwin and Lesch (2003), these steps were followed (adapted from Corwin and Lesch (2003)):

a) define the survey’s objective  
b) establish site boundaries  
c) establish survey strategy  
d) record site metadata  
e) geo-reference site boundaries and significant physical geographic features with GPS  
f) measure EC$_a$  
g) correct measured EC$_a$ for drift  
h) exploratory EC$_a$ analysis  
i) analyse the physico-chemical properties of interest as defined by the survey’s objective  
j) statistically analyze EC$_a$ data using soil samples taken based on the observed EC-variability

Additionally in this study a land evaluation will be performed based on the observed variability in both sensor measurements and soil samples.
3.5. **Soil sampling strategy and physico-chemical soil sampling data**

Soil samples of the study area were taken to interpret the ECₐ-observations. While choosing the sample locations, specific attention was given to the ECₐ-variability of both depth response measurements and the desired equal spread over the study area.

Maps of ECₐ were used to establish the soil sampling design. A directed sampling strategy was chosen to obtain an equally spread coverage of the whole study area while keeping an eye on the observed ECₐ variability. Thirty two sampling locations where chosen (Figure 8). The locations were fed to a GPS-receiver (Garmin eTrex 10) and at the time of sampling corrected.

On each of these sampling locations, a sample from the top soil (0-40 cm) and the deep soil (40-80 cm) was taken to characterize the soil. Composite soil samples were prepared from two soil augerings taken within 1 m radius of each sampling points. Those two soil samples were mixed and a sub sample (about 500 g) was taken. Each of these soil samples were air dried, crushed and passed through 2 mm sieve prior to analysis. The fraction that was separated during this stage is the percentage of coarse fragments.

![Figure 8: Location map of the soil samples in Bandiripuwwa estate](image)
It is important to determine significant physico-chemical properties influencing the parameter of concern, which in this case is crop yield. The performance of coconut chiefly depends on (Chan and Craig, 2006):
   a) Rooting depth
   b) Fertility status of the soil
   c) Aeration and drainage status of the soil
   d) Moisture availability
As however the whole area is characterized by a dry soil (and low water table, about 3m), aeration is not highly variable and does not form a real problem. Furthermore, an ideal rainfall distribution helps to avoid moisture stress. Important parameters to analyze were:
   a) Soil texture
   b) Cation Exchange Capacity
   c) Total exchangeable bases
Additionally, some general soil parameters were analyzed as well:
   d) pH
   e) Electroconductivity (saturated soil paste)
Organic matter is a soil property which also has an important influence on coconut performance. Organic matter helps to hold nutrients and moisture which are both important factors in coconut cultivation. However, in this case no information on organic carbon was measured. The methods used to analyze the soil samples are fully explained in annex 4.

3.6. Design of EC$_a$ map

Interpolation methods
With the Dualem sensor, measurements were made at regular time intervals following parallel lines as will be explained later. The measurements themselves are not located on a fixed grid and therefore need to be interpolated. With interpolation, the value of Z at an unknown position $x_0$ is estimated ($Z^*$) as the weighted average of all the measurements $Z(x_{\alpha})$ in the direct neighborhood around this unknown value.

$$Z^*(x_0) = \sum_{\alpha=1}^{n(x_0)} \lambda_\alpha Z(x_{\alpha})$$

In which $\sum_{\alpha=1}^{n(x_0)} \lambda_\alpha = 1$, $\lambda_\alpha$ is the weight attributed to each of the surrounding values $z(x_{\alpha})$. $n(x_0)$ is the number of observations in a predefined neighborhood.

The way the weight $\lambda_\alpha$ is attributed to the surrounding points differs according to interpolation methods. Mostly, ‘inverse distance weighing’ and ‘ordinary point kriging’ are used as interpolation techniques for dense proximal sensor-data.

Using inverse distance weighing, or inverse distance to a power, data are weighed during interpolation such that the influence of one point relative to another declines with distance from the
grid node. Weighing is applied to data through the use of a weighting power, which controls how the weighting factors drop off as distance from the grid node increases. The greater the weighting power, the less effect the points, far removed from the grid node, have during interpolation.

The equation used to determine the value of the weights \( \lambda_\alpha \) of an observation \( Z(x_\alpha) \) at a distance \( d_{0\alpha} \) of \( x_0 \) with Inverse Distance to a Power is:

\[
\lambda_\alpha = \frac{d_{0\alpha}^{-\beta}}{\sum_{\alpha=1}^{n(x_0)} d_{0\alpha}^{-\beta}}
\]

The weights are thus mostly determined by the distance \( d_{0\alpha} \) between \( x_0 \) and \( x_\alpha \) and a user-defined power \( \beta \). This implies that the closer this measurements are to the location of the unknown value, the more weight this measurement will get in the estimation of the unknown value. This also implies that this interpolation method is sensibly local, and that clustered points carry an artificially large weight. In the case of the sensor measurements used in this thesis, this can cause biased maps, as the measurements are made in separated lines, and more measurements are thus present in the lines than in between. Therefore another interpolation method is needed.

Kriging is a geostatistical gridding method that has proven useful in many fields. This method produces in essence visually appealing maps from irregularly spaced data. In Kriging a variogram model is used to assign weights to the neighboring measurement points instead of only using the distance.

This variogram model mathematically specifies the spatial variability of the data set and the resulting grid. The interpolation weights, which are applied to data points during the grid node calculations, are direct function of the variogram model (Naoum and Tsansis, 2004). The variogram is a measure of how quickly things change on the average. The underlying principle is that, on the average, two observations closer together are more similar than two observations further apart (auto-correlation). The models are expressed by a semivariance \( \gamma \), which quantifies this degree of spatial correlation between two points at a certain distance. In fact the semivariance measures the average dissimilarity between \( N \) pairs of measurements separated by a lag distance \( h \).

To determine which variogram model to use, an experimental variogram is needed. In this experimental variogram, or semivariogram, the dissimilarity between observations is plotted as a function of the separation distance (Groovarts, 1998). Theoretically, at zero lag distance, the semivariogram value is also zero. But due to sampling and assaying errors and due to short scale variability (i.e. spatial variation occurring at distance closer than the sample spacing), the variogram intercepts the ordinate at a point greater than zero (Vitharana, 2008c). This effect is called the Nugget effect. Other terms to describe the semivariogram are Range (Length) and Sill (Figure 9)
A theoretical variogram model has been fitted to the experimental variogram to estimate the semivariogram values at any lag distance and hereby smoothing fluctuations (Groovaerts, 1998). In this study, Linear models, Exponential models and Spherical models were used. This theoretical variogram model has then been used to calculate the semivariance between sampling locations and unsampled locations thereby the weights $\lambda_i$ can be obtained.

Surfer Golden Software was then finally used to create the continuous maps of the ECₐ grids calculated by Ordinary kriging interpolation. Values of ECₐ at the locations of sampling were determined using ESRI ArcGis.

**Interpolation ECₐ**

Ordinary point kriging was the interpolation method used. When fitting a model to the experimental variogram it is important to have a good fit at small lag distances. A resolution of 2.5 by 2.5 meters is chosen while kriging, based on the intended use and the detail required. The search ellipse, which defines the local neighborhood of points to consider when interpolating each grid node, was adapted.

The search radius in both directions is set to 50m, as the variogram model fit before was also focused on this distance. It is possible to make one radius slightly bigger to exclude the effect of measuring lines, but as in this study area the direction of measuring was constantly alternated, it is better to make use of a four-sector search, measurement points in each of all four sectors contribute to the calculated grid node.
3.7. Statistical data-analysis

Depth weighted soil properties

Samples were taken over depth intervals of 0-40 cm and 40-80 cm. In order to better relate results of the sample analysis to ECₐ measurements, ECₐ-equivalent sample results can be calculated. This method has been described by Saey et al. (2009b). As explained before, ECₐ measurements are determined by a depth response curve (Figure 7). This means higher contribution of specific depths to the signal. Using this cumulative response at specific depths, a weighted average of the different soil properties can be made using following equation:

\[ Z_{lw} = \frac{Zi_1 \ast (R(d_1)) + Zi_2 \ast (R(d_2) - R(d_1))}{R(d_2)} \]

Where \( Z_{lw} \) represents the weighted soil property, calculated based on the measured \( Zi_1 \), which is the specific soil property in the first soil sample (0-40 cm) and \( Zi_2 \), the soil property in the second sample (40-80 cm). These properties are weighted following the depth response curves which give a cumulative percentage \( R \) at a certain depth \( d \). This means \( d_1 = 40 \text{cm} \) and \( d_2 = 80 \text{cm} \). The cumulative depth response for the different coil configurations was given by McNeill (1980) for both the perpendicular \( (R_p) \) and horizontal \( (R_h) \) coil configuration:

- \( R_p = 2z(4z^2 + 1)^{-0.5} \)
- \( R_h = 1 - (4z^2 + 1)^{-0.5} \)

The lower boundary of sampling was 80 cm. However, the response of the measured ECₐ signal still has a contribution of the soil volume below this depth. Therefore the weighted response should be divided by the total response from the top 80 cm for both coil configurations. This value is 47% for the horizontal configuration and 84.8% for the perpendicular. Directly it is clear that our samples will not be able to explain all of the variability observed in the ECₐ signal. Especially in the case of ECₐ-HCP, only 47% of the response depth has been sampled.

Bivariate Analysis

As we want to analyze a possible relation between ECₐ-measurements and soil characteristics, bivariate analyses will be performed. This analysis includes the computation of a Pearson correlation coefficient, which is a measure of the linear correlation (linear dependence) between two variables. The goal of this study is to determine suitability of land using sensor measurements, therefore a relation should be found between the sensor measurements and the land characteristics which firstly influence coconut yield and secondly are reflected in the sensor-output. Spatial linear regression (SLR) models that relate sensor measurements (independent variable) to soil properties (dependent variable) are the outcome of this analysis.
3.8. **Design of thematic maps of relevant soil properties**

When significant relations are found between EC₅₆ measurements and measured soil characteristics, grids of those soil properties can be obtained. Using found linear relationships between sensor measurements and soil samples, sensor measurements permit to estimate a continuous spread of soil characteristics. However, this always implies an estimation error. Since those errors are found to be quite low and the suitability of an individual soil property mostly consists of a certain range, estimations are thought to be quite accurate.

As linear relations are found to be valid for only a part of the study area, estimations of soil properties could only be established in this part. For the other part then ideal growing conditions (for coconut) are assumed. Based on observations when sampling, not a big error is introduced doing so, because at every part where a certain soil property is limiting coconut production, this soil property could be characterized by sensor measurements.

3.9. **Continuous land suitability classification**

*Procedure*

The first step in a land suitability assessment is to identify, characterize and map the different kinds of soils occurring in the area. As thematic maps of relevant soil properties are now available, it is possible to recalculate those soil properties to land-evaluation rating regarding coconut at every location. This rating is based on the soil requirements table set up by Sys et al. (1993).

Every absolute value of a limiting soil property can be translated in a degree of limitation. Direct relations can be derived between soil characteristics and suitability rating for several soil properties as sum of basic cations, pH, slope and others through interpolation. A rating for texture however is based on the USDA-textural class, therefore an extra step is necessary that recalculates sand, silt and clay content to a textural class. This textural class can then easily be converted into a rating. When a rating needs to be assigned to a non continuous soil characteristic (e.g. textural class), in this technique the most favourable corresponding rating is selected.

In this study, coarse fragments (petroplinthite) are observed. In that case, a downgrading of the textural rating is required. The following criteria are used to determine the correction factor (%) to be applied to the textural rating :

- ≤ 5 vol% : correction =100  
- ≥5 and ≤ 75 vol% : correction = 100-0.929x(%gravel)  
- ≥75 vol% : this horizon is a root limiting layer

Finally then suitability maps of possible limiting soil properties are available. They can now be combined to get to an overall continuous suitability rating. Therefore the Storie method can be applied, the overall suitability index is calculated as follows :
$I = A \times \frac{B}{100} \times \frac{C}{100} \times \frac{D}{100} \times \ldots$

In which $I$ is the overall index and $A, B, C, D, \ldots$ are ratings of different (possibly limiting) soil characteristics.

Normally, all 8 parameters (mentioned in literature study) that are needed to express the fitness of the land characteristics following the parametric method are used in this overall index. However not all of them are available or relevant. Firstly data on climate is not relevant in this study as we are looking on a small scale. But it would be possible to include climatic data as well. Including a suitability rating for climate allows to compare different climatic zones. Further, flooding and slope are not relevant in this area, but again the possibility exists to include them. As measurements of elevation are provided by the sensor itself, a raster containing slope values can be used in the land evaluation. Also drainage is not included in the research. As all soils of the area are very sandy and dry however, and moisture availability does not form a limitation regarding climatic conditions, this does not form a major problem. Information about organic matter content however would possibly have had an influence on the result, but the samples were not analyzed for organic matter. However, the problem of low organic matter is well known in Sri Lanka and some management practices are already implemented.

**Approach to preliminary validation**

To ideally perform validation of the suitability classification, spatial yield data would be needed. As no specific information on the yield is available for Bandiripuwwa estate, an exact validation of the methods applies is impossible. However, because of the availability of other suitability evaluation research (CRI, annex 2) and field observations a qualitative validation to the outcome is possible.

**3.10. Testing the performance of proximal soil sensing in a contrasting agro-climatic zone**

During the visit to Sri Lanka, some tests with the DUALEM-1S were performed in another climatic zone as well. A 5 ha study field was surveyed in the dry-zone of Sri Lanka, where the climate is quite different. The so called dry-zone receives between 1200 and 1900 mm of rain annually. Much of the rain in these areas falls from October to January; during the rest of the year there is very little precipitation. It is clear that these conditions already form a limitation for the growing of coconut.

The field tests here were in close collaboration with an ongoing research at Peradeniya University, department of Soil Science. The objective of this research was to explore short scale variability of soil physical and chemical properties of the Reddish Brown Earth soil, the dominant great soil group in the dry zone of Sri Lanka (Panabokke, 1996). The same procedure as described for Bandiripuwwa estate was used here, except for the sampling procedure. Sampling was performed following a sampling grid plus random sampling because sensor measurements were not yet available at the time of sampling.
4. Results and Discussion

4.1. Exploratory $EC_a$ analysis

The actual data set contained 15072 data-points with information about their location, conductivity and magnetic susceptibility. The location of these data points in the field is shown in Figure 10. Some parts of the study area have less dense measurements due to difficulties with accessibility.

![Figure 10: Location of the measurement points of $EC_a$ in Bandiripuwwa estate](image)

To get an overview on the $EC_a$-data, Figure 11 shows the distribution of measured $EC_a$-PRP (apparent EC measured with perpendicular coil configuration) in a histogram. A very narrow distribution is found, but quite some data-points (about 6%) deviate from the overall pattern. These points are found isolated at the far ends of the histogram. The histogram shown in Figure 11 is zoomed in to clearly shown the outliers, highest frequency of data is 14133. The same result is found for $EC_a$-HCP (annex 6).
Figure 11: Histogram ECa–PRP total dataset Bandiripuwwa estate (max frequency= 14133 [0-5])

Also some summary statistics of the PRP and HCP ECa are shown in Table 2. Variance ($s^2$) and Coefficient of Variation (CV) indicate a very variable dataset.

Table 2: Descriptive statistics ECa measurements (n=15072) before filtering (m:mean, $s^2$: variance, CV: coefficient of variation)

<table>
<thead>
<tr>
<th></th>
<th>m</th>
<th>min</th>
<th>max</th>
<th>$s^2$</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECa-PRP</td>
<td>1.0</td>
<td>-412.3</td>
<td>187.8</td>
<td>43.2</td>
<td>669.3</td>
</tr>
<tr>
<td>ECa-HCP</td>
<td>4.9</td>
<td>-33.8</td>
<td>148.8</td>
<td>79.4</td>
<td>214.9</td>
</tr>
</tbody>
</table>

In the dataset of the coconut estate, a lot of outliers (in both conductivity and susceptibility data) were found. An outlier is a data point that comes from a distribution different from the bulk of the data. These values are very improbable regarding soil properties because firstly they are (geographically) isolated points and secondly their magnitude is either very high or very low. When including all these values in interpolation, resulting maps are biased at these locations (Figure 12). The location of the outliers generally is very scattered, although some areas have a larger number of deviant measurement points. When surveying the coconut estate, already a lot of metal objects and other garbage was found scattered at the surface. In particular in the northeastern part where a high number of deviating conductivity values were found, there were some remnants of a barbed wire fence.

In Figure 12 the location of these outliers is shown and an interpolation (via Inverse Distance to a Power) was made to show the influence of the extrema on the map. Only the northeastern part is shown on this figure, in the other parts of the field only few outliers were found.
Based on these observations, and no other explanation was found for the reason of these outliers, the dataset was filtered. Measurement points that did not have HCP-conductivity values between 2 and 10 mS/m or/and PRP-conductivity values between 0 and 3 mS/m were removed (based on both histograms and Stem-and-Leaf plots, annex 7). The resulting dataset contained 14154 measurement-points.

Table 3 shows the summary statistics of the DUALEM-1S EC₃ measurements obtained at the study site after filtering. A large reduction of the variance and coefficient of variation due to the elimination of outliers is clear while the mean remains unchanged. The mean EC₃ values measured with coil configurations that give a larger weight to deeper soil layers are the largest, meaning that the subsoil can be considered more conductive. Furthermore, the coefficient of variation tends to be lower at deeper soil layers, which indicates a more homogeneous sub-soil.

Table 3: Descriptive statistics EC₃ measurements (n=14154) after filtering (m:mean, s²: variance, CV: coefficient of variation)

<table>
<thead>
<tr>
<th></th>
<th>m</th>
<th>s²</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>mS/m</td>
<td></td>
<td>(mS/m)²</td>
<td>%</td>
</tr>
<tr>
<td>EC₃-PRP</td>
<td>1.1</td>
<td>0.3</td>
<td>47.6%</td>
</tr>
<tr>
<td>EC₃-HCP</td>
<td>4.9</td>
<td>1.1</td>
<td>21.7%</td>
</tr>
</tbody>
</table>

To further illustrate the measured bulk electro conductivity after filtering, two histograms shows the spread of the measurements of both coil configurations (Figure 13). These indicate slightly
asymmetrical distributions with positive skewness. Kolmogorov smirnov tests confirm the non-normality. Webster and Oliver (1990) indicated that the normal distribution is not essential in describing the spatial distribution of soil properties.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure13.png}
\caption{Histograms of bulk electro-conductivity (a)EC\textsubscript{a}-PRP and (b)EC\textsubscript{a}-HCP}
\end{figure}

\section*{4.2. Spatial variability EC\textsubscript{a} and soil properties}

\textit{Interpolation EC\textsubscript{a}}

A spherical model gives a quite good overall fit (Figure 14a), but it considerably deviates from the semivariance values at lag distances between 20 and 50 m. As the study area is only about 500m in length, it is better to focus on the best fit for smaller lag distances. In the case of the HCP-EC\textsubscript{a} and that of the PRP-EC\textsubscript{a} a linear model gives the best fit with the experimental variogram (Figure 14b and Figure 15). The parameters used to characterize the models are shown in Table 4 and Table 5.
Figure 14: Comparison modelfit experimental variogram HCP-EC_a (a) spherical model (b) linear model

Table 4: Parameters theoretical variogram model EC_a-HCP

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Spherical</th>
<th>Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0 (nugget variance)</td>
<td>0.14</td>
<td>0.155</td>
</tr>
<tr>
<td>C1 (sill)</td>
<td>1.22</td>
<td>/</td>
</tr>
<tr>
<td>a (range)</td>
<td>120</td>
<td>/</td>
</tr>
<tr>
<td>Slope</td>
<td>/</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Figure 15: Linear modelfit experimental variogram PRP-EC_a

Table 5: Parameters theoretical variogram EC_a-PRP

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Spherical</th>
<th>Linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0 (nugget variance)</td>
<td>0.1</td>
<td>0.11</td>
</tr>
<tr>
<td>C1 (sill)</td>
<td>0.21</td>
<td>/</td>
</tr>
<tr>
<td>a (range)</td>
<td>135</td>
<td>/</td>
</tr>
<tr>
<td>Slope</td>
<td>/</td>
<td>0.0018</td>
</tr>
</tbody>
</table>
**Apparent EC maps**

The resulting maps of apparent soil electro-conductivity measured with the different coil configurations (PRP and HCP) are shown in Figure 16 and Figure 17.

![Apparent EC maps](image)

*Figure 16: PRP EC$_a$ (mS/m) of the Bandiripuwwa estate*
The measured apparent electromagnetic conductivity was found very low. This was most likely caused by the fact that the soils in the estate are very sandy (about 80-90%) and highly weathered. Moreover, in the period previous to measuring, an exceptional drought occurred in Sri Lanka. Dry soils of course result in lower conductivities as well. Nevertheless, clear patterns are surely observed in both PRP-EC\textsubscript{a} and HCP-EC\textsubscript{a}. Yet these patterns are very different when comparing the two different measuring depth profiles. This is confirmed by a very weak (Pearson-) correlation of 0.276.

HCP-EC\textsubscript{a} tends to be a lot higher than PRP-EC\textsubscript{a} soil in some regions, indicating the fact that at those locations the sub soils is more conductive and soil profiles are heterogeneous. On the HCP-EC\textsubscript{a} map (Figure 17), a very sharp border is observed in the northeastern part of the study area which was not observed at the field-visit. This sharp transition is somewhat followed in PRP-EC\textsubscript{a}, but here a more smooth transition is found.

The differences between PRP and HCP-EC\textsubscript{a} are not constant over the study area. In the central part the magnitude of conductivity remains quite constant indicating a homogeneous soil profile. However, big differences arise in other parts which indicate heterogeneous soil profiles. Based on the soil properties (annex 4) the reason of this could be storage of water in deeper soil layers. This would
also explain the higher conductivities measured with EC\textsubscript{a}-HCP. The very sandy and gravelly parts still have low EC\textsubscript{a}-HCP, indicating their lower capacity to store water.

**Soil properties**

The location of the sampling points is shown on both the PRP and HCP-EC\textsubscript{a} in Figure 18.

![Figure 18: Location maps of soil samples on EC\textsubscript{a} maps of Bandiripuwwa estate (a) EC\textsubscript{a}-PRP and (b) EC\textsubscript{a}-HCP](image)

The data of the soil sample analysis is given in annex 5. Some descriptive statistics are given in Table 6. As the coefficient of variation measures the variability of measurements independently of the unit of measurement, they can be compared. The coefficient of variation as well as the variance/standard deviation suggest strongly variable soil properties. Only pH range is quite narrow. This is in contrast comparing to Table 1, set up by CRI, where all soil characteristics were quite homogeneous over the whole study area and even constant within soil series. The soil map in annex 2 should be based on these representative soil characteristics, but while making the soil map also field observations were incorporated. Therefore the representative soil profiles do not reflect the variability of soil series enough. This important variation in soil properties should be accounted for when classifying suitability.

No large differences are found between the samples at different depths (0-40 versus 40-80), indicating a quite homogeneous soil profile up to 80 cm. The differences in measurements with different coil configurations however indicate a clear difference. Probably at depths higher then 80cm, soil profiles will change (possibly higher moisture content).
Soils found in the southern and southeastern part typically have a petroplinthite (laterite-) layer formed. The so called ‘Cabook’, soft laterite which becomes irreversibly hard upon drying, made the sampling in this areas very hard as a hammer had to be used. These areas are known to require decent management to grow crops. The areas where this Cabook (which is prominent due to the low amounts of rainfall the last few months) is found are represented by Boralu and Pallama series on the map made by CRI. Red yellow podzolic soils are indeed known to have a subgroup with soft or hard plinthite. Looking at the samples, a very high gravel content arises at this locations. This gravel content will have an important effect on possible coconut-yield. Clearly the central part of the study area contains an increased amount of gravel.

The other places in the study area typically have low clay content (10%), low base saturation (0.5 cmol/kg soil) and high amounts of free sand (85%). They have poor water holding capacity and need good management for growing crops as well. For coconut growing however, these soils mostly have a good texture, and the coconut trees grow very good here if it rains regularly. The soil reaction is acidic and organic matter content is very low. The low organic matter and poor water holding capacity of these soils is currently treated by leaving coconut-leaves and husks on the field, husks are sometimes even buried directly to improve the soil water holding capacity.

The highest contents of free sand are found in the northeastern part of the study area. Soils with more than 90% sand are no exceptions here. All other places have sub-optimal soil texture for growing coconut based on the samples.
4.3. **Relationship between EC<sub>a</sub> and soil properties**

The bivariate analysis has been performed on all the available soil data, but only the most relevant ones are showed here. Correlations are shown between measured apparent EC and weighted soil properties (following the sensor’s depth response curves of both PRP and HCP).

Table 7: Pearson correlation coefficients between EC<sub>a</sub> and profile weighted soil properties (whole study area)

<table>
<thead>
<tr>
<th></th>
<th>elevation</th>
<th>gravel,w</th>
<th>silt,w</th>
<th>clay,w</th>
<th>sand,w</th>
<th>SBC,w</th>
<th>pH,w</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRP</td>
<td>Pearson</td>
<td>.253</td>
<td>.469</td>
<td>.191</td>
<td>.484</td>
<td>-.411</td>
<td>.634</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.163</td>
<td>.007</td>
<td>.303</td>
<td>.006</td>
<td>.022</td>
<td>.000</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>32</td>
<td>32</td>
<td>29</td>
<td>28</td>
<td>28</td>
<td>32</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>gravel,w</th>
<th>silt,w</th>
<th>clay,w</th>
<th>sand,w</th>
<th>SBC,w</th>
<th>pH,w</th>
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<tbody>
<tr>
<td>HCP</td>
<td>Pearson</td>
<td>.019</td>
<td>-.294</td>
<td>-.248</td>
<td>-.283</td>
<td>.299</td>
</tr>
<tr>
<td></td>
<td>Sig. (2-tailed)</td>
<td>.917</td>
<td>.103</td>
<td>.194</td>
<td>.137</td>
<td>.115</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>32</td>
<td>32</td>
<td>29</td>
<td>28</td>
<td>28</td>
</tr>
</tbody>
</table>

The relationships between EC<sub>a</sub> (PRP) with clay and gravel fractions (petroplinthite gravel) as well as sum of base cations were significant (0.01 significance-level), indicating the potential of EC<sub>a</sub> to be used as an ancillary information to predict these properties in this study area (Table 7). Furthermore, the properties showed to be reflected in the PRP-EC<sub>a</sub>, have an important influence on coconut-yield.

Good correlations with HCP-EC<sub>a</sub> are not found, partly because of the fact samples were only taken for the top 80 cm of the soil, which only contributes 47% to the signal. If the soil profile would be homogeneous at larger depths, still a good correlation is to be expected. In this case other factors will contribute at depths deeper than 80cm. Probably one of those factors is moisture content.

During the field visit, a clear difference in soil types was already observed. One of the observations was the presence of coarse fragments (petroplinthite gravel) in a part of the study area. The location map in Figure 19 shows where coarse fragments are found in the soil samples. Additionally the histogram in Figure 20 shows the frequency distribution of gravel content in these samples.
Figure 19: Location map of (depth weighted) samples with coarse fragments (%) in Bandiripuwa estate

Figure 20: Histogram of (depth weighted) coarse fragments (%) in samples of Bandiripuwa estate
A closer look to this map confirms the fact that gravel is only found in a certain part of the study area. Additionally, the histogram in Figure 20 suggest 2 different populations, in one part of the study area zero to little coarse fragments are found, while in the other part high content of gravel was found. In order to look closer into potential linear relations, the field is split in two parts based on this presence of gravel. The variability in the ECₐ signal is a contribution of different soil properties, but as no gravel is found in some areas, this factor can be excluded in those areas.

The study area map is thus split in two parts based on the presence of gravel. This gravel was already clear by visiting the field, but using the soil samples a clear idea of the location could be established. Based on Figure 19, showing the locations with coarse fragments the boarders of splitting are obtained. To a certain extent these borders are the same of those of the soil map by CRI in annex 2 (between boralu and pallama soil series). The two resulting sub-areas are shown in Figure 21.

![Figure 21: Stratification of the study area based on gravel presence](image)

In the petroplinthite rich zone a strong correlation is found between gravel content and the measured PRP-ECₐ using 14 samples (13-20 + 22-26 + 32) (Table 8). This correlation has improved since the dataset is split, as in the other parts few or no coarse fragments are found. The ECₐ-PRP signal in this area is clearly most correlated with weighted gravel content.
In the other part of the study area, the part where no petroplinthite gravel is found, following correlations are found (Table 9).

**Table 9: Pearson correlation coefficients of ECₐ and different soil properties (non-gravel part)**

<table>
<thead>
<tr>
<th></th>
<th>elevation</th>
<th>gravel.w</th>
<th>silt.w</th>
<th>clay.w</th>
<th>sand.w</th>
<th>SBC.w</th>
<th>pH.w</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRP</td>
<td>Pearson</td>
<td>.279</td>
<td>.223</td>
<td>.081</td>
<td>.817</td>
<td>.762</td>
<td>.850</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>.261</td>
<td>.375</td>
<td>.756</td>
<td>.003</td>
<td>.005</td>
<td>.000</td>
<td>.491</td>
</tr>
<tr>
<td>N</td>
<td>18</td>
<td>18</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>HCP</td>
<td>Pearson</td>
<td>.296</td>
<td>-.017</td>
<td>-.253</td>
<td>-.157</td>
<td>.224</td>
<td>.171</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>.233</td>
<td>.947</td>
<td>.328</td>
<td>.547</td>
<td>.388</td>
<td>.497</td>
<td>.352</td>
</tr>
<tr>
<td>N</td>
<td>18</td>
<td>18</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

Using the samples in this area(1-12+21+27-31), a clear relation is found between sum of base cations (weighted) and ECₐ-PRP (Table 9). Furthermore, this result indicates that clay and sand (which of course are interacting parameters) also correlate with the observed ECₐ-PRP, sensor measurements seem to reflect texture very good. Texture and sum of base cations are of course strongly interrelated.

The soil characteristics which have a significant (0.01-level) influence on the ECₐ-measurements following the bivariate analyses are found to be : gravel content, clay (or sand content) and sum of base cations. Based on the ultimate goal of this study, these findings are promising as coconut productivity potential/land suitability is strongly determined by these properties.

Based on the landscape and soil requirements for coconut, the possibility of predicting soil characteristics with ECₐ measurements to the found soil characteristics can now be investigated.

### 4.4. Prediction models

Using an linear regression model for the whole field is impossible since clearly at different parts, different factors determine the sensor-output. Therefore, the field was divided in different areas. This is also a logical step regarding land evaluation. As it seems, the ECₐ signal is influenced the most by that factors which might limit yield in every zone of the study area. The zone where high gravel content is found, texture class (USDA) is sandy clay loam to sandy loam, which only has slight limitation. The gravel content itself however can make the soil completely unsuitable, and it is this gravel content that is reflected by the sensor measurement. In the zone where little to no coarse
fragments are found, the sensor signal is made up by contribution of soil texture (sand/clay content) and sum of base cations, two (related) soil characteristics which also have their influence on coconut-yield.

Only significant linear relations are expected for the sub areas where significant Pearson correlations were found. Linear relations between EC$_a$ and weighted soil properties are only valid at those locations where the sensor signal reflects the respective soil properties. This means that land evaluation will be based on a very limiting number of soil properties, mostly only one, sometimes two (sum of base cations + texture). This seems incorrect, but looking at the sample data, no other factors are limiting coconut yield noteworthy anywhere. Using only the most limiting factors which are in fact reflected in EC$_a$-measurements and not regarding other optimal (or sometimes sub-optimal) factors will only create a small error. In the parametric method, all the other ratings will assumed to be 95 in the case of texture and 100 in the case of SBC. It is quite stunning though, that exactly the parameters that limit yield are reflected in sensor analysis at every location.

The best linear relations are expected where Pearson correlation is highest, so for gravel of course only the part were gravel is present will be reviewed, the other parts will get a rating of 100 regarding land evaluation, since they form no limiting factor. Since sum of base cations is high enough for coconut production in the gravel part, a rating only needs to be calculated for the rest of the field. A very low clay content (meaning a very high sand content) can finally also limit yield, since this problem only arises in the northeastern part, linear relations in part 2 will be enough to implement this.

We want to use perpendicular sensor measurements which are available quite contantly to predict soil properties at every location, therefore relationship between EC$_a$-PRP and the properties will be established.

Four linear regression models are found were sensor measurements can be used to predict soil characteristics, the model characteristics and performance is summarized in Table 10.

- Part 1: Gravel content (%) = 8.163 + 29.172 * EC$_a$-PRP

- Part 2:
  - Sum of base cations (cmol/kg soil) = -0.785 + 2.567 * EC$_a$-PRP
  - Clay content (%) = -1.423 + 6.678 * EC$_a$-PRP
  - Sand content (%)= 95.841 – 6.717 * EC$_a$-PRP
Table 10: Summary linear model characteristics and performance

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
<th>s</th>
<th>t</th>
<th>Sig.</th>
<th>R²</th>
<th>STEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>intercept</td>
<td>8.163</td>
<td>10.506</td>
<td>0.777</td>
<td>0.452</td>
<td>0.520</td>
<td>12.18%</td>
</tr>
<tr>
<td>ECa-PRP</td>
<td>29.172</td>
<td>8.094</td>
<td>3.604</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SBC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>intercept</td>
<td>-0.785</td>
<td>0.428</td>
<td>-1.836</td>
<td>0.085</td>
<td>0.722</td>
<td>0.603 cmol/kg soil</td>
</tr>
<tr>
<td>ECa-PRP</td>
<td>2.567</td>
<td>0.398</td>
<td>6.451</td>
<td>0.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>intercept</td>
<td>-1.423</td>
<td>1.625</td>
<td>-0.876</td>
<td>0.404</td>
<td>0.672</td>
<td>2.63%</td>
</tr>
<tr>
<td>ECa-PRP</td>
<td>6.678</td>
<td>1.504</td>
<td>4.439</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>intercept</td>
<td>95.841</td>
<td>1.911</td>
<td>50.15</td>
<td>0.000</td>
<td>0.603</td>
<td>3.74%</td>
</tr>
<tr>
<td>ECa-PRP</td>
<td>-6.717</td>
<td>1.769</td>
<td>-3.797</td>
<td>0.004</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Gravel content can be predicted using the linear model, but has only an $R^2$ of 0.520. This is not the best estimate, but still it is enough to evaluate land suitability as the range of gravel in every suitability is quite large itself. At every part every regression models is valid, the predicted soil characteristic(s) can be estimated. The other parts will get ideal soil characteristics regarding coconut cultivation for those particular soil properties, which is based on observations.

4.5. Estimation of soil characteristics

The maps (Figure 22-23) show predictions of sum of base cations and gravel content, they could be classed following the limits for land evaluation set by Sys et al. (annex 3). As explained before, predictions can only be made where linear relations are valid. At every other location the specific soil properties get an ideal score regarding land evaluation. Of course possibly a small error is introduced doing this.
Figure 22: Prediction sum of base cations, cmol(+)/kg soil
Figure 23 : Prediction gravel content, %

Regarding texture, maps of clay as well as sand are made, based on these two then a texture class can be determined in GIS (using the textural triangle of USDA). This is because land evaluation is based on textural class. This texture class can then be converted into a rating (Figure 24).
4.6. Land evaluation

The maps of estimated soil properties can easily be transformed into a rating using the parametric method as explained in the Materials and Methods section. Using the landscape and soil requirements as defined by Sys et al. (annex 3) following relation between soil characteristics and land-evaluation-rating is derived for sum of base cations

\[ I_{SBC} = 8.3333 \times SBC + 71.667 \]

In which \( I_{SBC} \) is the rating calculated based on the sum of base cations, \( SBC \) (cmol(+)/kg soil).

For texture, the USDA textural class can directly be converted into a rating. This rating is 60 in the case of sand soils or 95 when textural class is sandy-clay-loam, sandy-loam or loamy-sand (Figure 24) following the requirement table by Sys et al. (1993).

![Image of land evaluation rating graph]

Figure 24: Suitability rating for texture

Clearly, texture is closely related to sum of base cations (Figure 22 and Figure 24). Low sum of base cations is found at locations with high sand content. This is of course logical as sum of base cations is closely related to texture. Low clay content typically results in low CEC and low sum of base cations.

The rating calculated based on textural class (Figure 24) can be corrected for gravel content using following formula:
\[ I_{text-correct} = I_{text} - (100 - 0.929 \times Gravel) \]

In which \( I_{text-correct} \) is the rating calculated based on the texture rating \( I_{text} \) and the gravel content \( Gravel \).

Using these equations, the maps which contain the different soil properties can now be transformed into rating-maps of texture/coarse fragments and of sum of base cations. Doing this the maps in Figure 22-24 are simply recalculated into a score. This score represents a suitability of the specific soil property regarding coconut cultivation.

An overall suitability index is finally determined by applying the Storie method using the available ratings:

\[ I = A \times \frac{B}{100} \]

in which \( I \) is the final index, based on the individual ratings \( A \), which is the rating for sum of base Cations and \( B \) which is the rating for texture (corrected for gravel content).

Finally then a map representing the suitability score at every location was obtained (Figure 25). The obtained scored can be classed into suitability classes using Table 10 set by FAO resulting in a classed map (Figure 26). Of course in the calculation of the ratings, at every location every single estimation is used, classing the ratings is only a final step.
Figure 25: Actual suitability rating for coconut

Table 11: Index values for the different suitability classes (FAO)

<table>
<thead>
<tr>
<th>index</th>
<th>suitability class</th>
</tr>
</thead>
<tbody>
<tr>
<td>75-100</td>
<td>S1, very suitable</td>
</tr>
<tr>
<td>50-75</td>
<td>S2, moderately suitable</td>
</tr>
<tr>
<td>25-50</td>
<td>S3, Marginally suitable</td>
</tr>
<tr>
<td>0-25</td>
<td>N, unsuitable</td>
</tr>
</tbody>
</table>
Figure 26: Actual Suitability classes for coconut
These maps (Figure 25-26) show very sharp borders which are quite strange for soil maps. This is caused by the fact coarse fragments are only found in the central part of the field, and are only limiting yield here. In the other parts, sum of basic cations and soil texture are limiting yield, but not to that extend that gravel content is. Coarse fragments are only found in the central part, where it’s concentration is fairly high. In the other parts no gravel content is measured.

The suitability maps are based on gravel content, soil texture and sum of basic cations. It are these 3 parameters which are related to EC<sub>a</sub>-PRP. Possibly in reality, also other factors play a role. As no relation has been found with EC<sub>a</sub>-HCP with sampling to a depth of 80 cm, probably new factors will play a role here as EC<sub>a</sub>-HCP reflects conductivity-values from below 80 cm as well (53% of total). Moreover no information is available on drainage class, organic carbon and soil depth, which are also parameters which can limit yield.

Limiting factors defining the suitability for coconut are physical soil characteristics (land-suitability subclass s) and soil fertility characteristics (f). Regarding management, physical soil characteristics are hard to improve as the reason for yield-loss is gravel content. Plinthosols come with considerable management problems. Most petroferric soils are unsuitable for arable farming, they are used for extensive grazing and firewood production (Driessen and Dudal, 1989). Plinthite formation and its subsequent hardening pose a big threat to agricultural production (Asiamah and Dedzoe, 1998). Soil fertility characteristics however, could be improved with using inputs. Therefore potential suitability is not equal to actual land suitability (which is in fact on the map in Figure 26). The high amounts of sand limit yield because of the low nutrient availability (and in a small extend also low moisture availability, but thanks to climatic conditions, this is not really an issue here). Both problems could be managed by incorporation of organic material and split applications of fertilizers.

It is also important to consider site specific socio-economic conditions, local contexts and farmers’ preferences in the land use planning process. Not every, based solely on soil characteristics, suitable lands are possible to use as agricultural land.

4.7. Discussion

Basically sensor measurements are used in this study to obtain suitability classes for coconut growing soils. However, in the method described in this study, field observations as well as samples are still very important. Not only do they determine the observed EC<sub>a</sub> variability but more importantly the samples helps to identify limiting soil characteristics regarding coconut cultivation. The actual benefit of using a sensor in these areas is firstly the ability to determine a very efficient sampling pattern and secondly estimating important soil characteristics in the whole field on a big scale (very detailed), resulting in very detailed suitability maps.

Another possible way of approaching would be to classify the field into management zones based only on sensor measurements (Fuzzy classification). After this the different zones could be
characterized using soil samples which determine the suitability for coconut for each of these zones. However in this method relative homogeneous soil characteristics are needed in every based-on-sensor-measurements zone. This would not be the case in this study as firstly different soil characteristics are reflected in sensor measurements depending on the location of measuring. More importantly, locations who have the same magnitude in EC₅ measurements would be classed in the same zone. Since EC₅ measurements are determined by other soil characteristics but still obtaining the same magnitude however, this would result in strange results. For example, a high gravel content results in a high EC₅-PRP (Figure 16 and Figure 23). The same high EC₅ values are found however at locations with high clay content (Figure 16). While they have the same values for apparent EC, they result in very different suitability classes for coconut cultivation, as high clay content is favorable for coconut growing while high gravel content is limiting.

Therefore, in this study, the option to use the requirement table as a tool to define suitability zones directly is chosen. This implies that still samples and field observations are necessary. If however, the sensor measurements would reflect the same (coconut-limiting) soil properties in the whole field, in other words if no gravel would be present, the extra step of stratifying the field would not be needed. In this case only a few samples would be enough to create a suitability map for the whole field.

### 4.8. Land evaluation validation

When comparing the final suitability outcome (Figure 26) based on the sensor measurements with the available map of coconut growing soil series by CRI (annex 2 and figure 2), following observations are made. First roughly the same limiting factors for coconut cultivation are identified. EC₅ measurements are found to reflect not only the presence of coarse fragments, in this case petroplinthite gravel, but also limiting soil texture is identified. Secondly, as it is possible to identify variability detailed using sensor measurements, the spatial extend of the soil limitations is found to be somewhat different then the estimations by CRI. Coarse petroplinthite fragments are found to be very limiting, but only if they are present in high concentrations (>50-60%). As other soil properties in the area with gravel are found to be optimal or sub-optimal for coconut cultivation, suitability classification by CRI is too strict. In fact, the soil series as defined by CRI are still not detailed enough to perform small scale suitability assessment, soil characteristics within each soil series have been generalized too much. Locations of marginally suitable zones however (S5 in figure 2, S3 in figure 26) are roughly the same in both land-evaluation systems.

The spatial extend of the sandy soil texture however is highly correlated with the findings by CRI. The Sudu soil series as defined by CRI are very sandy, resulting in low nutrient and moisture holding capacity. This low nutrient holding capacity and sandy texture is reflected in sensor measurements and also result in marginally suitable lands. Again, in absence of petroplinthite gravel, sensor measurements would be able to characterize land suitability more easily as they reflect (apart from
soil depth) the most important soil properties for coconut cultivation: moisture availability, aeration and fertility status.

Based on field observations, the final outcome of this study (Figure 26) presents a good representation of the variation of yield in the study area. However, the petroplinthite zone does seem to result in lower yield then the area where high sand content is found. This is because the easier manageability of texture-limited coconut growth. Already some management practices were performed as leaving crop residues on the field to improve water storage as well as nutrient holding capacity. Nevertheless rainfall was exceptionally low in the months before survey, a good distribution of that rainfall permitted a good moisture uptake of coconut trees. Furthermore management practices in the petroplinthite part were absent, which resulted in difficult accessible land due to rough undergrowth (Figure 10).

4.9. **Comparison of EC<sub>a</sub> behavior in the Dry zone**

Only a short resume of the results obtained here will be given as this was not the objective of this study. However, surveying another agro-climatic zone of Sri Lanka indicated the potential use of precision agriculture-tools in the whole country.

**Samples and EC<sub>a</sub>**

The spatial distribution of EC<sub>a</sub> measurements of the study area in the dry zone (Mahailluppallama) is shown in Annex 6. High EC<sub>a</sub> measurements are observed in the northern and eastern part of the study area. As these high measurements are caused by in the first case a salt patch and in the second case the use of hydrogel in the chili field, they may not be very useful in further analysis. Extra information about Kriging parameters, sampling locations in this study area are summarized in annex 6.

Descriptive statistics of measured soil properties are given in Table 11. The mean percentages of sand, silt and clay percentages imply that average soil textural class of the research field is sandy clay loam according to the USDA textural classification. Variability of silt, clay and EC is considerable within the study area, while the other soil properties are quite narrow.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Median</th>
<th>CV (%)</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay %</td>
<td>23.6</td>
<td>23.7</td>
<td>17</td>
<td>15.3</td>
<td>33.3</td>
<td>0.22</td>
<td>-0.35</td>
</tr>
<tr>
<td>Sand %</td>
<td>59</td>
<td>58.7</td>
<td>9</td>
<td>49.9</td>
<td>74.5</td>
<td>0.52</td>
<td>0.35</td>
</tr>
<tr>
<td>Silt %</td>
<td>11.5</td>
<td>11.1</td>
<td>24</td>
<td>6.3</td>
<td>18.6</td>
<td>0.21</td>
<td>-0.26</td>
</tr>
<tr>
<td>EC [dS/m]</td>
<td>0.04</td>
<td>0.04</td>
<td>32</td>
<td>0.02</td>
<td>0.09</td>
<td>1.13</td>
<td>2.21</td>
</tr>
<tr>
<td>pH</td>
<td>4.94</td>
<td>4.92</td>
<td>7</td>
<td>4.32</td>
<td>6.17</td>
<td>1.12</td>
<td>1.85</td>
</tr>
</tbody>
</table>

As the sampling depth at this site was only 30 cm, it doesn’t make sense to include HCP-measurements into the correlation analysis. It should also be stated sampling was performed in June,
while an EC-survey was only done by the end of August. Pearson correlation between EC$_a$ and other measured soil properties did not show significant correlation. But as mentioned, the EC$_a$ measurements in the areas where either hydrogel is used or salt is found, could be the cause of this. Presence of extreme EC$_a$ values could have masked overall correlation. When the sample points in those areas of high salt content and hydrogel are left out, a significant correlation is found between EC$_a$-PRP measurements and clay content, indicating potential to use the measurements here as well in land evaluation or precision agriculture.

**Figure 27**: EC$_a$-PRP of Mahailluppallama study area

**Conclusion**
Electro conductivity values are quite variable at the different locations in Sri Lanka. The main reason for this is that measuring fields are found in different agro-climatic zones of the country. As climate is the main influencing factor on soil formation, other soils are to be found in different agro-climatic zones. The wet zone and intermediate zone of the country, where the coconut estate is found, typically has very weathered soils because of the high temperatures and big amounts of rain. Because of this of course CEC tend to be very low. Combined with very high sand contents, EC$_a$ values typically are very low, making interpretation difficult. Moreover, due to this low conductivities, errors have a greater effect on the result which should be handled with care. The dry zone soils have lower amounts of sand and higher CEC (or thus less weathering) and therefore they result in higher conductivities.
Sampling in the dry zone showed that EC, clay and sand content of the soil are strongly variable within this study field. They could serve as attributes to identify contiguous areas within the field, delineating different management zones. Conducting an EMI survey shows potential to identify saline patches, these areas can then be carefully managed to avoid the problems related to high salinity. The relationships between EC$_a$ and clay-content was significant, indicating the potential of EC$_a$-measurements to use as an secondary information source to predict soil texture. But as this correlation is quite low, EC$_a$ measurement variability should be explained using more (or a combination of) parameters.

Nevertheless since sensor output significantly correlates with soil characteristics, and those soil characteristics are very variable within the study area, possibilities of using the EMI sensor (or precision agriculture in general) arise.
5. Conclusions

The island of Sri Lanka has a wide variety of temperature and rainfall regimes resulting in a wide variety of soil types. As various land characteristics such as texture, CEC and others are very variable on a small scale as well, the use of site specific management could offer great possibilities in agricultural practices. Of course, it is not obvious for farmers of a developing country to perform precision agriculture, so a lot of help from research centers is needed in this. Not only the use of this EMI sensor, but also more instruments should be included in the survey. Also still a reality check needs to be done for the different sites, as a survey does not give a direct image of the yield.

In this study, using an EMI sensor proves to provide a solid base to perform land suitability classification as the crop limiting soil characteristics are reflected in the sensor output. Of course it is possible other soil properties on which no information is available, still affect coconut yield in this area. Previous studies by Wijebandara (2010) imply that percentage of organic matter could also be a limiting factor regarding coconut cultivation (Table 1) following the crop requirements by Sys et al. (1993), annex 3. However, the problems regarding low organic matter are well known in Sri Lankan agriculture and already a lot of management practices are part of daily activities. In coconut cultivation this practices include leaving palm leaves on the field and burying coconut husks. Furthermore, previous suitability classification was also based on drainage conditions, a factor no information was available on in this study. Nevertheless soil samples have been analyzed thoroughly and a lot of possible yield-influencing factor have been reviewed.

Even though surveys of EC_a are a quick and reliable means of characterizing spatial variability of a variety of physico-chemical properties, there still are major limitations. Response of an EMI-sensor is very site specific, therefore soil samples remain needed. The big advantage is the possibility to reduce sampling. However, EC_a-directed soil sampling can only spatially characterize soil properties that correlate with and are measured by EC_a. If there are other soil properties that significantly influence yield but are not shown in EC_a measurements, delineation of management zones based on this EC_a measurements becomes very difficult. Furthermore, in order to be able to completely explain observed EC_a-variability, soil samples up to 150 cm are desirable. This was not the case in this study as time and resources for sampling was quite limiting.

The parametric method in land evaluation permits to include slope and climate, indicating its potential to apply in different agro-climatic zones. Also information on drainage, flooding and organic matter could be included. Land-evaluation has no specific rules, methods applied are adapted to specific site conditions and the available information. When more information can be included, a more correct land suitability classification is expected. However this regularly is an obstacle in land evaluation as time and money are very scarce. In this perspective, using sensor measurements proves to provide a possible alternative to intensive sampling. Furthermore the crop requirements used in this study are the ones defined by Sys et al. (1993). These are widely used tables, but still
different crop-requirements listings exists. For example the requirements for growth of coconut defined by Djaenudin et al. (2003) are slightly different which can result in a different outcome.

The final suitability map (Figure 26) however shows very sharp borders, which is not very convincing in soil science. As soil properties show gradually spatial changes in general, gradually changing suitability scores should the outcome of this research. The reason for this sharp border however is caused by the appearance of coarse fragments at a very specific sub-area of the field. At other parts, no coarse fragments are found whatsoever. As this coarse fragments form a strict limiting factor regarding coconut cultivation, their appearance has a great effect in the suitability score. Probably by raising the number of sampling points, a more gradual change in gravel content would be found resulting in more gradual changes is suitability score. The good relation with coarse fragments appearance and sensor output, masks other variable soil properties in these regions. Thereby the possibility of setting up linear relations in the whole field is eliminated. If this was not the case again a more gradually changing suitability map would be the result.

EC_a-measurements mostly reflect only a limiting number of soil properties (significantly). Chances of finding exactly those soil properties who limit specific coconut yield are rather slim. However in this study, at every location, exactly those soil properties who limit coconut yield are reflected in sensor measurements. This will not be the case in every field. The method used to perform land suitability classification could be applied at every field where at least one yield limiting soil factor is reflected in sensor measurements thereby reducing the number of samples needed to perform solid land suitability classification.

Samples will remain needed in every case. They are used to explain observed bulk electrolytic conductivity variability, but in land evaluation they are also needed to determine possible yield limiting soil properties. Probably the sensor output will be used more as an extra information source together with soil samples in land evaluation. Using the parametric method for land suitability classification it is possible to combine kriged maps based on soil samples alone with recalculated (via for example linear relations) EC_a maps. Thereby different information layers are combine to determine an overall score. This is the direction land evaluation, but also soil science in general will most likely take.
6. Further work

There is no question that geospatial measurements of ECa have found their place in site specific management research and they will likely continue to serve a significant role in the future. However it remains difficult trying to relate ECa measurements to yield, as different soil properties are reflected. Moreover the soil properties reflected in the electro conductivity signal are very site specific, so an working procedure cannot be established for the general application. Up until now it has been needed to relate the signal found with soil properties using soil sampling. Though sampling can be optimized using the EC-survey, it remains a time and money consuming factor.

Possibly however through the integrated use of multiple remote and ground-based sensors, a more general working procedure could be established, thereby eliminating the need for samples. However, this is a method situated in the far future as a lot of work will be needed for this. As this principle is not even established in developed countries, the use of those methods (regarding precision agriculture) in developing countries is still far away.

As for a possible application in Sri Lanka, both visited climatic zones showed a large variability of soil properties on a small (within field) scale indicating the potential of precision agriculture. Through international collaboration, the introduction of new technologies helping the local institutes to perform this precision agriculture is possible. Of course it is not evident for local farmers to perform precision agriculture, so the role of local institutes and educational systems will be crucial.

As this study was the first of its kind in Sri Lanka, still a lot of improvements are necessary. Firstly, soil samples should be taken be able to maximally explain sensor-measurements variability (depth and soil characteristics). However, when working in the context of land evaluation, it is advisable to only sample to the rooting depth of the specific crop that is reviewed, thereby saving work. Subsequently, if possible, yield data should be included. A possible relationship between mapped ECa and yield could offer a quick alternative. In that case ECa-measurements could serve as a foundation for delineating productivity zones. Furthermore the yield data could be used as an extra information layer or as a tool to evaluate land suitability classification.
7. References


Annexes
annex 1: Soil map of Sri Lanka
annex 2: Soil map of Bandirippuwa estate

Well drained to moderately well drained, moderately deep soils with yellowish brown to dark brown sandy to loamy surface horizons with hard ironstone gravel over brownish red to red hard ironstone gravel & yellowish clayey sub soil. Land suitability Class is S4.

As described above, but with the gravel layer having a thickness more than 15cm consisting more than 50% gravel & occurring of a depth of 50cm or less. Land suitability Class is S5.

Moderately well drained to imperfectly drained, deep, dark brown to yellowish brown coarse loamy soils with hard ironstones in the lower part of the profile. Land suitability Class is S2.

Moderately well drained to imperfectly drained, deep, light grayish brown to yellowish brown, coarse loamy over fine loamy soils. Land suitability Class is S1.

Poorly drained, deep, light gray to grayish brown sandy soils. Land suitability Class is S6.

Imperviously drained to poorly drained, deep, dark yellowish brown to brown & light brownish gray & light gray sands of alluvial - colluvial deposits. Land suitability Class is S3.
Suitability class S1

Highly suitable, lands have no significant physical limitations to sustained coconut cultivation and will also not require inputs above an acceptable level. Coconut palms on these lands have the potential of yielding more than 15 000 nuts/ha/year up to a maximum of 25 000.

Suitability class S2

Suitable to highly suitable. Lands that have minor limitations to sustained coconut cultivation that will slightly reduce productivity, and will also not require inputs above an acceptable level. Coconut palms on these lands will have the potential of yielding 12 500 to 15 000 nuts/ha/year.

Suitability class S3

Suitable. Lands that have some limitations to sustained coconut cultivation that will reduce productivity, and also requiring increased inputs to the extent that the overall profit is attractive but will be inferior to that from S2 lands. Coconut palms on these lands will have the potential of yielding 10 000 to 12 500 nuts/ha/year.

Suitability class S4

Moderately suitable. Lands that have limitations which in aggregate are moderately severe for sustained coconut production. The limitations will reduce coconut productivity, and it will also require increased input to the extent that the overall profit will be moderately attractive, but appreciably less than that expected from class S3. Coconut palms on these lands potentially produce 5000-10 000 nuts/ha/year.

Suitability class S5

Marginally suitable. Lands that have severe limitations for coconut growth. Very high inputs are needed limiting the overall profit. Coconut palms will have the potential of yielding 2500 to 5000 nuts/ha/year.
### annex 3: Requirements for growth of Coconut (Cocos nucifera L.)

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<th>Class, degree of limitation and rating scale</th>
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<td>Gypsum</td>
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<td>ECe (mmhos/cm)</td>
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<td>ESP (%)</td>
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*After Sys et al. (1993)*
annex 4: Sample analysis methods Bandaripuwwa estate

(a). Soil texture

Soil particle separation was done on the remaining fraction using the pipette method (Gee and Or, 2002). Soil particles suspended in solution settle out at a rate that depends on the size of the particles, the larger the particle, the faster it settles. This principle is given by stokes law:

\[
v = \frac{2}{9} (D_s - D_l) g r^2 / \eta
\]

Where

- \(v\) is the settling velocity \([cm\ s^{-1}]\)
- \(D_s\) is particle density \([g\ cm^{-3}]\)
- \(D_l\) is water density \([g\ cm^{-3}]\)
- \(g\) is acceleration due to gravity \([cm\ s^{-2}]\)
- \(r\) is radius of particle \([cm]\)
- \(\eta\) is water viscosity \([g\ cm^{-1}s^{-1}]\)

From this velocity, the settling time can then easily be calculated using a certain distance. Using a distance of 10 cm and substituting the appropriate values in Stokes’ Law gives following settling times:

- silt + clay (0.005 cm) : 36 s
- clay (0.002 cm) : 6h 16 min

Thus, if a soil sample is completely dispersed in water and agitated so that at time zero sand, silt and clay particles were uniformly distributed in the water, an aliquot of this suspension taken after 36 seconds and at a depth of 10 cm will not contain any sand, only silt and clay. Similarly, an aliquot taken at 6h16min will only contain clay particles. From these two aliquots, percentages clay, silt and sand can be determined. Normally the fraction of sand is determined by using the fact percentages clay, silt and sand sum to 100, but to have a more accurately value for sand percentage, the remaining suspension in the sedimentation jars is passed through 53 µm sieve. Using wet sieving, the sand fraction can be determined. After determining these fractions, USDA soil classification system was used to determine the textural class.

(a). pH-KCl

The pH of the soil was measured using a 1:2.5 soil:liquid mixture. As liquid, 1 M KCl was used, as described by Reeuwijk, 2002. 10g of soil was mixed for 20 minutes with 25 ml of 1M KCl solution using a glass rod. pH of the suspension was measured using a calibrated pH meter.
(b). EC
To measure the electrical conductivity of the soil samples, an EC meter was used in a 1:5 soil:water suspension. 10g of air dried soil was shaken vigorously with 50ml of water for about 1 minute after which it was kept for 20 minutes to settle the larger soil particles. Same procedure was followed for each of the soil samples.

(c). Cation Exchange Capacity (CEC)
The dominant residual charge on most soil colloids (usually clay, organic matter and sesquioxides) is negative. These negatively charged sites attract and adsorb positively charged ions (cations) out of the soil solution. Adsorbed cations resist removal by leaching water but can be replaced (exchanged) by other cations. This exchange of one cation by another is called cation exchange, Cation Exchange Capacity is then the amount of exchangeable cations per unit weight of dry soil. This method is the pH 7.0 ammonium acetate procedure as defined by Chapman (1965). To measure this capacity an ammonium acetate solution at pH 7 is used in order to replace all exchangeable ions by ammonium ions. After this the remaining ammonium concentration is measured by titration, from which the CEC can be obtained.

(d). Total exchangeable bases
Exchangeable Na⁺, K⁺, Ca²⁺ and Mg²⁺ are the major basic cations in soils and the sum of these four cations is generally considered as major exchangeable bases. Percentage saturation of CEC by these bases is termed as Percent Base Saturation (%BS), the other free spaces are mainly occupied by acidic cations like H⁺ and A³⁺. Sum of K⁺, Ca²⁺ and Mg²⁺ concentrations are defined as the sum of basic cations (SBC), Na is omitted out since it is included in the ESP property. The concentrations of these bases are obtained by displacement of the basic cations by ammonium after which the displaced cations are measured using both Atomic Absorption Spectrophotometer (AAS) and Flame Emission Spectrophotometer (FES).
### Annex 5: Soil properties of study area 1 (Bandiripuwwa estate) at sampling locations

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annex 6: Data analysis Mahailluppallama study area

Figure 28: Location measurement points ECa Mahailluppallama study area

Table 13: Parameters theoretical variogram model ECa-PRP

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<td>C1 (sill)</td>
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<td>a (range)</td>
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Figure 29: Location maps soil samples on EC$_2$-PRP maps of Mahailluppallama study area
annex 7: Exploratory EC\textsubscript{a} analysis Bandiripuwwa estate

Figure 30: Histogram HCP-EC\textsubscript{a} total dataset Bandiripuwwa estate (max frequency = 13667)

Figure 31: EC\textsubscript{a}-PRP Stem-and-Leaf Plot
**Figure 32 : HCP-EC₃ Stem-and-Leaf Plot**

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Stem width: 1.00

Each leaf: 13 cases